Automated People Movers and Transit Systems 2013

Half a Century of Automated Transit—Past, Present, and Future

Proceedings of the 14th International Conference

ASCE

EDITED BY
William H. Leder, P.E.
William J. Sproule, Ph.D., P.E

TRANSPORTATION & DEVELOPMENT INSTITUTE

AUTOMATED PEOPLE MOVERS AND TRANSIT SYSTEMS 2013

HALF A CENTURY OF AUTOMATED TRANSIT—PAST, PRESENT, AND FUTURE

PROCEEDINGS OF THE FOURTEENTH INTERNATIONAL CONFERENCE

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Preface

The 14th International Conference on Automated People Movers and Automated Transit Systems was held at the Phoenix Marriott Mesa Hotel in Mesa, Arizona. The theme of the conference was *Half a Century of Automated Transit – Past, Present and Future***.** Almost half a century ago the Urban Mass Transportation Act of 1964 provided $375 million in matching funds for public transit in the United States and this legislation has been seen as the beginning for APMs. In terms of an historical perspective, it is noted that the 1966 Reuss-Tydings Amendments to the original1964 legislation required, among other things, that the Secretary of Housing and Urban Development *"...undertake a project to study and prepare a program of research, development, and demonstration of new systems of urban transportation that will carry people and goods within the metropolitan area speedily, safely, without polluting the air, and in a manner that will contribute to sound city planning."*

The Conference Proceedings include over 50 papers that looked back over the past fifty years of APM development, examined the current state of APMs and ATS, and explored what the future might hold. The papers covered a wide range of topics including history, Personal Rapid Transit (PRT) applications, airport projects and other major activity centers, system improvements, facility planning and design, safety, security, standards, automated train control, and policy. All papers included in the Proceedings have been peer reviewed and accepted for publication.

The Phoenix area provided an exciting setting for the conference as a technical tour and several papers focused on the new PHX Sky Train™ APM at the Phoenix Sky Harbor International Airport. The first phase of this APM had just opened for public service, and the system included several significant fixed facility and operating system components.

The first conference was held in Miami, Florida in 1985 and since that time subsequent conferences have bought together planners, inventors, designers, suppliers, builders, owners and operators of automated transit of all forms to share their experiences, reveal innovations, and discuss what they have learned. Past conferences have been held around the globe and have built an international collegial community and the Proceedings have become an invaluable reference source. In 2011, automated transit systems were added to the automated people mover focus in recognition of exciting applications on line haul metro systems, and the Phoenix conference continued that addition.

1985	Miami, Florida	2001	San Francisco
1989	Miami, Florida	2003	Singapore

1991	Yokohama, Japan	2005	Orlando, Florida
1993	Irving, Texas	2007	Vienna, Austria
1996	Paris, France	2009	Atlanta, Georgia
1997	Las Vegas, Nevada	2011	Paris, France
1999	Copenhagen, Denmark	2013	Phoenix, Arizona

The editors acknowledge the significant efforts of the many authors and reviewers who through their efforts have created these Proceedings in both time and place.

Bill Sproule
Bill Leder

Acknowledgments

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APMs and Airport Mobility – Historic Trends and Future Possibilities

David D. Little, AICP[1] and Sarah Elizabeth Ross, AICP[2]

[1] Principal, Lea+Elliott, Inc., 44965 Aviation Drive, Suite 290, Dulles, VA 20166; PH (703) 968-7883; FAX (703) 968-7888; email: DDLittle@LeaElliott.com
[2] Transit Planner, Lea+Elliott, Inc., 44965 Aviation Drive, Suite 290, Dulles, VA 20166; PH (703) 537-7450; FAX (703) 537-7451; email: SRoss@LeaElliott.com

Abstract

APMs have helped meet the evolving passenger mobility needs at major international airports for over 40 years. Since the first APM implementation at Tampa in 1971, APMs' mobility capabilities have improved in terms of speed, capacity and frequency. These improvements have allowed airports to grow in size and still meet the level-of-service requirements of the traveling public. With a number of airports approaching passenger volumes of 100 million annually, the demand for the high quality mobility service provided by APMs has never been greater.

This paper documents the technical improvements of the APM technology over the past 40 years and correlates these mobility improvements with the increases in airport annual passenger volumes. APMs are placed into the context of the range of technologies that serve today's major airports mobility needs. The use of APMs at airports in a growing number of world regions is also detailed. Finally the paper looks at potential future improvements to the APM technology that will allow airports to handle annual passenger volumes far in access of 100 million. APM Conference topics covered in this paper will include:

- History – past experience and lessons learned
- Airports – assessment of newly implemented projects
- PRT – status of on-going and planned PRT projects at airports

This paper should benefit the professional Airport and transport community by defining the historic relationship between airport's internal transport systems and the airport's annual passenger volume and to see what that relationship may mean for the future.

1.0 APM AND AIRPORT HISTORICAL GROWTH

There has been tremendous growth in the size and the passenger volumes of major international airports around the world over the last 40 years. The original airside (secure) airport APM was opened in 1971 at Tampa and consisted of multiple, dual-lane shuttles ranging from 183 to 305 meters (600 to 1,000 feet) in length. Today, the longest airside system is over 25 times longer than the original Tampa shuttles. In 1971, Atlanta's airport handled 18 million annual passengers (MAP) while by 2011 it accommodated 92 million and has projected to reach 110 million by 2020. As airports have grown in passenger traffic, they have also grown in physical size.

The number of APMs at airports grew slowly during the 1970s with two systems opening after Tampa. Seattle opened a tunnel APM system with two separate loops and a shuttle in 1973 and Dallas/Fort Worth implemented a complex landside system in 1974. Five more airside APMs opened in the 1980s; four in the U.S. and one at London-Gatwick. Twelve airside APMs opened for service in the 1990s with four in the U.S., three in Europe and five in Asia. In the first decade of the new millennium, another eleven airside APMs were implemented with three in the U.S., four in Europe, three in Asia (including one in China), and one in Mexico. As the current decade proceeds, new airside systems have opened in the U.S. (Miami) and the Middle East (Dubai). Additional systems are currently in various stages of planning, design and implementation in many regions of the world with China and the Middle East expected to see the strongest relative growth in airport APM implementation in the near term.

The emergence and growth of APMs at airports since 1971 can be attributed to two main factors: (1) improvements in APM-related technologies, and (2) airport passenger volume growth.

1.1 APMs' Technical Improvements

The beginnings of the APM technology can be traced back to the early 1960s and Westinghouse Electric Corporation's Skybus automated technology. This technology development was funded in part by the U.S. federal government. In 1965, the South Park Demonstration Project opened in Pittsburgh and operated as an urban transport system for the next two years. While a few urban APM systems would open in the 1980s, it was in the airport environment that Westinghouse's improved version of the Skybus would flourish.

Source: www.pghbridges.com

Figure 1 – Pittsburgh Skybus Demonstration

A big reason behind the emergence of APM technology was the advent of improved transistor and solid-state technologies. Integrated circuits allowed the complex control equipment required for the safe and reliable operation of a smaller vehicle (approximately 12-meter (40-foot) long) to be compact and lightweight enough to easily fit on the vehicle. The necessary control and safety equipment could now be built into modules to be used for propulsion, braking, and door controls, as well as monitoring the performance of these subsystems. Microprocessor and software-based train control have continued to improve and expand the capabilities and capacity of APMs.

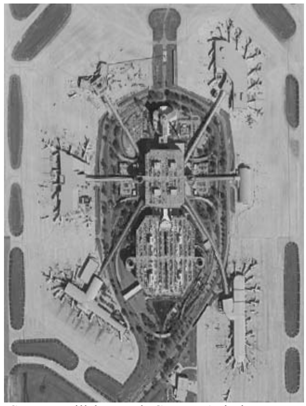
The APM switch, or crossover, allows an APM train to move between two parallel guideway lanes. The switch allows a train proceeding along one lane the option of either continuing along that lane or crossing over to the parallel lane. The initial shuttle systems did not require switches for their operations. The Seattle-Tacoma Airport system opened in 1973 and was configured with two airside loops due to a lack of a switch by the APM system supplier, Westinghouse. The original APM system at Dallas/Fort Worth (DFW) International Airport opened in 1974 as a complex landside network and had operating switches to allow trains to diverge from the mainline to off-line stations. These DFW trains moved only in a single direction.

The Westinghouse switch and “pinched-loop” operations for the airside system at Atlanta in 1980 were significant advances for the potential capacity of APM systems. The pinched-loop operations at each terminus station allowed multiple trains to operate on a dual-lane linear alignment. Atlanta opened with six 2-car trains operating along its 1,219-meter- (4,000-foot-) long system. An equivalent shuttle system would have required two 6-car trains to provide the same capacity and its stations would therefore be three times longer.

Advances in automated train control (ATC) technology, which allows for the safe operation of the driverless trains, have been instrumental in APM capacity improvements. The ATC system provides adequate distance between successive APM trains to ensure that a following train will stop in time if a lead train makes an emergency stop. The system keeps track of train speed and position in order to achieve the safe separation. Improvements in ATC technology have allowed the location of each train to be updated more frequently thus allowing the safe separation distances to decrease and an APM system frequency and capacity to increase.

Historically, APM train suppliers provided their own proprietary, “fixed block”, ATC subsystem that provided train operation, train protection and train supervision functions. Early fixed-block systems were relay-based and eventually microprocessor-based when trains occupied “blocks” or specific segments of given guideway length. A trailing block of guideway behind a guideway block occupied by an APM train could not be entered into by a trailing APM train. In the 1980s, communication-based train control (CBTC) was developed and allowed train location to be continuously updated, thereby greatly reducing the separation distance between successive APM trains.

1.2 Airport Annual Passenger Volumes

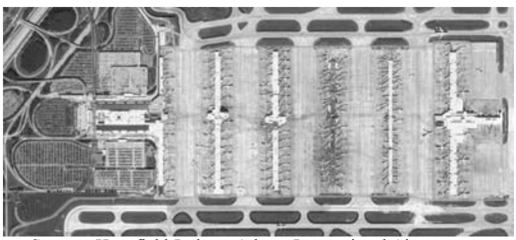


Source: Hillsborough County Aviation

Figure 2 - Tampa International Airport

Airport passenger volumes, increased substantially in the U.S. during the late 1970s and 1980s. The U.S. Airline Deregulation Act of 1978 was a big reason for this increase. Competition among the airlines led to lower ticket prices and greater numbers of flights. Enplanements rose from 170 million in 1970 by almost three-fold in just twenty years. New, so-called “discount airlines”, emerged in the early 1980s and helped to drive this increase. Airlines began transitioning their operations from point-to-point service to hub-and-spoke service with central airports serving as an airline’s hub, with multiple spokes serving hub airports. Airline “hubbing” operations increased airside (secure side) passenger conveyance needs significantly at these hub airports. The growth of passenger volumes overwhelmed the older terminal facilities at some airports, necessitating the addition of new terminal buildings and satellites for which the APM was well-suited to connect. Some new airport terminals built in the 1970s, such as Tampa, and Orlando, used APM technology as an integral part of their configuration for airside mobility of origin/destination passenger traffic.

The hub-and-spoke system was a more efficient way for an airline to transport its passengers. The big increase in overall passenger volumes and the concentration of passengers at hub airports put tremendous strain at those airport’s existing terminal facilities with a greater importance on gate-to-gate connections as opposed to the old ticketing-to-gate movements.



Source: Hartsfield Jackson Atlanta International Airport

Figure 3 – Hartsfield Atlanta International Airport

The new Atlanta Hartsfield International Airport that opened in 1980 was designed to better accommodate connecting passengers with its “Central Passenger Terminal Complex” located between the runways. This complex consisted of a terminal building with ticketing/ baggage processing, and four remote rectangular concourses holding a total of approximately 100 aircraft gates. Each of the parallel concourses was only about 305 meters (1,000 feet) apart and all buildings were connected by the underground APM. The APM allowed quick and convenient connections between all 100-plus gates. Each 610-meter (2,000-foot) long rectangular airside concourse was "double-loaded", with aircraft gates along the two long sides of the building. Prior terminal design typically had single-loaded corridors with gates along one side and processing functions along the other side. The terminal roadway and parking would be adjacent to the terminal processing functions. This design minimized the parking to gate walk distance for the dominant airline passenger: the origin/destination (O/D) passenger.

The new airside concourse design at Atlanta minimized the walk distance for its predominant airline passenger; the connecting passenger and their gate-to-gate journey. Other airports have replicated the Atlanta design of parallel, rectangular and remote concourses. The new Denver International Airport and Hong Kong Airport built in the 1990s on "green field" sites incorporated this design while the airports such as Houston, Cincinnati, Phoenix and Heathrow have been reconfiguring their existing terminal design into this more "connection-friendly" configuration.

Airport expansion can be measured in terms of many different variables. The airport expansion variables discussed previously include annual passengers accommodated, number of aircraft gates, and number of terminal buildings. The resulting expansion of these major international airports was to push the physical boundaries of the airport. While the classic origin/destination airport, Washington National Airport (DCA), built in the 1920s, required a land area of 3.4 square kilometers (1.3 square miles), the later O/D airport design of Tampa in the late 1960s required only 12.9 square kilometers (5 square miles). The "hub" airport design at Atlanta required close to 25.9 square kilometers (10 square miles) while a similar hub airport design in Denver has a land area of over 129.5 square kilometers (50 square miles).

2.0 AIRPORT MOBILITY TECHNOLOGIES

For airside conveyance of airline passengers between aircraft gates and main terminal functions (check-in, security and bag claim) as well as connecting transfer passengers between aircraft gates; there are three conveyance technologies historically employed: moving walkways, apron buses and APMs. More recently personal rapid transit or PRT has been implemented to transport airport passengers.

2.1 Automated People Movers

APMs are fully automated, driverless vehicles operating on fixed guideways or tracks along an exclusive right-of-way. APMs are divided into two major groups: cable-propelled and self-propelled. Monorails, rubber tire and larger steel-wheel technologies are considered within the self-propelled group.

Cable-Propelled - This type of technology consists of medium- to large-capacity trains using cable propulsion. System line speeds of 48 kilometers per hour (kmph) (30 miles per hour (mph)) can be achieved with longer station-to-station distances but the typical airside station-to-station speeds average 32 kmph (20 mph). The fixed-grip-technology is best suited for two- or three-station shuttle applications with relatively straight guideway alignments of 0.8 kilometers (0.5 miles) or less. Detachable-grip is a new advance in the technology that allows for three or more trains to operate over distances of up to 4.8 kilometers (three miles).

Self-Propelled - Self-propelled trains use a two-rail guideway system with rubber tires on concrete or steel wheels on steel rail. System maximum speeds range between 56 and 72 kmph (35 and 45 mph) depending on the supplier's technology with longer station-to-station distances but the typical airside station-to-station speeds are 40 to 48 kmph (25 to 30 mph).

Source: Poma-Otis Transportation Systems

Figure 4 – Cable APM

System capacity for both types of airside APMs can reach 10,000 passengers per hour per direction (pphpd) assuming 75 passengers per vehicle (passengers with carry-on baggage), four-vehicle trains and two-minute headways. Longer trains and headways under two minutes will soon be providing capacities over 12,000 pphpd.

2.2 Personal Rapid Transit

Personal Rapid Transit (PRT) is a smaller automated technology that provides direct connection between any origin/destination station pair. The first airport implementation of the technology was at London Heathrow in a landside connection between Terminal 5 and an employee parking lot. The technology is best suited to provide personalized, non-stop service for small groups of one-to-five passengers over a grid-like network and should achieve capacities of 600 to 750 pphpd for a single lane of guideway as larger systems are implemented at airport settings.

Source: Bombardier Transportation Systems

Figure 5 – Self-propelled APM

Source: Raytheon PRT

Figure 6 – PRT Vehicle

2.3 Apron Buses

Rubber-tired apron buses are a common transport mode at many airports around the world. At-grade bus operations are able to accommodate a variety of passengers and destinations with good flexibility and lower costs.

Buses are very flexible; routes and stations (stops) can be changed or added easily. These driver-operated vehicles are typically diesel-powered. Maintenance can occur either on-airport or off-airport. Bus lengths are typically 13.7 meters (45 feet) and bus width is around 2.6 meters (8.5 feet) for regular transit buses (with minimal seating) or up to 3 meters (10 feet) of width for specialized apron buses.

Source: Cobus Industries, LP

Figure 7 – Apron Bus Conveyance Technology

Apron buses may have to cross active taxiways, where aircraft have the right-of-way, and can only achieve operating speeds well below their maximum speeds. Buses can carry 80 to 100 passengers in an airside application (carry-on baggage). A main terminal to remote concourse bus system with a single route at three-minute headways can achieve system capacities of 1,500 to 2,000 passengers per hour.

2.4 Moving Walkways

Moving Walkways provide a level or slightly inclined, continuous moving surface of pallets, that move passengers (standing or walking) and their baggage over moderate distances. These devices are sometimes referred to as moving sidewalks, moving walkways, movingwalks, and travelators.

Source: Lea+Elliott, Inc.

Figure 8 – Movingwalk Conveyance Technology

Typical walkway speeds range between 27 and

36 meters per minute (90 and 120 feet per minute) or half the normal walking speed of a pedestrian. The resulting passenger speed ranges from 27 meters/minute (90 feet/minute) (passenger standing) to 64 meters/minute (210 feet/minute) when passengers walk on the movingwalk. Moving walkway segments range in length between 9 and 152 meters (30 and 500 feet) and widths between 0.6 and 1.4 meters (24 and 55 inches). Passenger conveyance capacities are a function of width, passenger density, passenger passing ability, walking/ standing ratio and the moving walkway's speed. For an airside airport application with baggage, movingwalk capacities can reach 4,000 passengers per hour.

3.0 APM APPLICATIONS BY WORLD REGION OVER TIME

Airside Shuttles: 1970s-1980s

The original airport airside APM system opened at Tampa in 1971. Airside two-lane shuttles, operating single trains on each of the lanes, dominated airport APM implementations for the next twenty years These systems were relatively short in length (182 to 610 meters (600 to 2,000 feet)), served two stations, and had relatively simple propulsion and train control. Each train had a single lane "to itself."

Source: Bombardier Transportation Systems

Figure 9 - Airport Airside Shuttle APM

Tampa, Miami and Orlando are examples of the typical elevated airside shuttle APM systems that were predominant during this period. Seattle and Atlanta were two notable exceptions. The Seattle APM consisted of two independent multi-train loops installed in a tunnel and connected by an independent single lane shuttle. Atlanta opened its airside APM system in 1980 with two parallel guideways lanes that are "pinched" at both ends, thus allowing trains to change over to the opposing lane for the return trip. This feature permitted simultaneous operation of more than two trains. However, simple shuttles were the dominant guideway configuration of the first two decades of APM applications with Westinghouse's C-100 technology as the dominant technology.

The majority of these airport APMs were implemented in the U.S. during this time period. A single system was built in Europe, and all systems tended to be in warmer climates where snow and ice on the guideway were not factors.

Pinched Loops and Shuttles: 1990s

Longer APM systems with pinched-loop operations serving many terminals became more commonplace with APM implementations in the 1990s. Hong Kong, Denver and Frankfurt, all major hubbing airports, implemented airside pinched-loop APM systems, similar to the system in Atlanta. High-capacity transport of passengers over greater distances, from 1,524 to 3,048 meters (5,000 to 10,000 feet), became possible by running multiple trains with service frequency as low as two minutes. As the demand for these systems grew, a greater number of APM suppliers began to provide the longer systems, and expanded station spacing led to an increased emphasis on greater speeds between stations than with the earlier shuttle applications.

Although pinched-loop systems were becoming more prevalent, the 1990s also saw implementation of new airport shuttle systems. While earlier shuttles were often self-propelled, with motors on vehicles, a number of shuttles, such as Cincinnati and Tokyo (Narita), were now cable-propelled using wayside motors. New airport APM systems were opened in countries outside North America, with new airport implementations in England, Germany, Hong Kong and Japan.

APMs Multiply and Emerge in New Regions: 2000 to 2012

As airport APMs entered the 21st century, innovation and expansion occurred in all areas: the configuration of guideways, train speed, system length, vehicle propulsion and suspension, the number of APM suppliers and the number of countries implementing APM systems. Some of the industry innovations included:

- Communications-based train control
- Detachable-grip cable allowing pinched-loop operations
- Spanning runways , under and around, and spanning taxiways, under and over
- Train control and vehicle upgrades while maintaining operations

In the first twelve years of the new century, the number of airport airside APMs has almost doubled, as shown in Table 1, in comparison to the number of systems built in the initial twenty-nine years of the technology.

Table 1 – Summary of Existing Airport Airside APMs

Airport	Started Service	Average Length km (miles)	Capacity[2] (pphpd)
Tampa[1] (4)	1971	1.1 (0.7)	6,500
Seattle	1973	2.7 (1.7)	7,500
Atlanta	1980	1.9 (1.2)	10.000
Miami – Conc. E	1980	0.3 (0.2)	6,750
Orlando[1] (4)	1981	2.4 (1.5)	6,000
Las Vegas – C gates[1] (2)	1985	0.6 (0.4)	7,000
Singapore Changi[1] (7)	1990	2.4 (1.5)	1,000
London Stansted	1991	0.6 (0.4)	3,200
Pittsburgh	1992	0.6 (0.4)	8,500
Tokyo Narita	1992	0.3 (0.2)	9,800
Cincinnati	1994	0.3 (0.2)	5,700
Frankfurt	1994	1.6 (1.0)	4,500
Osaka Kansai	1994	2.2 (1.4)	10,000
Denver	1995	1.9 (1.2)	8,300
Hong Kong[1] (2)	1998	0.6 (0.4)	5,000
Kuala Lumpur	1998	1.3 (0.8)	3,000
Houston	1999	1.6 (1.0)	4,900
Rome	1999	0.6 (0.4)	5,300
Detroit	2002	1.1 (0.7)	4,000
Minneapolis/St. Paul	2002	0.3 (0.2)	1,700
Taipei	2003	1.3 (0.8)	6,000
Zurich	2003	1.1 (0.7)	4,500
Dallas/Ft. Worth	2005	7.8 (4.9)	5,000
Madrid	2006	2.2 (1.4)	6,500
Mexico City	2007	3.0 (1.9)	540
Paris CDG	2007	0.6 (0.4)	4,500
London Heathrow	2008	0.6 (0.4)	6,500
Beijing	2008	1.9 (1.2)	4,100
Seoul Incheon	2008	0.9 (0.6)	5,184
Washington-Dulles	2010	2.4 (1.5)	6,755
Miami North Terminal	2010	1.1 (0.7)	9,000
Dubai[1] (2)	2012	1.2 (0.8)	5,425

Source: Lea+Elliott, Inc.

Notes: 1. Airport with multiple APM airside systems, number of systems in parentheses
2. Average capacity for overall APM system with multiple airside APM lines.

4.0 AIRPORT ACTIVITY AND APM CORRELATIONS AND TRENDS

In recent years, higher levels of economic growth have shifted to areas of the globe with greater population densities. This is greatly expanding the number of people able to fly for both work and recreation. This has resulted in planning of numerous airports, existing and new, that will exceed 100 MAP. This section of the paper looks at the general historic correlation of large airport activity levels (measured in MAP) and their APM capacity level. Possible future trends of the activity level to APM level are then projected.

4.1 World's Busiest Airports Today and APMs

Despite the economic slowdown worldwide over the past four years, airport traffic at the world's top airports has continued to grow. In 2008, the year before the economic downturn was fully realized, the cumulative annual passengers handled by the world's top ten airports was 631 million. Last year, the cumulative annual passengers handled by the world's top ten airports was 660 million, a 4.6 percent increase. While this is partly explained by a shift in the location of these top ten airports, the same finding is found in the top ten U.S. airports in this same timeframe with an increase of approximately one percent.

Historically, airside APMs are becoming more and more commonplace for the world's top airports. Of the top twenty airports in the world in 2001, as measured in MAP, eight had at least one airside APM. This number increased to ten some five years later, and increased to twelve another five years later in 2011. As the percentage of top 20 airports with APMs has increased over this timeframe, the location of these airports has changed as well. As shown in Table 2 below, these top airports have been shifting predominately to Asia and away from Europe and North America.

Table 2: Top 20 Airports by World Region

World Region	Number of Top 20 Airports		
	2001	2006	2011
North America	12	11	7
Europe	6	5	5
Asia	2	4	7
Middle East	0	0	1

Source: Lea+Elliott, Inc.

4.2 Airport Projected Growth

Airport planning is proceeding for expanded airports and new airports to accommodate passenger volumes upwards of 120 to 160 MAP. The upper end of these volumes are double that of today's busiest airports. These passenger volume estimates vary in terms of their split between O/D traffic and connecting traffic.

Growth in O/D traffic is typically tied to local population growth projections while estimated growth in connecting traffic is based on strategic airline assumptions.

For a number of airports, the use of an APM or APMs on the airside can be correlated over time to the airport's MAP activity level. For some airports, such as Atlanta's Hartsfield Jackson (ATL), its airside APM has been in operation for over thirty years and has grown with the airport. For other airports, newer airside APM systems have extension (length) and expansion (capacity) plans that coincide with future activity levels as measured in MAP.

4.3 Airport Activity and Airside APMs

While the specific APM configuration in terms of train length, system length, number of stations, and frequency, are all determined through detailed analysis, it is still possible to determine a correlation between MAP and APM capacity growth by looking at individual airports.

For the purposes of this paper, APM capacity is measured as a product of "passenger movement" capacity and system length. The passenger movement capacity is measured in terms of passengers per hour per direction (pphpd) which is the standard measure of an APM system's capacity at any given point along the system. System length is then multiplied by system capacity to obtain a more reflective measure of the amount of APM capacity provided at any given APM application.

Analyzing the data for a number of the top 20 airports worldwide found increases of 10 MAP resulted in increases in APM capacity from a low of 2,400 pphpd-km to a high of 6,500 pphpd-km. While the specific findings at individual airports are of analytical interest, they do not translate into a prescriptive correlation between airport activity growth and the need for airside APMs. The findings do, however, highlight the importance of this passenger conveyance technology in the future for the major international airports of the world. As airport activity level is forecast to increase at these airports in the future, they will likely need to implement or increase the level of their APM system(s). For example, an airport increasing from a current level of 80 MAP to a future level of 120 MAP would potentially need an additional 9,600 to 26,000 pphpd-km of APM capacity. These are significant numbers, as the current APM system at the largest airport in the world has an APM capacity of 19,000 pphpd-km.

The dynamic nature of airport passenger volumes, airline alliances, and airport terminal configuration, all point to the importance of flexibility and expandability in the design of an airside APM for a major international airport. The ability to extend an APM in length, and/or expand an APM's capacity, all while keeping the initial APM system in operations is critical to the continued success of a major airport. This requires special emphasis on "lessons learned" for issues such as station configuration, maintenance facility size and location, end-station switch configuration, and other issues. While building in flexibility and expandability to an initial system will cost more, the savings incurred during system expansion typically will more than pay for those additional initial costs.

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AIRPORT APMs – HISTORY AND FUTURE

William H. Leder[1] and William J. Sproule[2]

[1] Adjunct Professor and Distinguished Practitioner in Residence, Department of Civil and Environmental Engineering, Houghton, Michigan, USA; 906-487-1647; bleder@mtu.edu
[2] Professor, Michigan Technological University, Department of Civil and Environmental Engineering, Houghton, Michigan, USA; 906-487-2568; wsproule@mtu.edu

ABSTRACT

The first airport APM was placed in service at Tampa International Airport in 1971. Airport APMs at SeaTac and Dallas-Fort Worth followed in 1972 and 1974, respectively. Today there are 46 airport APM systems in operation world-wide, and several are under construction. The PHX Sky Train™ is the latest to enter passenger service. Although there have been many challenges over the past four decades, APMs are in the mainstream of airport planning, design, and operation. They are recognized as an acceptable and effective technique for overcoming the large scale of high capacity airports. This paper/presentation will trace the history of the development of airport APMs, discuss current status, and look into the future. Included are first person accounts of pioneers in the development of these early systems. What will be the future role of APMs as air travel continues to grow, and how might APM technology evolve?

AIR TRAVEL GROWTH AND AIRPORT EXPANSION

Air travel began growing rapidly after World War II, especially in the 1960s and 70s with the use of turbojet passenger aircraft. In Europe the Comet entered service in 1954, followed in the United States by the Boeing 707 and Douglas DC-8 in the late 1950s. In 1958, when the Boeing 707 began airline service, there were 53 million enplanements in the United States. Just 12 years later in 1970, the first Boeing 747 wide-body airliners were being delivered to the airlines, and enplanements had doubled to 108 million.(1) In response to increased demand, airport terminals and related facilities were expanding rapidly and long walking distances were a major concern of airport planners of the day. Only one half of the U.S. population had ever flown, but that was changing rapidly.

THE EARLY YEARS OF AIRPORT APMs

Three pioneering airport APM projects in the 1970s will be highlighted. These seminal projects, undertaken at considerable risk with a new technology that was required to perform with very high reliability, established a pathway for the scores of airport APMs that followed in subsequent decades.

TAMPA INTERNATIONAL AIRPORT

In the late 1960s, Tampa, Florida's Hillsborough County Aviation Authority, under the leadership of Director of Aviation George Bean, decided to take an innovative approach to new terminal facilities. Instead of simply collecting space, gate, and concession requirements, the Authority retained the airport consulting firm, Leigh Fisher Associates, to review the major airports in the United States and develop recommendations for a new Tampa terminal. In their review they found that walking distances tended to increase with the growth of air passengers, as simply lengthening piers, and thus walking distances, was the common means to add capacity. To reduce walking distances, an airside-landside concept placed aircraft gates in satellite terminals located on the apron and separated from a central terminal building as shown in Figure 1.

Figure 1: Tampa Landside-Airside Concept (http://www.wikipedia.org)

A key component of the concept was a reliable transit system that would shuttle all passengers between the satellite terminals and the central terminal building. The innovative airside-landside concept was born at the new Tampa terminal, and an APM developed by the Transportation Systems Division of Westinghouse was selected to shuttle passengers on dual lane guideways 240 to 300 meters (800 to 1,000 feet) long. The opening on April 15, 1971, marked the first significant airport application of a transit technology known as the Automated People Mover. (2) Westinghouse was well positioned to supply the Tampa APM based on refinement of its Skybus technology that had been demonstrated at South Park in Pittsburgh, Pennsylvania.(3) Neighboring Orlando International Airport would follow in 1982 with a similar airside-landside concept that employed APM shuttles. The Tampa APM has undergone modernization, remaining in service today, transporting all airline passengers and many employees.

Larry Smith, former Director of Facilities at Tampa (retired), has provided the following account.(4)

"In the late 60s, I had a secure and promising job with the Aviation Dept. of the Port Authority of NY & NJ. I was on the PA's Speakers Bureau and my specialty speech was "The New Newark International Airport Redevelopment Project". The presentation included a segment on the "future inter-terminal transfer device" and featured elaborate slides showing the "Notch" Right of Way throughout the terminal cross-sections.

A future inter-terminal transfer device was presumed to be years away and would have to have demonstrate a proven track record, (the notch remained empty for 20 years). The Port Authority Airports JFK, LGA, EWR were leading the world in handling air passengers and was a leading innovator in all aspects of transportation – but there was no proven inter-terminal transfer device.

Along comes The 30th ranked US Airport, (Tampa) with a bold new untried, untested, airport development concept that was totally dependent on driverless, self propelled, "horizontal elevators" – I just had to get in on this. The small team at Tampa Airport was committed to the concept, but we were also very much aware that the only prototype was the Westinghouse South Park demonstration project that had little in common with a "must ride' Airport link and demanding airline passengers instead of seasonal fair attendees.

The new and bold Tampa airport concept was loaded with innovations – a green field site miles from the existing terminal: The new multi level hub for terminal parking, ticketing, bag claim, hotel and concessions, and four spokes for remote airsides accessed by eight "must ride" shuttles. The old terminal was store front at street level and had no moving parts, (elevators, escalators, loading bridges, bag belts, automatic doors, no hot water in restrooms-really old school!) The proposed People Mover system and escalating project budgets was the delight of the press and led the debates of 'what ifs.'

Job security was often defined as 'must succeed or else.' Of the seven director level staff, only three of us were directly linked or considered at risk – the remaining 70 employees were civil service. The airline negotiators had insulated themselves with 30 year long term leases with the first five years at a fixed rate – failures could not be covered with bailout money.

The Challenge

There were no APM standards, no experienced APM technicians, no APM performance histories, no such thing as test tracks, no maintenance facility, no spare car, and no way to remove a car other that by huge mobile crane, (an early proposal to provide built-in car hoisting elevators at each track was scrapped). The only passenger access between airside and landside was the emergency walkway, and buses were not an option with this airport layout, and there were no existing competitors. The airport had to simultaneously open four airsides and serve 11 airlines.

Lea+Elliott formed a few years later. There were a few consulting professionals with automatic transit systems experience and a few inventors with great ideas.

What If

Our security blanket was spelled out in a first ever sole source contract with a five year maintenance provision with vague performance criteria but no real data to benchmark. Our maintenance contract stipulated a crew of six and one supervisor – at least one person on duty at all times. If the system failed it meant that we, the contractor, and the concept failed.

The Dubious Penalty Clause

Figure 2: Westinghouse APM vehicle at TPA, 1971 (http://www.brokklineconnection.com)

The failure to perform clause required that we send a full rate telegram, ($5 for first 15 words, guaranteed delivery within 4 hours – is that the forerunner of the tweet?) to our contractor in Pittsburgh to establish the exact time of the failure. We recorded each of the eight car outages separately on a continuous roll of drafting paper, a pattern of reliability gradually evolved based on time between events and time to restore. Troubleshooters rode bikes on the walkway to speed restoration, (no grace period when the world is watching). We never sent a telegram, and the original penalty of $10/hr for every hour over twelve accumulated in a month was handled on site with a dedicated team from the local Electric Service Division of Westinghouse. These technicians were astute troubleshooters who worked on all types of heavy equipment from draglines to generators – no one had APM experience. Their ability to keep our system performing helped establish the first performance benchmarks that followed other systems. Roy Love, Westinghouse, the first Airport APM Site Supervisor, set the standard of excellence and all of us in the APM industry benefited.

Point of No Return

On the evening of April 14, 1971, after the last flight arrived, the old terminal was completely closed and a continuous airline convoy of trucks, trailers, baggage carts, transported EVERYTHING two miles to the new airport. A guard was posted at the old terminal sidewalk to advise stragglers where the airport went and how to get there. Then we awaited the first flight arrival at daybreak Thursday, April 15, 1971 and thus began the dawn of a new era."

SEA-TAC INTERNATIONAL AIRPORT STS

Sea-Tac International Airport is owned and operated by the Port of Seattle (Washington). The airport underwent a major expansion in the late 1960s and early 1970s that included the addition of north and south satellite terminals as shown in Figure 3.

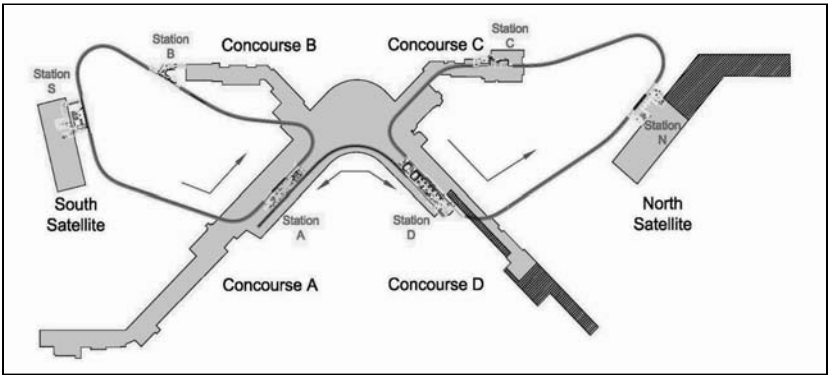

Figure 3: Sea-Tac Terminal Layout Plan (David Tomber, Port of Seattle)

Figure 4: South Satellite (www.portseattle100.org)

These airside satellites were connected to the landside terminal by an APM named the Satellite Transit System (STS). Single lane loop configurations operated in tunnels below the aircraft aprons. In addition, a shuttle configuration connected Concourses A and D. Guideway length was 2,700 meters (1.7 miles) with six stations. The operating system was designed and manufactured by the Transportation Systems Division of Westinghouse Electric Corporation. Public service began in 1972. A special feature was the use of transfer tables to move vehicles in and out of the below grade maintenance and storage facility. Shown in Figure 4 is the South Satellite.

The STS is still in service today, but it underwent a major renovation and modernization program between 1999 and 2003 at a cost of $142 million.(5) The modernization of this "must-ride" APM was especially challenging because of the single lane guideway configuration. As reported by Tomber and Gladney at this conference, studies are now underway to expand Sea-Tac's landside and it's venerable STS.(6)

Ted McCagg, an architect with TRA during the expansion program (retired), has provided the following account.(7)

"The Challenge

The Master Plan for Sea-Tac, prepared by The Richardson Associates (later to be known as TRA) in the late '60s envisioned a terminal area consisting of the original terminal and the four concourses expanded plus two satellites. The space available for the long term expansion was severely constrained by the existing runways on the west, Interstate 5 highway on the east, and airline hangars and other important facilities on the north and south. The space available for the terminal area development was very nearly the same area as all of downtown Seattle with the harbor on the west, I-5 Freeway on the east and extending north-south from the Seattle Center to Pioneer Square. Clearly there would have to be a major system to help passengers between the central terminal and their gates.

The site mandated 360 degree circulation around the satellites to maximize the area available for maneuvering and parking of aircraft to achieve the number of gates required both initially and in the future as it was then forecast. That dictated either an on ramp bus system or an under apron connection between the terminal which would continue to provide for ticketing and baggage claim and the satellites. The bus alternative was quickly eliminated due to limits on capacity and safety considerations. Some sort of underground conveyance system then became the only alternative.

Alternatives

The detailed planning and design of the system was undertaken by the consultant team lead by TRA working closely with the Port of Seattle Aviation Engineering and Planning Departments. Several alternative systems were imagined -- 'imagined' because there was at that time no appropriate system in operation for airport passengers. Several alternatives were investigated. Moving walks in a tunnel was considered but dismissed due to slow speed and limited capacity as well as cost as this alternative would require finishing the tunnel and providing air conditioning as well. There was also a concern that it would not provide safe transport for elderly, handicapped and passengers carrying children or other encumbrances such as carry-on bags. This then meant that there would need to be some sort of vehicular system. An initial idea was for an open vehicle similar to the system between the Congressional Office Building and the Capital in Washington, DC. Again the issues of cost related to finishing the tunnel and providing air-conditioning, as well as safety concerns as children would be riding in it, dictated the elimination of the open vehicle alternative. The concept of an enclosed, air conditioned vehicle, expandable by adding additional vehicles as needed in the future, was then accepted as the direction for implementation as a part of the expansion program already underway. Concourse

C's expansion included an enclosed space below ground for a future station. Having no dimensions at that time, a long empty space was provided and later part of it finished for the adopted system.

Final Configuration

Figure 5: Original STS vehicle (www.portseattle100.org)

The final configuration of the system and the vehicle requirements were included as a part of the Terminal Area Expansion Program that began in 1969 and was completed in 1972. The system included two loop tunnels with a connector between them under the terminal. It would be a must ride system with the terminal stations located on the axis of the terminal, north and south. It was decided that the South Loop would serve the South Satellite as its first stop, a distance of 365 meters (1,200 feet), serve a station at the end of Concourse B and then return to the terminal station, a clockwise loop. The North Loop by contrast would serve the North Satellite as its first stop, a distance of 305 meters (1,000 feet), then stop at the end of Concourse C and return to the terminal, a counter clockwise loop. A separate shuttle system would go back and forth connecting the Terminal North and South Stations. This provided the shortest ride for the departing passengers to the satellites while giving arriving passengers an intermediate stop at the end of the concourses, thus providing the airlines time to get the bags to the terminal bag claim areas. It also provided a way for a passenger arriving at either of the satellites to connect with a gate at the other satellite simply by riding the APM with a minimal walk.

The initial vehicles at Sea-Tac had doors only on one side, and the only windows were on the ends of the vehicles. This required that there be a turntable at the A and D Stations, and consequently the car doors were located on the outside of the two loops. By contrast, the shuttle under the terminal had its doors on the opposite side -- therefore the need for the turntable so that vehicles could be deployed on an interchangeable basis. Also, the station doors were elevator doors, i.e., solid with no glass. The whole system was referred to as a horizontal elevator.

More recent upgrades of the STS have included doors on both sides of the vehicles, replacement of the turntables with transfer tables, and glass in the station doors so you can see when the train arrives. An access hatch was provided south of the terminal for delivery and removal of vehicles. The STS also would require the vehicles to be able to move in either direction. This also allowed for the system to work in a shuttle mode should there be a breakdown of a vehicle in one of the loops.

Implementation

As noted above, there was a limited selection of systems available when the Sea-Tac STS was preparing to bid. Westinghouse had a test track in operation outside of Pittsburgh, and there was a company in Salt Lake City working on the development of a European system. A performance specification was prepared for the system. A very high reliability requirement was included, nearing 100%, as it was a must ride system. It included safety considerations related to acceleration and deceleration as it might affect standing and handicapped passengers. Ultimately the contract was awarded to Westinghouse. A multi-year maintenance program was included in the bid requirements insuring immediate presence of knowledgeable staff to ensure uninterrupted operation of the must-ride system.

With the selection of Westinghouse as the system provider, consequently the size, capacity and turning radius of the vehicles was determined. The final design of the tunnels and the curve layouts could then be completed, as well as the length of the stations to be finished as a part of the initial program to meet the anticipated ridership. Since the two loops were to be located adjacent to the existing concourses, tunneling vs. open cut was considered. Fortunately the ground under the airport is quite stable and an open cut construction method was employed, removing three operational gates from service at a time, completing the tunnel, backfill and new apron paving before moving on to the adjacent three gates. The Concourse B Station was built beyond the end of the already existing concourse. The shell of the station at Concourse C was incorporated into the system and finished. A safety walk for the full length of each loop was included in the tunnels to allow for evacuation of passengers if required. A system breakdown would call for the passengers to remain in the vehicles and be pushed or towed to the nearest station unless a fire was involved.

A utility tunnel was also included as a part of the bundled tunneling program allowing the Central Plant in the Main Terminal to serve the satellites as well. Also included as a separate but connected tunnel was a passage for baggage conveyers, including a walkway for maintenance workers as international arriving passengers would be cleared at the South Satellite but would be required to recheck their bags back to the terminal baggage claim area. Carrying their bags on the transit system would severely impact its capacity. The North tunnel also included a baggage tunnel with a walkway as United Airlines would do their baggage make-up at the ramp level of the North Satellite immediately adjacent to the new location of all of their gates.

The STS went into full operation in mid-1972 following a prolonged test period. The system at Sea-Tac as well as at Tampa benefitted from the research and development undertaken by Westinghouse prior to any airport contracts."

DALLAS-FORT WORTH INTERNATIONAL AIRPORT

Officials in the north Texas cities of Dallas and Fort Worth began planning a new regional airport in the 1960s. Some 17,500 acres of land was acquired between the two cities, and ground was broken on December 11, 1968 on what was then the

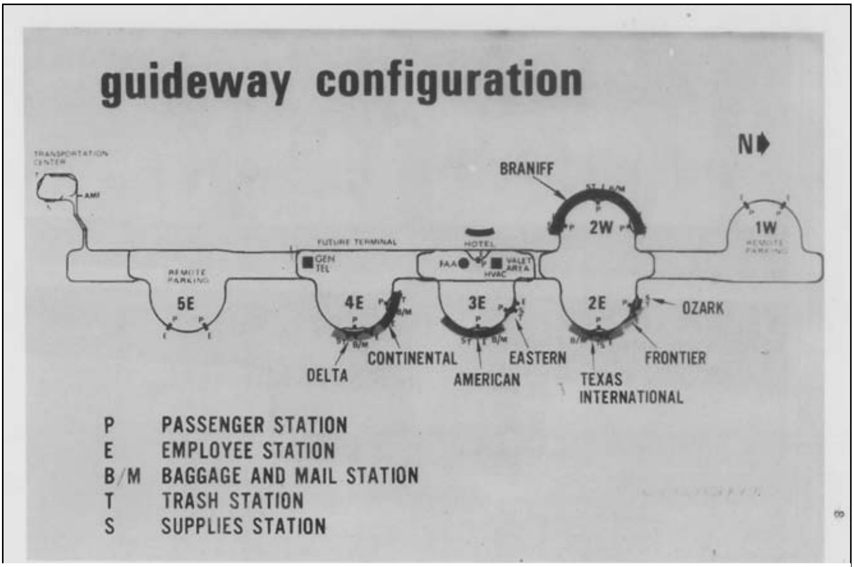

Figure 6: DFW Airport Legacy Airtrans Layout Plan. (David Casselman, Lea+Elliott)

world's largest airport. The scale of the project was immense even by today's standards. In keeping with the futuristic perspective of the airport developers, a landside APM named Airtrans was planned to connect unit terminals, an airport hotel, remote parking, rental car facilities, and a postal service mail distribution center. A layout plan is shown in Figure 6. The distance between 5E and 1W is approximately 3,600 meters (12,000 feet).

When Airtrans opened on January 13, 1974, it included 21 kilometers (13 miles) of single lane guideway, 53 off-line stations, and a fleet of 68 vehicles.(8) There were five overlapping passenger routes operating simultaneously on loop configurations. In addition to passengers and employees, this APM was designed to transport, connecting baggage, supplies, mail, and even trash in specially designed vehicles. However, these additional services were soon discontinued. Arguably the 1974 system remains the most complex APM ever designed and constructed. Remarkably, Airtrans was designed, built, and tested in just 30 months by the LTV Aerospace Corporation in Grand Prairie, Texas, for $41 million. At 4% annual compound interest, the cost would be $197 million today, about $9.4 million per kilometer ($15.2 million per mile). After three decades of service, Airtrans was replaced by another APM in 2005 known as Skylink that connects terminal airsides.

Dennis Elliott, former Director of Engineering at DFW (retired), has provided the following account.(9)

"From 1969 to 1977, I supervised the Airtrans project on behalf of the Dallas-Fort Worth Airport. As Manager of Engineering, I represented the Airport to the Airtrans contractor, LTV Aerospace Corporation, and the myriad other engineering companies, architects and contractors who were designing and constructing the airport. Thus, Airtrans was the focus of my professional life for eight years. I have been asked to record my personal recollections of the project -- what it was like to be there. Needless to say, the recollections are many. Those recounted below are just a few that spring to mind at this writing. I hope they are of interest to those currently engaged in large, multi-disciplinary projects.

Context

Readers must keep in mind that Airtrans was built between July, 1971 and January, 1974. Looking back, the scope of the project was audacious -- almost unimaginable today. It was conceived (and built) as a totally automated system to transport airport passengers and cargo. Specifically, the contract specifications prepared by the Airport provided specific requirements for the transportation of:

- Airport passengers
- Airport employees
- Airline baggage
- USPS airmail
- Airport terminal supplies
- Airport terminal trash

Airtrans was the largest automated people mover system ever built. Consider that the system had:

- 51 automated passenger vehicles, which could be configured as one or two-car trains;
- 17 automated cargo vehicles, which automatically loaded, transported and off-loaded dedicated containers of baggage, mail, supplies and trash;
- 21 kilometers (13 miles) of dedicated guideway which was fully electrified and signaled;
- A dedicated Central Control room, where all aspects of the system operation were dynamically displayed in real time, and where the Airtrans controllers could automatically direct and/or modify the movement of all trains;
- A total of 53 stations which were automatically served by the passenger and cargo trains;
- A dedicated, 4 hectare (10-acre) maintenance facility, with a maintenance building, storage and departure test facility.

So what was it like to manage Airtrans? Exhilarating! The concept of improving people's mobility and convenience through automation captivated me; so much so that when I departed the Airport's employment I began a one-man consultation business, specializing in automated transport systems. With the help and added expertise of many talented people, that inauspicious start eventually grew into Lea+Elliott, Inc.

To facilitate my recall, I have organized the following thoughts chronologically, by phases of the project: Master Planning; Airtrans Planning; Prototypes; Procurement; Implementation; Testing; Early Operation; Litigation; and Steady-state Operation. In addition, I have added a final section, "Lessons."

Master Planning

The master planning of the DFW Airport was accomplished by Tippets-Abbet-McCarthy-Stratton (TAMS), a New York A/E firm with extensive airport planning experience. Recall that the 1960's anticipated the operation of huge airliners; the 747 was thought to be just the beginning of jumbo-liners. Thus, TAMS made sure that DFW had enough space for the efficient maneuvering of these large planes. But, once the immense size of the airport sank in, the planners began to ask the question: 'How are we going to tie these wide-spread facilities together?' Realizing that conventional buses and trucks would swamp the airport roadways, they borrowed an idea from Tampa International Airport, which was then building an 'automated passenger shuttle.' Automation!!! That would be the answer for DFW. So, TAMS included in the DFW Master Plan a spider-web of dotted lines indicated as the 'airport transportation system.' No one had a clue about how such a system would be developed. But everyone was confident that it would be.

Airtrans Planning

Beginning in 1969, the Airport began specific planning for the 'transportation system.' At that time, the U.S. Urban Mass Transportation Administration was offering grants to encourage the development of ‘automated people mover systems’ for urban applications. (Such systems were ultimately built in Miami, Jacksonville, and Detroit.) The Airport decided to ‘make a run for the money’ and instructed me to prepare an application. Again, I hadn't a clue. I remember obtaining some tourist literature for the cities of Dallas and Fort Worth to use as background information. Back then, before computers and word processors, the common practice was to ‘dictate’ a document by speaking into a recorder; the ‘tape’ was then provided to a secretary who ‘transcribed’ the document by listening to the tape and typing the spoken words. So I closed my office door, fired up the Dictaphone, and talked for a couple of days about the Airport's concept of a fully-automated, Airport transportation system. I recall repeating the words ‘airport transportation system’ so many times that I decided an acronym would be helpful. I spliced the words together and selected certain letters and . . . Voila! AIRport TRANsportation System – ‘AIRTRANS.’ It stuck.

Somehow, we had to develop specific means to implement the vision of the planners -- routes, operational strategies, etc. The first attempt was just to connect every pair of terminals and/or cargo facilities with a ‘route.’ It soon became apparent that such an un-sophisticated approach would never work; there would simply be so many trains that the guideways would be overloaded. For help, the Airport engaged the transportation consulting firm of Arthur D. Little, (ADL) located in Cambridge, Massachusetts. Being in Cambridge, ADL was (conveniently) staffed with MIT graduates. We reasoned that the MIT guys could bail us out! ADL did provide considerable help in focusing on reasonable solutions, but they, too, were pushing the envelope. In their report to the Airport, ADL provided a conceptual routing scheme for the Airtrans system. As an inside joke, (and an acknowledgment that none of us really knew what we were doing) ADL labeled the routes the ‘S’ route, the ‘W’ route, the ‘A’ route and the ‘G’ route -- SWAG. To my knowledge, none of the senior Airport staff or Board Members ever caught on to the joke!

Back to the ‘dotted lines.’ By the time serious planning for Airtrans was underway, we were playing serious catch-up. The designs for the Airport roads (dedicated passenger and service road systems) were well-along, with no right-of-way for Airtrans! So I approached the roadway designers and asked for space. My request was met with incredulous looks. First phase, expansion -- all of the available land area was required for roads. Realizing that I represented the Dallas-Fort Worth Regional Airport Board, and with the expressed endorsement of my superior (Ernest Dean, Director of Engineering) I made a second run at the designers and again ‘requested’ that space be provided. This time I received a cooperative, professional response. Using geometric criteria that were thought to be applicable, ‘track layouts’ were developed for Airtrans, interspersed with the roadways and interchanges. Based on this generic information, underpasses were added to the service roads at each end of the terminals, to provide train access and egress. Likewise, using approximate dimensions for the then-known people-mover systems, a right-of-way for Airtrans was added to the terminal buildings. Some designers' egos were bruised, but accommodations were made and the ‘right-of-way’ crisis was averted.

Prototypes

Using the federal grant money from UMTA, supplemented with additional funds, the Airport sponsored the development of two, competing prototype automated systems. One was the 'Dashaveyor' system, and the other was the "Varo" system. Dashaveyor was the brainchild of Stanley Dashew. Mr. Dashew was the inventor of the embossing system used to make credit cards and was determined to devote some of his considerable wealth to the development of a new form of transportation. His starting point was a mine train which he had deployed at the White Pine Mine at a remote location in Michigan's Upper Peninsula. But he was convinced that this technology could be transformed into a train system for DFW. The hardware involved wheeled vehicles running on a semi-conventional 'track.'

'Varo' was an aerospace manufacturer located in Garland, Texas. Their idea was what we now call "PRT." Their concept was based on a plethora of 6-person 'cabs' which were suspended from an overhead track supported by columns. I remember that one of the 'advantages' of this approach was that 'super-elevation occurs automatically in the turns.' Well I guess it does.

Both Varo and Dashaveyor ultimately produced test tracks and operating vehicles, but only by partnering with large firms with credible engineering expertise. Dashaveyor partnered with Bendix Corporation, and Varo partnered with LTV. Members of the Airport Board and staff were invited to ride these demonstration systems. The Dashaveyor vehicle had such abrupt braking that one of the elderly Board Members was thrown down; the Varo vehicle got stranded mid-ride with no way to egress the vehicle. It is amazing that the Board continued to press on with the Airtrans concept after these dismal prototypes.

Procurement

As I recall, there was one abortive contract competition between Dashaveyor and Varo -- I'm not sure exactly. But by this time, the DFW Board and staff realized that some serious professional advice was required. The Board then contracted with Batelle Memorial Institute, Columbus Laboratories to prepare procurement specifications for Airtrans. Battelle's senior representative was Mr. Charles (Chick) Shields; Mr. Shields was a seasoned veteran of railroad signal systems, and had advised on the implementation of the BART system.

Batelle got us headed in the right direction. Based on the Airport's espoused goals for Airtrans, specifications were prepared. Rather than return to Columbus, Ohio (home), the Batelle representatives (four engineers) arranged hotel accommodations in Arlington, Texas, which was then the location of the Airport's offices. A 'tiger team' was formed, which I headed. Also, Don Ochsner (who would ultimately direct the operation of Airtrans) participated for the Airport. Battelle representatives included Mr. Shields, Ray Thompson and two others whose names I can't recall. We set about writing 'performance' specifications, which was a new concept in transportation system procurement. Previously, specific, detailed designs were prepared by the procuring agency and submitted to train suppliers for 'bids.' For Airtrans, we instead described exactly what the system had to do, the numbers/quantities of passengers and cargo to be transported, and the times to which the system had to conform. Also, safety and operational requirements were included, as well as the Airport's legal requirements.

Upon recent review, I was amazed at how detailed and prescient the Airtrans specifications were. Comparing the Airtrans technical specifications with documents being used today, it is very clear that the Airtrans procurement approach, as well as specific requirements language, has served as a pattern for all subsequent APM procurements.

Again, this was all before office computers and word processors. Wonder how editorial changes were made as the documents were produced? It was literally ‘cut and paste.’ Text to be deleted was literally cut out of the page. New text was typed; it was then ‘pasted’ into the correct location in the document. This was usually done on a line-by-line basis so that a block of new text could be added by applying a piece of clear tape across the full width of the page, usually on top of the original page and/or previous changes. After repeated editorial changes and addendums, some of the master pages for the Airtrans specifications were literally nearly 1/4 in. thick! This meant that the page wouldn't go through the copier automatically, and had to be copied individually.

Implementation

Implementation of Airtrans involved three activities: Construction, manufacturing, and testing. The implementation phase began in July of 1971 and concluded with the system's opening in January of 1974; a total of 30 months. In retrospect, it was an incredible accomplishment. Today, 30 months is considered a minimum time to implement a simple shuttle system. To have completed and opened (albeit prematurely) the largest APM system ever built in such a short time is a testament to the expertise and dedication of LTV's engineers, managers and corporate officers, as well as the many consultants, other contractors and Airport staff that were involved.

Construction: Construction at the Airport focused on the guideway system and other supporting facilities. Since Airtrans went into, under or over virtually every other feature of the Airport, the interfaces were myriad and sometimes intractable. Fortunately for me, the Airport's policy was that, when push came to shove, Airtrans got the nod. That made me an unpopular guy in many instances. But everyone involved in the Airport construction seemed to recognize the importance of Airtrans, and went out of their way to accommodate our needs.

There were successes and failures. LTV had hired an experienced, highly-regarded Texas highway contractor to build the at-grade guideway. Their on-site supervisor was a grizzled old highway man who was convinced that the guideway parapet walls – 15 centimeters (6 inches) thick and about 61 centimeters (24 inches) high -- could be slip-formed. Consequently, several months were spent (wasted) trying to perfect this technique. Unfortunately, it was not to be. Ultimately, virtually every foot of the guideway walls were formed and poured the old-fashioned way - at considerable expense.

The elevated guideway was designed by ABAM structural consultants in Tacoma, Washington. ABAM had distinguished themselves as cutting-edge structural designers, using precast, post-tensioned beams. ABAM had designed the guide beams for the Disney Monorail; so they seemed like a perfect choice. ABAM's design was wonderful; graceful, unobtrusive, supported by slender, tapering columns. It was a beautiful thing, but difficult to build. The beams were cast in Dallas by a highly-regarded concrete pre-caster. Before the technique was perfected, a number of beams (a dozen or so) were scrapped. They went over the side of a big hill where the precast plant was located. For many years they could be seen from IH 30; they were known locally as ‘the bone yard.’ Later, after Airtrans operations began, cracks began to develop in the beams; it was determined that inadequate provisions had been made in the design for the thermal expansion in the top of the beams caused by the intense sun at DFW. Expensive retrofits were required to deal with this problem.

Construction did eventually get done, to accommodate a (too) brief testing phase, described below.

Manufacturing: The achievement of Airtrans is largely due to the systems approach and experience that LTV brought to the project from the aerospace industry. Their expertise in organizing, managing and coordinating a very large number of designers, suppliers and contractors from disparate industries was responsible for getting the project finished in record time. This was especially so in the manufacture of the 68 automated vehicles; 51 for people and 17 for cargo. Design of the vehicles followed aerospace protocol; a detailed work breakdown structure (WBS) was employed; peer reviews were made on all designs, and manufacturing ‘lines’ were set up in the LTV hangars. Vehicles progressed through various stages of assembly, starting with the frame and running gear. Aerospace terminology crept in; we had ‘hangar queens’ in the fleet; the early proof-of-concept tests (with a special test vehicle) were called ‘test flights’ and so forth.

At first, I didn't know nor appreciate the stature of the staff that LTV assembled for Airtrans, but over time I came to understand that they were among the best and brightest in the aerospace industry -- men (and a few women) who had designed and produced fighter airplanes capable of supersonic flight. Late in the program, I learned that LTV's senior train-control engineer held a primary patent (for LTV) for inventing a key component of terrain-following radar. Think how that has transformed modern flight/warfare.

At the end of the program, fearful for its local reputation, LTV committed virtually its entire engineering staff to getting Airtrans finished. There were nearly 500 engineers and technicians working feverishly to get the project done! LTV's Senior VP of Engineering, Mr. Bob Buzard, moved to the Airport and directed field operations. A brilliant man, capable of motivating and directing such a large force, Bob became a trusted colleague and good friend. Anecdote: During the late stages of the project, it became apparent that a remote section of the guideway lacked sufficient power to propel more than one train at a time, because of the too-great distances to the feeding transformers. An additional substation was clearly required. At a meeting on the subject, Don Ochsner, my colleague, directed LTV to install an additional substation. Bob's eyes flashed, then softened; he smiled and said 'OK but we'll see you in court.' It never went to court, but it was a claim that was ultimately resolved mutually by the Board and LTV.

Testing: The testing phase commenced as soon as a vehicle(s) were available from manufacturing. It was very discouraging at first. The power collectors on the vehicles would not stay on the rails in curves. Vehicles stopped for no apparent reason. Riders had to be placed on the vehicles to 'reset' the vehicle computer when the train stopped. In time, many (but not all) of these problems were ironed out before the Airport's opening. Testing was directed from Central Control. Unfortunately, the Airport-provided Central Control room was not available when LTV needed to start pre-operational testing. The solution that was devised was for LTV to construct a 'temporary' Control Center, which they did. The facility was a pre-fab building which was located on an un-used section of a roadway bridge near the center of the terminal area. This worked fine until the roadway system was completed and heavy construction and delivery trucks began to drive by. Then, the whole bridge, and the temporary Central Control, would bounce up and down for several seconds. For those stationed there, it was like working on a trampoline!

Early Operation

Airtrans opened for service in January of 1974, along with the opening of the Airport. My recollection is that passenger and employee services were operational on opening day; the various cargo services followed a few weeks later. As has been widely documented (and mocked on Johnny Carson) the service was un-reliable (charitably). Passengers were stranded and missed flights. Angry riders abandoned stalled trains and walked in the guideway, which posed serious safety and operational problems. A strong case was made to the Airport's senior management to delay the opening of the system. However, the decision was made that Airtrans was the "crown jewel" of the Airport, and it would open with the rest of the Airport.

During this time, my staff gave me a coffee mug, which I still have, which bears the message 'The light at the end of the tunnel is the headlight of an oncoming train.' That seemed true more often that I wished.

Litigation

The litigation between DFW and LTV over the cost over-runs on the project, and the many damages suffered by the Airport and its passengers, was by far the most fun of the whole project. The original contract amount for Airtrans was about $31 million, including all design, equipment and facilities. I believe that the total paid by the Airport, including settled claims, came to about $41 million. LTV absorbed vastly more than they ever were paid in claims. The project had a profound (negative) effect on the company's finances and also its local reputation.

The litigation brought out the biggest guns on both sides. For the Airport, the Mayor of Dallas, Mr. Erik Jonsson, founder of Texas Instruments, personally directed strategy. The City Attorneys of both Dallas and Fort Worth were involved, as were many of their staff. During the tussle, the Airport Board members and senior staff spent much of their time either negotiating or planning for negotiations. The airlines then at DFW also were involved as named parties to a lawsuit. It was a major 'dust-up.' Both sides hired outside counsel to advise their in-house lawyers. The Airport hired Locke, Purnell, Boren, Laney & Neely, a prestigious firm in Dallas. LTV, not content with just local counsel, hired Strasburger, Price, Kelton, Martin & Unis, another prestigious Dallas firm. In addition, they retained Fried, Frank, Harris Shriver & Kampleman based in Washington, D.C. The name Shriver should be familiar – it was Sargent Shriver, a brother-in-law of President John Kennedy.

For me, it was a heady experience, to say the least. As the Airtrans Project Manager for the Airport, I knew more than anyone else on the "Airport side" about the design, operation, status, successes and failures of the system. Consequently, I had a front-row seat to all deliberations. Often it was the hot seat, but front-row nonetheless. My opinions were sought by many, and were always received with respect. I was on a first-name basis with legendary men, including Eric Jonsson, Mayor of Dallas; Thomas Sullivan, Executive Director of the Airport; Board Members who were local entrepreneurs and businessmen; Paul Thayer, legendary test pilot and Chairman of LTV, and many other notable representatives, including giants in the airline industry. For a young engineer (34), things couldn't have been any more exciting.

I recall one pivotal meeting in which the DFW delegation first proposed a settlement amount. There was silence in the room. Finally, LTV's Senior Vice President for Finance spoke: 'Well, that's the first ridiculous offer.' Everyone laughed and discussions continued. Eventually a settlement was negotiated that both sides could abide.

One memorable recollection came when the Order of Dismissal was executed. This document terminated the various lawsuits that both sides had filed. The Order was prepared by the attorneys for both sides; it has signature blocks for six attorneys, including the City Attorneys of Dallas and Fort Worth, the attorney for DFW, and three private attorneys who had been hired to represent the parties. Six attorneys. Yet when the document was submitted to Judge Walter Jordan, the presiding judge in the matter, it was discovered that the document had no place for the Judge to sign signifying his order. So Judge Jordan just drew a line on the page, signed his name, and printed 'Judge' below the line. Six of the highest paid, smartest attorneys in the country, and they forgot to give the judge a place to sign!

Steady State Operation

It is important for the record to emphasize that Airtrans ultimately met all of its design requirements -- for passengers, employees, baggage, mail, supplies and trash. However, for various reasons, the cargo services were either not implemented because 1) requirements had changed (baggage); or 2) were tried for a time and abandoned (mail, supplies and trash).

The Airtrans passenger and employee services were ultimately made very reliable and supported the operations at DFW for many years. The system ultimately closed in 2005, having served 250 million passengers. During its lifetime, Airtrans was modified and expanded on several occasions to support changes in the Airport requirements. New stations were added, and new routes were created. Notably, Airtrans vehicles and wayside equipment were re-engineered to allow operation of three-car trains which comprised the AA Train; this service transported American Airlines connecting passengers between separate terminal buildings when American expanded into multiple terminals.

Despite the many successes of Airtrans, it never overcame the negative publicity that overwhelmed the system at its opening. What is telling, however, is that, when it came time to replace Airtrans, the Airport opted for another automated system (Skylink) rather than a fleet of buses! I think that reflects the confidence that the Airport ultimately had in the system.

Figure 7: A Skylink train passes over a soon-to-be decommissioned Airtrans train at DFW Airport in 2005 (Ronald Sheahan, Lea+Elliott)

Lessons

Why write this much and not try to draw some instructive ‘lessons learned?’ Besides serving DFW passengers and employees for many years, the Airtrans project informed the design of all airport APMs that followed -- both in the “what to do” sense and also the ‘what not to do’ sense. Those of us who followed our DFW employment with private consultation never forgot what we learned on Airtrans. Some observations:

- Redundancy -- Airtrans' Achilles heel was the fact that the guideway system was all single-lane. One stalled train in a strategic location could (and did) stop the entire system. Thus, a primary goal in all new APM system planning should be redundant facilities, insofar as possible. A good example is the Skylink system, which now operates at DFW. It is comprised of dual guideway loops; trains circle the two loops in opposite directions. If service is interrupted on one loop, passengers can still reach their destination on the other loop. The trip time may be longer, but they can still get there.
- Failure Management -- Even with redundant guideways, provisions must be made for managing failures. All transit equipment will fail; including system features and procedures for such eventuality is paramount. Crossovers between guideways and reverse running are two examples.
- Perception of Speed -- Airtrans' top speed was 27 kilometers per hour (17 mph). This was sufficient to meet the trip time requirements in the specifications, but to passengers, it felt ‘pokey.’ The Airtrans specifications did not specify a minimum speed -- another “lesson learned.” For maximum passenger acceptance, vehicles and trains should operate at a minimum speed of say 50 kilometers per hour (30 mph).
- Testing, Testing, Testing -- As consultants, Lea+Elliott representatives are often challenged by clients and suppliers regarding the (seemingly) long periods mandated for testing and pre-revenue operation. There can never be too much preparation for passenger service.

Conclusion

In the final analysis, perhaps Airtrans got the last laugh. In the context of ‘informing subsequent designs’ it is relevant (and somewhat ironic) to note that rights to the Airtrans designs were licensed by LTV to Niigata Engineering Company in Japan. From there, the basic configuration of the system (rubber tires, side guidance) was adopted by the Japanese government as the standard for all APM systems constructed in Japan. So the legacy of Airtrans, which embodied the hopes, aspirations, expertise and efforts of so many people, lives on -- albeit in Japan!”

THE EVOLUTION OF AIRPORT APMs FOLLOWING THE 1970’s

Air travel continued to grow. In 1990, there were 466 million enplanements in the United States. In 2000 there were 600 million U.S. enplanements, a six fold increase in the three decades since 1970. And world-wide air travel was growing at a considerably faster rate than in the United States. In addition to shuttles at airports such as Cincinnati, Tokyo Narita, Las Vegas, Miami, London Gatwick, and most recently Sacramento to name just a few, pinched loop configurations of large scale and complexity began appearing as both landside-airside connectors, airside circulators, and landside circulators. During the past two decades, many APM systems have opened at airports in other parts of the world.

In 2001 the APM at Newark International Airport was expanded to an Amtrak station on the northeast passenger rail corridor. For the first time, an airport APM had extended its reach beyond its boundary. In 2003 Airtrain followed at New York Kennedy International Airport, providing passenger circulation between terminals and off-airport connections to the New York City subway and Long Island Railroad regional transit network.

Today below grade airside-landside pinched loops of very high capacity form a passenger movement backbone at large connecting hubs such as Atlanta and Denver. Landside circulators at airports such as Chicago O'Hare, Newark, San Francisco, Paris, and most recently Phoenix, connect terminal buildings to each other and also serve remote parking, consolidated rental car facilities, public transit, and passenger rail stations. Comprehensive information on 44 of the world's airport APMs has been summarized by the TRB.(10) Today it is difficult to image how airports such as these would function without APMs. A timeline of some of the key events is presented in Table 1 below.

Table 1: Timeline of key airport APM developments

1961	Westinghouse Electric begins work on an automated transit system "Transit Expressway" or "Skybus"; test track built in South Park, near Pittsburgh, PA
1963	Terminal planning work at the Tampa Airport introduces a new landside-airside design concept with a need for a dependable transportation system that transfer passengers between the landside and airside of the terminal
1968	Release of the report, "Tomorrow's Transportation: New Systems for the Urban Future", US DOT, Urban Mass Transportation Administration – introduces several new terms such as Automated Guideway Transit (AGT)
1970	Morgantown PRT demonstration project on the campus of West Virginia University is authorized and construction begins in 1971
1971	First airport APM begin service at Tampa International Airport using a Westinghouse Transportation system
1972	Transpo'72 Exposition held at Washington Dulles International Airport
1974	AirTrans opens at the Dallas Fort Worth Airport – the first airport APM circulation system

1975 Release of the report, "Automated Guideway Transit: An Assessment of Personal Rapid Transit (PRT) and Other New Systems", U.S. Office of Technology Assessment – identified a research agenda and the Downtown People Mover (DPM) demonstration program

1975 In Canada, the Ontario government creates the Urban Transportation Development Corporation (UTDC) to continue development of automated ICTS (Intermediate Capacity Transit System)

1983 First airport APM system in Europe opens at the London Gatwick Airport

1984 First maglev APM system starts service at the Birmingham International Airport

1985 First ASCE APM Conference held in Miami, Florida

1990 First airport APM system in Asia at the Singapore International Airport

1991 First APM International Conference held outside of the United States. Held in Yokohama, Japan

1991 UDTC is sold to Bombardier

1992 First airport APM system opens in Japan at Tokyo Narita Airport; uses a Otis system

1997 First in a three-part series of ASCE APM Standards is released

2001 Bombardier acquires ADtranz which was previously known as AEG Westinghouse and Westinghouse Transportation

2002 The Airtrain system opens in New York and provides an off-airport connection to Kennedy International Airport; uses Bombardier ART system

2006 First airport APM system in Canada opens at the Toronto Pearson International Airport

2006 Updated ASCE APM Standards are released following an extensive review

2008 A PRT system opens at London Heathrow International Airport

2010 ACRP Report 37 released - "Guidebook for Planning and Implementing Automated People Mover Systems at Airports"

2012 ACRP Report 37A released – "Guidebook for Measuring Performance of Automated People Mover Systems at Airports"

2013 Fourteenth International APM Conference held in Phoenix, Arizona

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SIGNS OF A MATURE INDUSTRY

As we look back on the last four decades, signs of a mature, enduring technology are apparent.

Phoenix in 2013 marks the 14th APM conference. Since 1985 these forums have brought together planners, inventors, designers, suppliers, builders, government officials, owners, and operators of automated transit of all forms to share their experiences, reveal innovations, look to the future, and discuss lessons learned. Every conference has had numerous papers on airport projects. These conferences, held around the globe, have built an international collegial community.

NFPA 130, the fire life safety standard applicable to rail transportation systems, was expanded in the early 1990s to include APMs for the first time.

The ASCE APM Standards were first developed in the mid-1990s and continue to be a must-have reference for APM planners and designers. Many APM procurement documents incorporate these standards by reference. ASCE has maintained a leadership role in these peer- developed standards through the work of the APM Standards Committee.

Globalization of APMs has occurred, both in terms of airports with applications and manufacturers of systems.

Many of the older airport APM systems have or soon will be undergoing extensive renovation and modernization. These capital renewal projects are a sign that APMs are a recognized essential component of ground transportation at the airports they serve.

The Transportation Research Board, through the Airport Cooperative Research Program, has published two reports pertaining to airport APMs.

- ACRP Report 37, Guidebook for Planning and Implementing Automated People Movers at Airports.
- ACRP Report 37A, Guidebook for Measuring Performance of Automated People Mover Systems at Airports.

As airport APMs entered the 21st century, growth and innovation continued on all fronts – guideway configurations, system length, train characteristics and speeds, reliability, safety and security, communication based train control, and new developments such as automated passenger counting.

CONCLUSIONS

Today, 42 years after the APM at Tampa transported its first passenger, there are 46 airports world-wide with APM systems, several airports APMs are in various stages of development or expansion as reported at this conference, and others are including APMs in their master plans.

There were 732 million enplanements in the United States in 2012. The most recent FAA forecasts predicts 1.2 billion enplanements in 2032, about 12 times the activity in 1970.(11) The pattern of innovation since the late 1960s will need to continue in the coming decades to safely and efficiently process the growing number of passengers.

There is plenty of evidence that the market for airport APMs will continue to grow as airports and terminal buildings are expanded to accommodate future passenger demands. Extensions and expansion of existing systems and the refurbishment or replacement of vehicles and components in older systems will continue. New opportunities for airport circulation networks and off-airport connections will be explored and developed. There are several equipment suppliers world-wide offering a range of technology solutions in the airport people mover market, and many colleagues are watching the new London Heathrow PRT supplied by Ultra.

All indications are that future decades promise more exciting times for planners, engineers, and architects, managers, suppliers, and airport owners.

REFERENCES AND ENDNOTES

(1) www.bts.gov, Historical Air Traffic Statistics.

(2) In the late 1950s and early 1960s several small entrepreneurial firms interested in innovative transportation technology developed low speed automated systems that were being marketed for special purpose applications. Universal Design Limited developed a straddle beam monorail that was installed in ten amusement parks, fairgrounds, and zoos before being acquired by the Westinghouse Air Brake Company (WABCO). In the late 1960s, WABCO engineers developed a fully automated version which was installed at the Houston Intercontinental Airport in 1972. Charles Paine formed the American Crane Hoist Company. One objective of his venture was to develop a suspended monorail system for the Los Angeles Fairgrounds in 1962 and the New York World Fair in 1964-65. Out of his experience came the Braniff International Airways' Jetrail that connected a remote check-in and parking facility to Braniff's "Terminal of the Future" at Dallas Love Field. This system was abandoned in 1974 when Braniff moved to the new Dallas-Fort Worth International Airport. (www.wikipedia.org)

(3) Skybus was the APM technology developed by the Transportation Systems Division of Westinghouse Electric Corporation and demonstrated as the futuristic Transit Expressway South Park Project. The system operated between August 4, 1965 and June 7, 1966, during which it transported 40,998 revenue passengers. The project was a public-private partnership including the Port Authority of Allegheny County and Westinghouse. Grant funding was provided by the U.S. Department of Housing and Urban Development. (Martin Coleman, et. al., "Skybus – Pittsburgh's Failed Industry Targeting Strategy for the 1960s," University of Pittsburgh, 2000)

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(7) Ted McCagg, November 13, 2012.

(8) www.wikipedia.org/wiki/Vought_Airtrans.

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(11) FAA Aerospace Forecast – Fiscal Years 2012-2032.

Planning Partnership: Support for the PHX Sky Train

J. A. Capelli, P.E.[1] and A. D. Novak, P.E.[2]

[1]Kimley-Horn and Associates, Inc., Suite 109, 5200 Northwest 33rd Avenue, Fort Lauderdale, FL 33309-6343; PH (954)-535-5100; FAX (954)-739-2247; email: jill.capelli@kimley-horn.com
[2]Kimley-Horn and Associates, Inc., Suite 350, 601 NW Loop 410, San Antonio, TX 78216-5595; PH (210)-541-9166; FAX (210)-541-8699; email: adam.novak@kimley-horn.com

ABSTRACT

The PHX Sky Train is an extremely challenging and exciting project. Appropriately planning for a project of this magnitude required a "Planning Partnership" between the airport staff and the consultant design team. This paper focuses on the planning efforts and highlights improvements to the planning process resulting in increased support for the PHX Sky Train design. This paper summarizes the planning activities leading up to the selection of the APM alternative. A multi-modal simulation tool replicated the existing airport landside and evaluated alternatives. The calibration process essential in establishing the basis for the partnership and consensus building on the planning efforts for APM alternatives is discussed and presented. Alternatives, both with and without the APM system, were evaluated addressing specific challenges unique to PHX. The results were tailored to meet the airport's specific need of communicating across a large and diverse audience. The paper concludes with lessons learned and benefits realized.

INTRODUCTION

Phoenix Sky Harbor International Airport (PHX) is "one of the ten busiest in the nation for passenger traffic with a $90 million daily economic impact" (http://skyharbor.com/about/airportFacts.html). PHX consists of three terminals (Terminals 2, 3 and 4) arranged in an east/west orientation as illustrated in Figure 1.

Sky Harbor Boulevard travels east/west through the airport and provides access to the terminals. The PHX Sky Train is an automated people mover (APM) system that is currently under construction with operation anticipated for 2013. The APM alignment is being constructed in two stages. The first stage will connect to the South 44th Street Light Rail Station, East Economy Parking, and Terminal 4. The second stage will connect the remaining terminals and the consolidated Rental Car Center (RCC) located south on Sky Harbor Circle, south of Sky Harbor Boulevard.

PURPOSE AND NEED

The planning and design of the PHX Sky Train APM began in 2003. The APM alignment has several design challenges including a narrow and highly

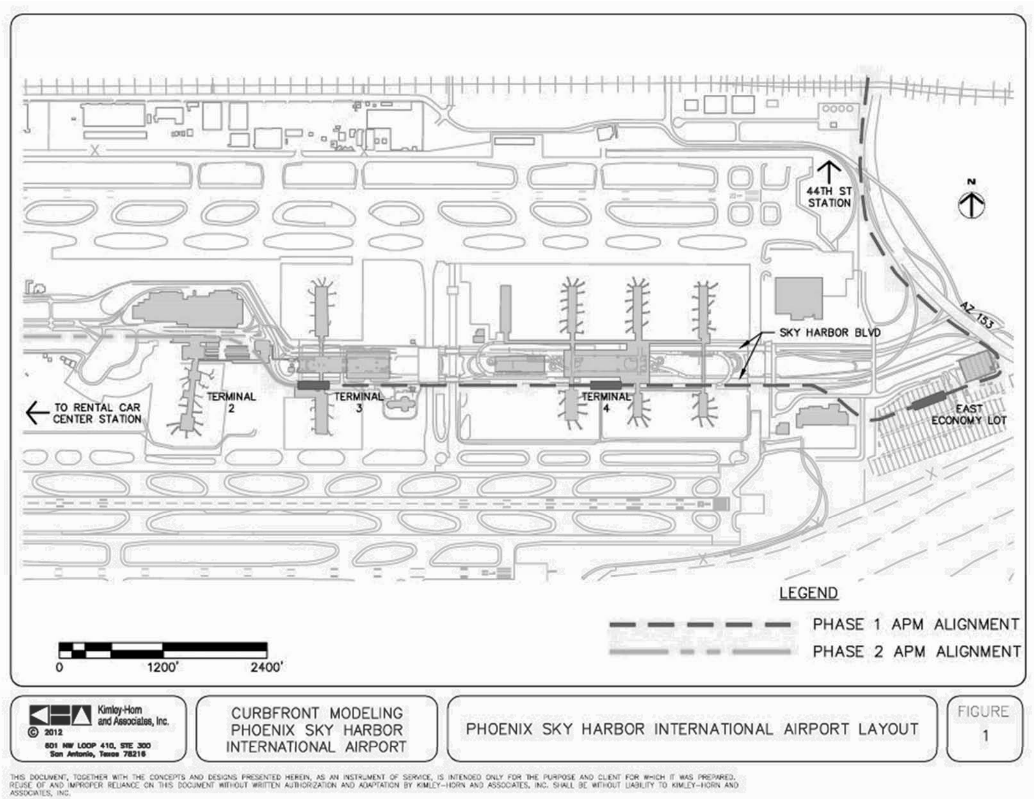

Figure 1. Phoenix Sky Harbor International Airport Layout

urbanized design corridor, minimization of impacts to airport operations, significant coordination with public and private stakeholders, analysis of airspace restrictions and impacts to airport users, and close coordination of construction phasing. Because of the high level of design challenges the 7.9-kilometer (4.9-mile) route resulted in a \$1.6B program cost.

In 2005, two years into the design planning, the airport asked the consultant design team to complete additional analyses to determine if there were cost-feasible options to the \$1.6B APM that would not sacrifice passenger level of service. The consultant design team was led by Gannett Fleming, Inc., who also completed the structural design. Other design team members included Kimley-Horn and Associates, Inc. (KHA) (Civil Engineer), Hellmuth, Obata and Kassabaum, Inc. (HOK) (Architecture), Lea+Elliott, Inc. (Systems/Procurement), and over 20 specialty subconsultants. As a result of the airport's request for additional analyses, KHA was tasked with completing the additional landside planning. Due to the extremely tight project schedule, these analyses were to be done extremely expeditiously and in parallel with the on-going design activities.

METHODOLOGY

KHA analyzed the landside operations at PHX using the Advanced Land-Transportation Performance System™ (ALPS™) set of computer simulation tools. ALPS is a suite of modeling and analysis programs that have been under development for over 30 years and allows the modeler to create multi-modal simulations that encompass the various transit, pedestrian, and vehicular movements within the landside environment, including the terminal building and APM stations. (ref. 1 and 2)

Fundamental to the ALPS concept is the ability to generate passenger demands based on the flight schedules. Passenger characteristics, such as visitor characteristics and trip timing, are applied to the flight activity to generate the passenger demands throughout a 24-hour period. Then transit and vehicular characteristics, such as mode split and vehicle occupancy, are applied to generate the transit and vehicular activity.

Once the transit and vehicular activity is generated, the individual vehicles, including APM vehicles, are routed through the roadway and guideway network and stop at their respective locations. Through the simulation capabilities of ALPS, the landside operations (including detailed APM train performance) and pedestrian movements can be visualized to observe the associated congestion at the various landside elements (curbfronts, access roadways, etc.). In addition to the visual representation of congestion, many quantitative results are captured within the ALPS program. Additional discussions on the results of the multi-modal simulation are provided later in this report.

The ALPS multi-modal simulation models were used to assist in the evaluation of alternatives which were capable of accommodating the future growth at the airport. The initial focus was on landside alternatives to the Sky Train. The Airport Roadway and Curbfront Model (curbfront model) was developed to assess the impact of numerous airport landside development options on the operations of the terminal curbfronts and the connecting airport roadways. First the existing conditions were replicated and validated. Then future year alternatives were developed for three airport passenger activity planning levels: 51, 58, and 65 million air passengers (MAP). Air passenger activity is provided in the form of a flight schedule, which as previously mentioned forms the basis of trip generation in airport applications of the ALPS model. Each planning level can also be referenced by the corresponding activity for million annual origin and destination passengers only (abbreviated in this paper as O&D). The O&D passengers represent only people that are beginning or ending their trip at the airport and does not include passengers connecting between flights. The O&D passengers represent the air passengers that will be using the airport landside system. The corresponding O&D planning levels are 30, 35, and 39 O&D. The baseline, existing conditions correspond to 42 MAP (25 O&D) and represented an activity level from the year 2005.

CALIBRATION AND VALIDATION PROCESS

The calibration process that occurred for the PHX Sky Train modeling was essential to the success of the planning efforts. The existing model was calibrated based on existing (2005) conditions and involved both a statistical analysis of the results as well as a validation process. The calibrated model is the reference point used to evaluate the future year alternatives. A calibration process is always essential to building an accurate model that can effectively evaluate the forecast year scenarios, but the additional stakeholder coordination that occurred during the validation process was the key factor in the "Planning Partnership" for the Sky Train project.

Statistical Calibration

The first step in the calibration of the model was to numerically confirm that the model was appropriately reflecting the anticipated demands through a comparison to the vehicle classification counts conducted at the curbfront. Table 1 through Table 3 present the comparisons between the modeled results and the vehicle counts.

The results of these comparisons were calculated using two statistical measures: R-square and Root Mean Square Error (RMSE), which are both identified in the tables. The R-square value is a standard statistical measure of the "goodness of fit" between predicted and actual values measuring a model's ability to predict base year values. The R-square values vary between 0 and 1, with larger R-square values reflecting higher quality predictions. When traffic models are appropriately predicting demands, the R-square value is closer to 1 and when the traffic models predict poorly the R-square tends towards 0. An R-square value of over 0.75 is acceptable, but for transportation demand modeling the R-square value should typically be greater than 0.88. The target R-square value was 0.95 for this model calibration.

It is unlikely for models with a high R-square value to miss major trends in demand. To ensure that the R-square value is an accurate reflection of model quality, a second statistical test called the RMSE is used. This test looks at the size of the errors on an aggregate basis, and larger RMSE values reflect larger errors. For transportation demand modeling, a RMSE of 30 or below is preferred. The target RMSE was 30 for this model calibration.

Table 1. Vehicle Classification Count Comparisons to ALPS Modeled Volumes and Corresponding Statistics, Terminal 3

	Terminal 3							
	North Side				South Side			
	Inside		Outside		Inside		Outside	
Vehicle Type	Count	ALPS	Count	ALPS	Count	ALPS	Count	ALPS
Private Auto	747	769	4,364	4,268	598	663	4,381	5,026
Taxi	17	5	297	355	6	10	266	347
Courtesy Shuttle	146	144	442	450	72	58	511	440
Airport Shuttle	0	0	199	284	0	0	213	88
Shared Ride (Supershuttle)	4	4	112	208	16	14	134	204
Luxury Limo	30	6	103	103	25	9	153	123
Van Service Vehicle	1	0	48	52	10	0	64	40
Charter/Intercity Bus	0	0	13	20	6	0	7	8
Public Transit	1	1	19	56	3	1	20	17
Other/Service Vehicles	18	17	198	193	19	17	231	148
Total Vehicles	964	946	5,800	5,989	755	772	5,988	6,441
R-square	**0.999**		**0.999**		**0.998**		**0.999**	
RMSE	**12.55**		**10.49**		**32.06**		**36.15**	

Table 2. Vehicle Classification Count Comparisons to ALPS Modeled Volumes and Corresponding Statistics, Terminal 4, Upper Level

	Terminal 4			
	Upper Level			
	North Side		South Side	
Vehicle Type	Count	ALPS	Count	ALPS
Private Auto	1,098	1,027	1,796	1,867
Taxi	63	30	60	98
Courtesy Shuttle	332	143	333	289
Airport Shuttle	117	196	129	216
Shared Ride (Supershuttle)	53	58	47	50
Luxury Limo	55	31	72	100
Van Service Vehicle	19	21	32	32
Charter/Intercity Bus	23	20	1	0
Public Transit	23	40	22	43
Other/Service Vehicles	56	33	43	27
Total Vehicles	1,841	1,599	2,548	2,722
R-square	**0.959**		**0.996**	
RMSE	**42.05**		**18.14**	

Table 3. Vehicle Classification Count Comparisons to ALPS Modeled Volumes and Corresponding Statistics, Terminal 4, Lower Level

	Terminal 4							
	North Side				South Side			
	Inside		Outside		Inside		Outside	
Vehicle Type	Count	ALPS	Count	ALPS	Count	ALPS	Count	ALPS
Private Auto	2,083	2,158	5,728	5,026	1,478	1,450	4,239	3,859
Taxi	6	28	273	347	5	0	259	331
Courtesy Shuttle	12	0	350	440	12	0	429	454
Airport Shuttle	0	0	116	88	0	0	130	68
Shared Ride (Supershuttle)	0	0	112	204	0	0	113	213
Luxury Limo	5	0	144	123	8	4	180	97
Van Service Vehicle	6	16	22	40	3	0	54	52
Charter/Intercity Bus	0	0	11	8	0	8	4	8
Public Transit	0	1	2	17	1	1	0	16
Other/Service Vehicles	62	61	142	148	124	85	221	176
Total Vehicles	2,174	2,264	6,919	6,441	1,631	1,548	5,630	5,274
R-square	**0.999**		**0.999**		**0.999**		**0.998**	
RMSE	**12.78**		**36.15**		**10.80**		**25.72**	

Airport Validation

In addition to accurately reflecting the volume of activity being simulated, the operations and observed conditions need to be replicated in the existing conditions model. As part of the validation process of each model, KHA coordinated extensively with airport staff to obtain input on observed congestion and typical "problem areas" at the airport so that the associated model incorporated the traffic and pedestrian patterns specific to Sky Harbor. To confirm that the model was appropriately reflecting the nuances of their airport, a series of workshops were conducted with various Ground Transportation staff from the airport. The Ground Transportation supervisors and staff are intimately aware of the unique operational challenges that occur on a daily basis and were able to communicate their expectations of the model. Following meetings with Ground Transportation staff, additional workshops were conducted with airport leadership and senior level managers. In some instances meetings with airline representatives were also conducted.

This validation process identified several changes required to reflect the unique nuances to the PHX landside operations. For example, the early morning congestion that occurs at the Terminal 4 Upper Level south curbfront was updated so that the "bunching" that occurs at the eastern most edge of the curbfront. Other areas of particular interest were the Terminal 3 pinch located between Terminals 2 and 3, and its associated queues that extend to the north of the Terminal 2 parking garage almost daily, the slowing of vehicles at the start of the Terminal 4 lower level curbfronts, and the tendency of transit vehicles/shuttles to stop in the non-curbfront lanes. The calibration changes within the existing conditions models were consistently applied to all future years, unless specific improvements were included to improve conditions such as increased roadway capacity. The changes were incorporated into the model through changes in input data, but some even required programming changes. In summary the incorporated modifications included:

- Rental car buses blocking through traffic
- Upper level curbfront vehicles clustering near the first door
- Extremely slow speeds in certain curbfront areas to replicate people monitoring curbfront for arriving passengers
- Recurring congestion at the "T3 Pinch" at off peak hours

This validation process was extremely critical to the Planning Partnership and had a direct benefit to the success of the planning efforts. This invaluable coordination occurred through a series of work sessions with airport staff that resulted in improved vehicle logic within the model. Although extremely intensive, this step established the foundation of the partnership and created trust in the model input. Once the airport staff was satisfied that existing conditions were being sufficiently represented, then it was used to test additional base year and future year alternatives including APM options. As such, there was buy-in to the results that were produced at each of the future year conditions for the various alternatives. This step was the most critical step in the Planning Partnership.

ALTERNATIVES

Due to its linear configuration PHX has specific challenges with respect to its landside capacity. Because of the close proximity of the airside there are significant limitations in the ability to add lanes throughout the terminal area. The dual access from both the east and west direction requires recirculation past unused terminals and can create challenging circulation patterns. The ability to access the airport from the east and west also adds a unique challenge to the airport's landside through the addition of cut-through traffic. During peak hours, non-airport users will use the terminal roadways to "cut through" and reduce their travel time.

Understanding these challenges in combination with the anticipated growth in activity, the consultant design team worked with the airport staff to identify alternatives mitigating these challenges. The multi-modal ALPS model is able to assess the impact of a wide range of options for the airport landside development. In addition, since the analysis is completed through a simulation type model, even drastic modifications to the airport configuration can be quickly evaluated to determine their potential benefit. The alternatives that were developed included:

- Implementation of the airport transit systems (such as the Sky Train APM)
- Expansion of roadway capacity
- Addition of ground transportation centers (GTC's)
- Changes in curbfront and traffic operations
- Changes in parking lot location and size

- Changes in the airport roadway configuration
- Addition of a new terminal
- Changes in non-airport traffic using airport roadways

The future year alternatives were developed by the project team in order to evaluate various options for the airport landside development and its effect on the anticipated vehicular congestion at both the existing terminal curbfronts and the airport roadway system. The development of the alternatives was an iterative process, initially including a large number future year alternatives. Table 4 shows the matrix of alternatives for the curbfront model and the components included in each alternative. And each component included in the alternatives and its general effect in the simulation model is summarized below.

- Remove T4 UL CTX Machines – Allow inner curb lane to be recaptured for vehicular traffic on Terminal 4 Upper Level.
- T2 & T3 Employees to Outlying Lots – T2 & T3 employees moved to Tonto West lot. Reduce employee auto trips in the airport, increase number of shuttle buses.
- Curbfront Redistribution – Optimal distribution of vehicular traffic along terminal curbfronts.
- East Stage n Go Lot – 90 space stage n go lot east of T4. Reduce vehicular recirculation traffic on the curbfront.
- Photo Radar System – Enforce terminal roadway speed limits.
- T3 & T4 Garage GTCs – Taxis, limos, supershuttle curbfront areas relocated to T3/T4 garages.
- Additional T3 Lanes – Additional through lane at T3 along outer curb (Sky Harbor Blvd). Provide additional bypass capacity at T3.
- Expanded East Economy Lot – Additional parking garage at EEL. Reduce auto trips through airport, increase bus trips.
- East Side Employee Parking Expansion – Additional employee parking lot on airport east side. Reduce employee trips through airport originating from east.
- Additional West Side Public Parking – Additional public parking on west side of airport. Reduce auto trips through airport, increase bus trips.
- Security Control Plazas – Security control plazas placed at east and west terminal area entrances. Slows incoming traffic in model.
- Parking Revenue Control Plazas – Parking Revenue Control Plazas placed at east and west terminal area entrances. All vehicles receive ticket entering airport. Vehicles parked over one hour pay fee. Reduce cut-through traffic 10%.
- Parking Revenue Control Plazas with Toll – Parking Revenue Control Plazas placed at east and west terminal area entrances. All vehicles receive ticket entering airport and pay fee upon exit. Reduce cut-through traffic 20%.
- West Terminal – New terminal, replacing T2, to house Southwest Airlines. Assumes unconstrained capacity for west terminal roadways and curbfronts. (Assumed for 58 MAP (35 O&D) and 65 MAP (39 O&D) planning levels only).

Table 4. Future Year Alternatives Matrix

		Alternative Input/Assumption																
Alt	**Description**	Remove T4 UL CTX Machines	T2 & T3 Employees to Outlying Lots	Curbfront Redistribution	East Stage n Go Lot	Photo Radar System	T3 & T4 Garage GTCs	Additional T3 Lanes	Expanded East Economy Lot	East Side Employee Parking Expansion	Additional West Side Public Parking	Security Control Plazas	Parking Revenue Control Plazas	Parking Revenue Control Plazas with Toll	West Terminal[1]	Cul-de-sac	Automated Train	East and West GTCs
1	2006 Existing Conditions																	
1A	2006 Existing Conditions – Modified	X																
2	Near Term Operational Enhancements	X	X	X	X	X												
3	Additional T3 Lanes	X	X	X	X	X		X							X			
4	T3 & T4 GTCs	X	X	X	X	X	X		X	X	X				X			
5	Security Plazas	X	X	X	X	X		X	X	X	X	X			X			
6	Parking Revenue Control Plazas	X	X	X	X	X		X	X	X	X		X		X			
7	Parking Revenue Plazas with Toll	X	X	X	X	X		X	X	X	X			X	X			
8	Automated Train	X	X	X	X				X	X	X				X		X	
9	GTCs for Commercial Vehicles	X	X	X	X	X			X	X	X							X
10	Automated Train with GTCs	X	X	X	X				X	X	X				X		X	X
11	Cul-de-sac between T3 & T4	X	X	X	X	X		X	X	X	X				X	X		
12	Cul-de-sac east of T4	X	X	X	X	X		X	X	X	X				X	X		

(1) West Terminal Implementation valid only for 58 and 65 MAP (35 and 39 O&D) planning levels

- Cul-de-sac – Reconfiguration of terminal roadways.
  - Option 1 – T4 access to/from east end only, T2/T3 access to/from west end only. Buses, airport and emergency vehicles provided access to all terminals.
  - Option 2 – All terminals accessed to/from west end only. East access removed.
  - Cut through traffic removed in both options
- Automated Train (APM) – Automated Train connecting all terminals, parking facilities, and Rental Car Center. All airport buses removed from terminal curbfronts.
- East and West GTCs – All commercial vehicles except taxis and limos removed from terminal curbfronts and relocated to two GTCs (one east, one west).

RESULTS

In addition to the calibration process the airport staff was extremely conscious of how results were provided and communicated. Although the core team was aware of the minute details of the airport's operation, airport staff recognized the need to communicate meaningful, but understandable, results to a broad audience. Another key aspect of the Planning Partnership occurred through the development of metrics that could facilitate this need.

Color Coded Metrics

In typical traffic analyses and roadway design, level of service (LOS) is combined with other measures to describe the operating characteristics of a road segment or intersection. LOS is a qualitative measure that describes operational conditions and motorist perceptions within a traffic stream. The *Highway Capacity Manual* defines six levels of service LOS A through LOS F, with A representing the shortest average delays and F representing the longest average delays.

Because of the need to communicate to a larger audience than a typically traffic analysis and to individuals that may not be familiar with traditional LOS metrics, the project team developed a system based on traffic LOS to evaluate the future year alternatives. The system used three color-coded conditions: green, orange, and red. Table 5 shows the qualitative evaluation measures used for the future year alternative analysis for the curbfront model in comparison to typical LOS designations. The results for the curbfront model are summarized in Table 6.

The color-coded results were used by airport staff to effectively communicate to a broad audience. Using the color coded results it was easy to see how congestion increased or was reduced with the various alternatives. In addition, by using multiple forecast years it was easy to see the duration of the improvements associated with each of the alternatives. Finally, because these results were easy to communicate, they could be presented by a larger group, not just the technical experts familiar with the detailed statistical metrics of LOS.

Table 5. Landside Alternatives Analysis Evaluation System

Evaluation Condition	Time Period	Average Day Conditions	Peak Day Conditions	Level of Service Equivalent
Green	Non-Peak Hours:	Free Flow	Heavy Traffic	A, B, C
	Peak Hours:	Heavy Traffic With No Backups	Backups Less Than 1 Hour Duration	
Orange	Non-Peak Hours:	Medium/Heavy Traffic	Backups Less Than 1 Hour Duration	D, E
	Peak Hours:	Backups Less Than 1 Hour Duration	Backups More Than 1 Hour Duration	
Red	Non-Peak Hours:	Backups Less Than 1 Hour Duration	Backups More Than 1 Hour Duration	F
	Peak Hours:	Backups More Than 1 Hour Duration	Backups Over 3 Hours Duration	

Table 6. Curbfront Model - Future Year Results Summary

Alt	Description	Activity Level		
		51 MAP (30 O&D)	58 MAP (35 O&D)	65 MAP (39 O&D)
1	2006 Existing Conditions	Orange		
1A	2006 Existing Conditions – Modified	Orange		
2	Near Term Operational Enhancements	Red		
3	Additional T3 Lanes	Orange	Red	
4	T3 & T4 GTCs	Green	Red	
5	Security Plazas		Orange	Red
6	Parking Revenue Control Plazas		Orange	
7	Parking Revenue Plazas with Toll		Orange	
8	Automated Train		Orange	Red
9	GTCs for Commercial Vehicles		Orange	
10	Automated Train with GTCs		Green	Green
11	Cul-de-sac between T3 & T4		Green	Orange
12	Cul-de-sac east of T4		Green	Green

Simulation Videos

In addition to the color-coded metrics, videos of the simulations were also prepared that offered a qualitative assessment of the operational scenarios. Figure 2 through Figure 4 illustrate computer screen images of how roadway congestion typically occurs within the multi-modal simulations. Specifically the computer screen images illustrate the early morning congestion that occurs at the Terminal 4 Upper

Level curbfront at the 42 MAP (25 O&D) activity level. Each of these figures represents the simulation model at the upper level of the Terminal 4 curbfront. For each of the figures, the light grey represents the background files where you can see the terminal areas and adjacent building structures. The magenta and green segments were used as pedestrian accumulation areas. The individual vehicle icons can be seen accumulating in the curbfront roadways. There are several different vehicle type colors representing commercial vehicles, private autos, visitors, taxis, etc. Figure 2 has the key icons and areas highlighted as a further point of reference.

In addition, Figure 5 illustrates a screen capture of the lower level bag claim pedestrian congestion that occurs in the vicinity of the bag claim carousels. This figure represents the simulation model at the Terminal 4 bag claim area. The pedestrian accumulation areas are modeled in more detail in this figure. For each of the figures vehicle icons are similar but there are several different types of pedestrian accumulation areas. For example the bag claim carousels are represented by a different color as the corridor and open space segments. In addition, the small black dots represent the individual groups of pedestrians. Figure 5 has some of the key pedestrian areas highlighted as a further point of reference.

Statistical Metrics

The primary measure of effectiveness (MOE) requested by the airport was the color-coded of level of service information with the supporting videos. This provided the airport consistent and easy to understand comparisons between alternatives, scenarios, and models. However, for the consultant design team additional statistics were also developed and requested including the following:

- Travel Times – travel times along terminal area roadways
- Waiting Times – the waiting times for pedestrians at the terminal curbfronts and the RCC curbfronts
- Pedestrian Accumulation – the number of people accumulating at the terminal and RCC curbfronts
- Bus Fleet Size – the number of buses in operation

Although the statistical results were not presented to a large audience, the benefit of having the quantitative analysis that supports the more qualitative assessment was an important part of the planning effort.

Conclusions

Based on the results, only two future year alternatives provided the airport with green evaluation conditions at the 65 MAP (39 O&D) planning level: Alternative 10 (Automated Train with GTCs) and Alternative 12 (cul-de-sac east of T4). Although the cul-de-sac option evaluated in Alternative 12 that eliminated through access along the terminal roadways provided significant benefit, airport staff indicated that this alternative would not be a feasible option for the airport. Eliminating access from both sides of the airport could create a significant operational complication for commercial vehicles as they would have to travel around the airport to access all the terminals and could require significantly more vehicles to maintain a similar customer level of service. Also, while previous surveys indicated that passengers arrive at the airport from the east/west sides of the airport at roughly a

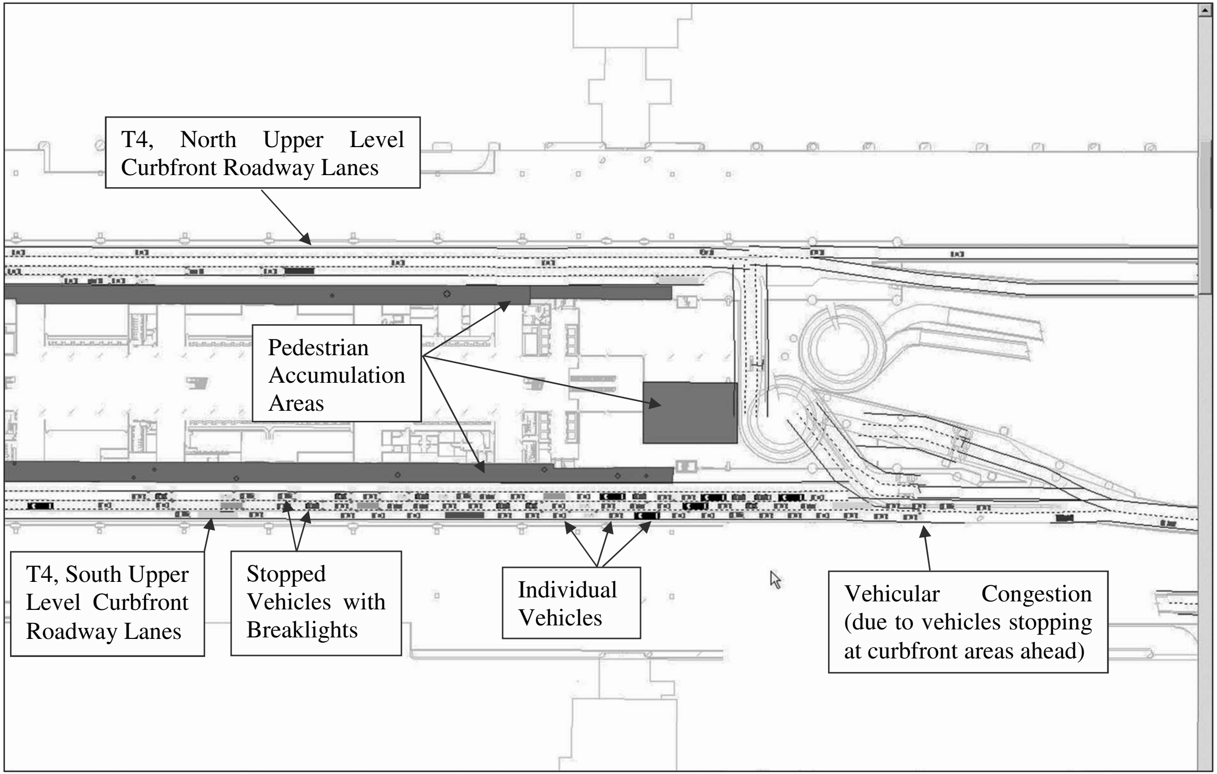

Figure 2. Terminal 4 Upper Level Vehicular Congestion – 42 MAP (25 O&D) No-Build, 6:15 AM

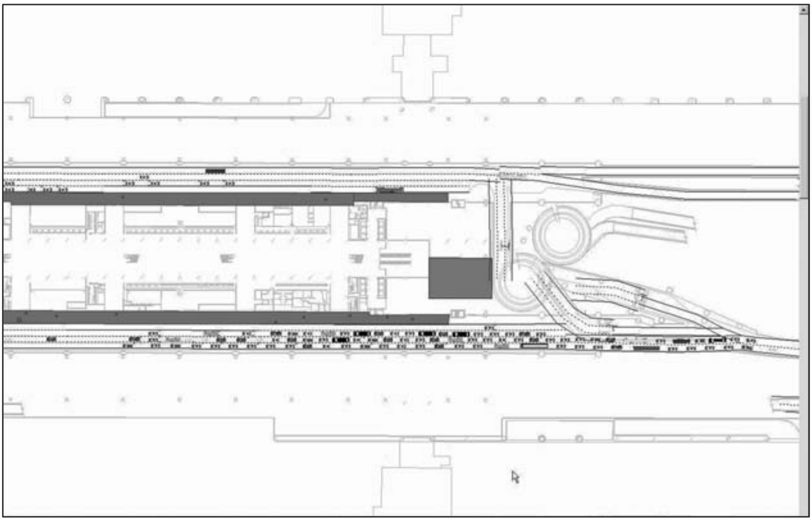

Figure 3. Terminal 4 Upper Level Vehicular Congestion - 42 MAP (25 O&D) No-Build, 6:20 AM

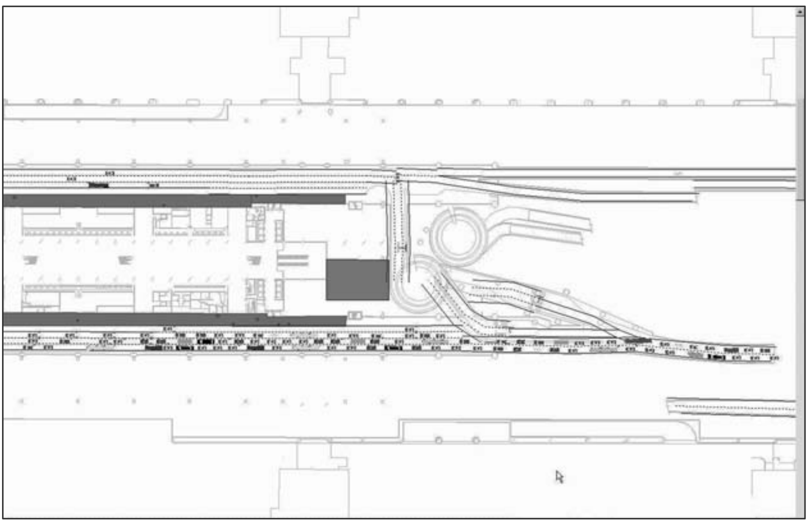

Figure 4. Terminal 4 Upper Level Vehicular Congestion - 42 MAP (25 O&D) No-Build, 6:25 AM

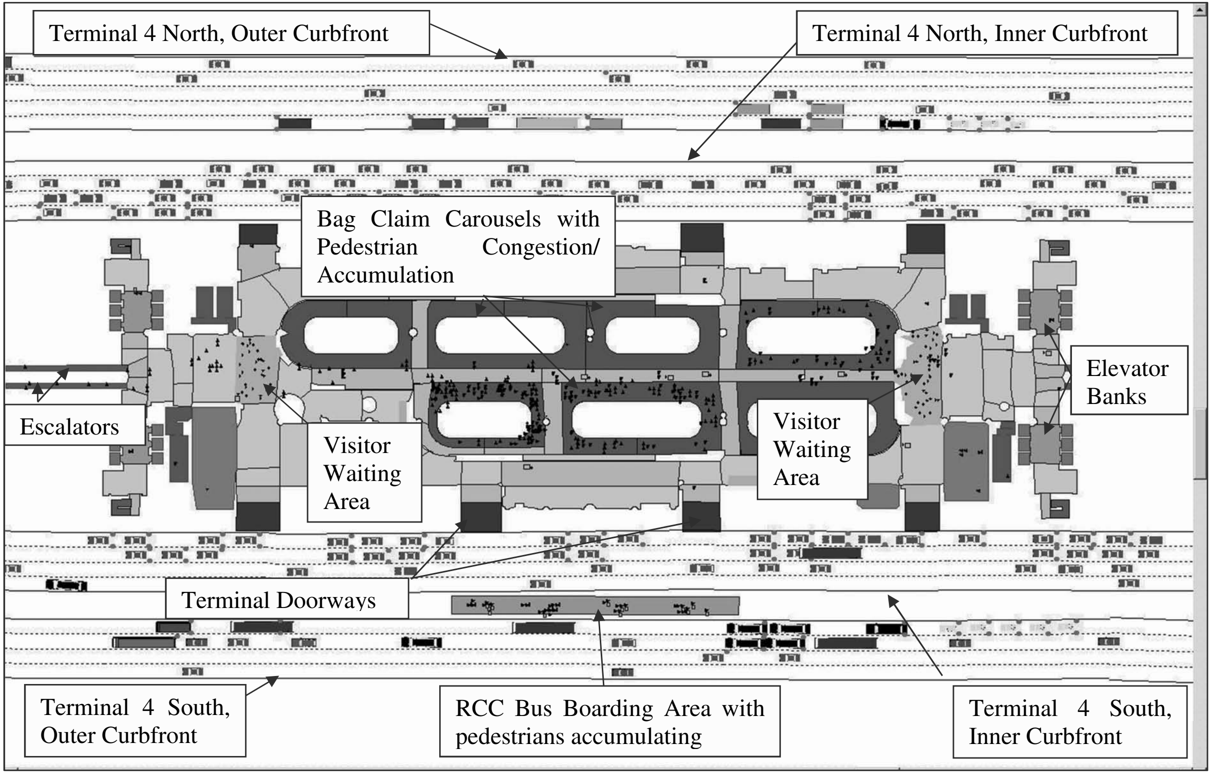

Figure 5. Terminal 4 Bag Claim Pedestrian Congestion – 42 MAP (25 O&D) No Build, 6:30 PM

25/75 split, more recent counts indicate that the split has changed to a roughly 50/50 split. In addition, the wayfinding signage that would be required on the airport access roadways to communicate the route to air passengers would be extensive and complicated.

A comparison between Alternative 10 and Alternative 3 showed a 25% drop in vehicular traffic along Sky Harbor Boulevard in the Terminal Core Area with the implementation of the APM system and the GTCs. Based on the iterative alternatives, it was found that Alternative 10 represented the optimum and most realistic option to provide the airport with additional capacity to handle growth on the airport roadways and terminal curbfronts.

ADDITIONAL SUPPORT

The initial focus of the ALPS modeling was evaluating landside alternatives to the Sky Train. However due to the success of the landside planning efforts the simulation models were further used to support the design development. Pedestrian models of the APM stations and adjacent terminals were developed as well as a detailed model of the RCC.

Terminal Circulation Models

As a result of the findings of the curbfront modeling, the airport proceeded with further evaluation of the Sky Train and GTC options. The introduction of an APM platform at the passenger terminals introduced numerous and potentially significant changes to the vertical circulation elements within the terminals. The Terminal 4 Circulation Model (T4 model) was developed in order to evaluate the placement of the APM platform at Terminal 4 and its effect on the vertical circulation patterns of passengers within the facility and the associated vertical circulation facilities.

Similar to the T4 model, a detailed model of Terminal 3 was also developed to evaluate the placement of the APM platform and its effect on the vertical circulation patterns of passengers within the facility.

Additional workshops were held with the airline as part of the validation process to discuss and present the operational conditions of the T4 model and incorporate airline specific information.

Rental Car Center Model

A RCC Model was developed to evaluate the effect of the timing of the final link of the Sky Train Project (Phase II, the connection from Terminal 4 to the RCC). The RCC was initially designed to accommodate the Sky Train; however the RCC is currently being served via an extensive bussing operation. This alternative evaluated the impact of using the bussing operation on the RCC loading/unloading platform and nearby roadways (East Sky Harbor Circle South, South 24th Street, and E. Buckeye Road). The goal of the RCC modeling was to determine at what air passenger activity level the RCC platform and surrounding roadways would fail.

Combined Model

Following the results of the RCC model, the airport staff then requested a combined model that had the ability to simulation the RCC congestion and its impact on the Terminal area operations. To facilitate this request, the curbfront, terminal, and RCC models were combined into one model. A series of the models were shown to Federal Aviation Administration (FAA) representatives and used in communication of the landside challenges PHX faces and present the need for the Sky Train.

Incident Scenario

Simulation models typically represent ideal conditions. Although some of the alternatives represent green and orange conditions, were an accident or construction to occur, the operations could quickly deteriorate to red for extended periods of the day. An additional scenario for the 51 and 58 MAP (30 and 35 O&D) activity level were conducted assuming a traffic accident occurs blocking one lane for a 60-minute period on Westbound Sky Harbor Boulevard between Terminals 2 and 3. This analysis showed that in addition to general passenger movement, the APM system also benefits the traffic congestion. The APM system reduces roadway traffic. When incidents such as traffic accidents occur, the vehicle queues are reduced allowing congestion to clear faster. Traffic accidents have the potential to dramatically increase delay to passengers using the airport facility. The congestion associated with the minor accident could be significantly increased based on the time of day of the incident or based on the actual location of the incident. The Sky Train removes large portions of the passengers (Economy Parkers, Rental Car Patrons and other passengers utilizing commercial vehicles) from the constrained airport roadway network. This allows the airport roadways to recover quickly when incidents do in fact occur.

BENEFITS AND LESSONS LEARNED

The planning success for the PHX Sky Train can be evidenced by the fact that the $1.6B PHX Sky Train is currently under construction. Looking back through the planning processes several critical steps and coordination efforts can be identified that directly led to this remarkable achievement.

Maximizing Available Tools

The use of simulation models allowed the airport and the consultant design team to brainstorm, analyze, and vet a large number of options in a very short period of time. Extreme options, such as implementing cul-de-sacs and significantly changing the airport's access, could be evaluated through simulation. Although a modeling atmosphere, because of the detailed calibration process the analysis generated quantitate metrics that allowed the design team to evaluate the viability and potential benefits of even these extreme options. In addition, the iterative process of developing the alternatives facilitated brainstorming, teamwork and resulted in a comprehensive look at potential options for landside access.

Planning tools can also be used during the design process. Because of the comfort with the results of the simulation model, the use of the model as a true planning tool was maximized and benefited not only the planning for the Sky Train but also the station design. The airport was also creative in utilizing the modeling tools to evaluate irregular operations such as a roadway incidents or terminal evacuations.

Stakeholder Partnership

The stakeholder coordination throughout the planning process was absolutely critical. Local stakeholders and facility users have an intimate knowledge of their environment and facilities and the consultant design team was able to benefit significantly from their input throughout all stages of the planning process. During the calibration/validation process, the input received from the Ground Transportation staff allowed the design team to implement nuances to help the model replicate the actual PHX environment. This increased the credibility of the simulation model creating a broad consensus on the reliability of the future year results.

Clear Communication of Results

In addition to the stakeholder input during the calibration/validation process the stakeholder input to the presentation of results was also extremely beneficial. As the ground transportation staff clearly understood the landside challenges, the airport project leadership also understood the need for clearly and effectively communicating the results across a broad audience. This effective communication led to a unique level of service metric that was well received across a broad audience. In addition to trusting the results, understanding the results is equally as important.

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Phoenix Sky Harbor International Airport
PHX Sky Train™ - Making Tracks in the Arizona Desert

Anne Kurtenbach[1], Darryl Jaquess[2]

[1] PHX Sky Train™ System Program Manager, Aviation Department, City of Phoenix, 3400 East Sky Harbor Blvd, Suite 3300, Phoenix, AZ 85034-4405
anne.kurtenbach@phoenix.gov, phone: 602-683-3793
[2] Senior Associate, Lea+Elliott, Inc., 500 S. 24th Street, Phoenix, AZ 85034,
djaquess@leaelliott.com , phone: 623-512-2681

Abstract

Phoenix Sky Harbor International Airport serves more than 100,000 passengers per day, with 1,500 flights per day, and a daily economic impact that surpasses $90 million for the Phoenix metro area. Phoenix Sky Harbor International Airport takes pride in meeting the needs of the region's thriving population, and planned improvements will add to its ability to remain America's Friendliest Airport™. Sky Harbor serves nearly 40 million passengers every year. To keep pace with the Valley's growth, Phoenix Sky Harbor Airport will need more terminal space and parking, better roads, airfield improvements, and options for moving people and airplanes around the Airport more quickly. The PHX Sky Train™ is an integral part of the Airport Development Plan.

Construction on the PHX Sky Train™ system began mid-2009, and is positioned to begin passenger service in the first quarter of 2013. The first stage, Stage 1, of the PHX Sky Train™ system will replace the existing bus connection between the Metro Light Rail station at 44th Street and Washington, East Economy Parking and Terminal 4. A system extension, Stage 1A, is currently underway and will provide an APM connection to Terminal 3 and Terminal 2 by early 2015. The final stage, Stage 2, will continue to extend the system to the west ultimately serving the Rental Car Center. Figure 1 illustrated the stages of the PHX Sky Train™ project.

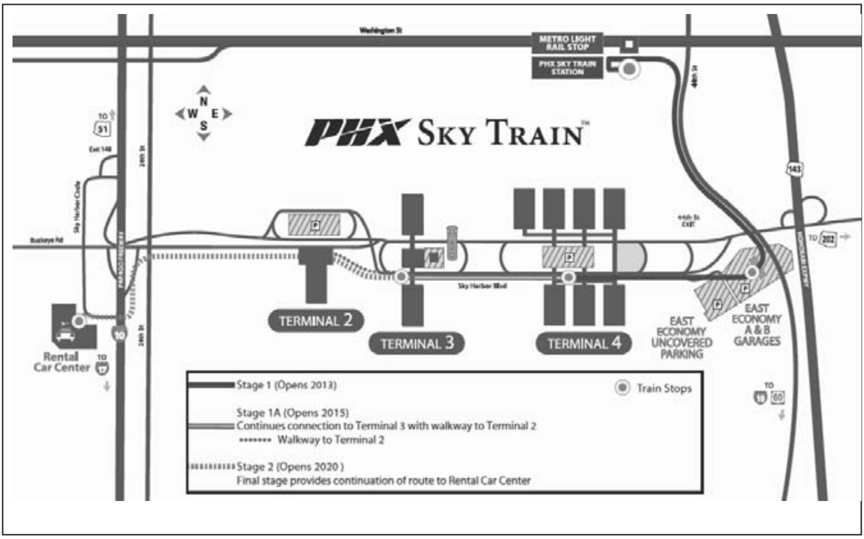

Figure 1. Stages of the PHX Sky Train™ project (Sky Harbor International Airport)

This paper will address the implementation, testing and operation of the Stage 1 system including provisions for the expansion of Stage 1A; the Maintenance and Storage Facility (MSF) spur track and future major system expansions. The Stage 1A planning and design was accelerated during Stage 1 to be implemented within two years of Stage 1 operations to enhance service to all the passenger terminals and reduce the need for bus service from the light rail interface station and east economy parking to the terminals. The expansion of the spur track will open with Stage 1 and will allow more efficient vehicle movements within the MSF yard. In addition, this paper will provide an update on the current status of system implementation, testing, system improvements, innovations, and lessons learned. Finally, the paper will discuss the plan to complete the system expansion to the existing rental car facility approximately two miles west of the passenger terminals. The expansion provisions are a key feature of the system which is designed to accommodate about 2.5 million riders in the first year and about 35 million riders in 2035, while minimizing interruptions to passenger service.

Project Structure

The PHX Sky Train™ was structured as a fast track project with two separate designers for the system and fixed facilities. The City supplemented the two designers with City project managers that presided over the designers and the contractors. Lea+Elliott was selected as the System Designer and Owner's Representative for the system and Gannett-Fleming was selected as the fixed facility designer. The City's general contractor for the fixed facilities is Hensel Phelps Construction Co. for the

Stage 1 portion of work and Kiewit/McCarthy Joint Venture for the Stage 1A portion of the project. The contractor for the system is Bombardier. During the design phase, Bombardier provided interface information to the fixed facility designer and contractor to help ensure the fixed facilities were designed and constructed to accommodate their unique requirements. Lea+Elliott ultimately served as the construction manager between the two contractors to help facilitate the construction and implementation of the system.

The project delivery methods for the two contractors were very different. The fixed facilities procurement method was construction manager at risk (CMAR). This method allowed the owner some flexibility during the design and construction with regard to additions and subtraction to the project through Owner's and project contingencies. The System contract was procured as a design, build, operate and maintain (DBOM). Under this project delivery method, the System Supplier (Bombardier) was awarded two separate contracts, one for the design, manufacturing, construction, installation, testing and commissioning, and the second for Operations and Maintenances services. This best value approach allowed the City to get the best product for the budget.

Stage 1 System Overview

Stage 1 of the system operates on a dedicated right of way from 44th street and Washington to the East Economy Parking lot and terminates at Terminal 4. The 44th street station serves the light rail passengers via a conditioned connector bridge equipped with moving walkways from the PHX Sky Train™ station to the Valley Metro light rail platform. In addition this station serves employee parking, short term parking for customers to pick up passengers and not have to travel to the busy terminal area. From the 44th street station, the guideway heads south and dips down below the Union Pacific Rail Road and travels at grade before it transitions up over the terminal roadways to a station at the east economy parking lot. This station serves all of the east economy parking garages as well as the surface parking. This station incorporates remote bag pickup whereas passengers who are checking luggage can check in their bags first and then ride the train to their terminal. From the East Economy Station the system heads westward and over Taxiway Romeo approximately 33 meters (109 ft) above the taxiway and arrives at the passenger level at Terminal 4.

The Stage 1system operates as a pinched loop with four, two-car trains during the peak hours. Stage 1 is approximately 2.7 kilometers (1.7 miles) of dual lane guideway and incorporates 17 mainline cross-over switches and 9 yard switches. The 18 vehicle fleet can operate in either 2 or 3 car consists for Stage 1 and can be expanded up to 4 car train consists in the future. Each vehicle will hold approximately 53 passengers which account for luggage, bag carts, wheel chairs and other items passengers my load onto the vehicle. During peak hours, the Stage 1 system operates on 3 minute headways and can transport up to 3000 passengers per hour per direction. The System cost was approximately $186 million dollars and the fixed facilities cost were approximately $458 million dollar for a total project cost of approximately $644 million dollars. Figure 2 depicts the extents of the Stage 1 system.

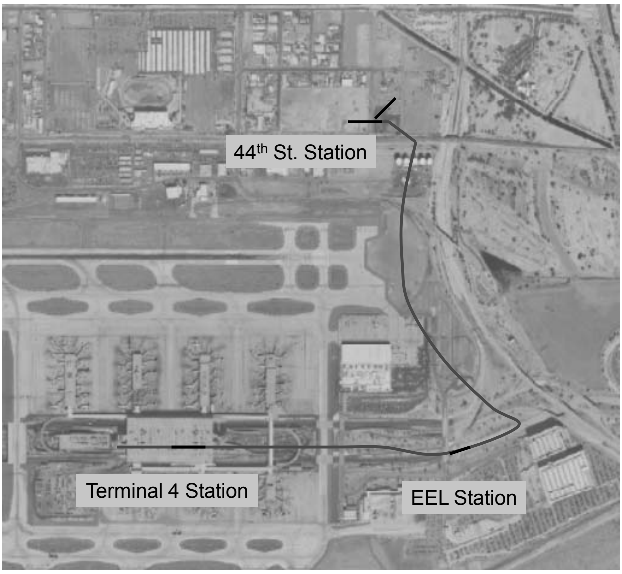

Figure 2. The Stage 1 System (Sky Harbor International Airport)

The City's fixed facility contractor is Hensel Phelps Construction Co. HPCC constructed all the fixed facilities including the stations, guideway and the traction power substations. The City's system contractor is Bombardier. They are responsible for providing the barrier wall system in the stations, the running surface, guidebeam, power rails, emergency walkway, power distribution equipment, train control, wayside equipment, vehicles, the maintenance and storage facility (MSF) and the vehicle storage yard.

Construction activities on the MSF building began June of 2010 and the facility was completed in January of 2011. Construction on the guideway for the running plinths began in November of 2011. Installation of the station equipment began in February of 2012. The Maintenance and Storage Facility is located at 1111 S. 44th Street which is on the far east side of the airport property. A photo of the MSF building is included in Figure 3. The Stage 1 building is approximately 3,159 square meters (34,000 sq ft) and is design to be expanded to approximately 6,503 square meters (70,000 sq ft) to accommodate the Stage 2 fleet.

Figure 3. Maintenance and Storage Facility (Sky Harbor International Airport)

Testing/Commissioning

To comply with the Technical Provisions of the system contract, Bombardier had to verify over 450 specific requirements. Approximately 300 acceptance tests were performed to verify contract compliance for roughly 20,000 discreet technical requirements on the system equipment and system fixed facilities. After all of the system elements were verified to perform as an integrated system, the system entered into the acceptance phase.

Substantial Completion

Once the system has been verified to be capable of operation as an integrated system, Bombardier is required to demonstrate system operations according to the contract specifications for a 30-day consecutive period. During system demonstration, the system operates 24 hours per day according the system operations schedule and the system must perform with a system service availability of 98.5%. Also during this period Bombardier must demonstrate operational readiness in train operations and recovery, as well as maintenance, Bombardier is required to complete System Demonstration in order to achieve substantial completion.

Final Acceptance

Once system demonstration was completed, the system was determined to be reliable and safe to enter into passenger service and the Operations and Maintenance contract is in force. Also during this period, Bombardier must continue to operate maintain the system service availability requirement of 99.5% for a period of 180 days after substantial completion to achieve final acceptance.

Figure 4. Sky Train on the Taxiway Flyover (Sky Harbor International Airport)

Stage 1A System and Future Extensions

The Stage 1A extension is scheduled to complete in January of 2015 just before the NFL Super Bowl hosted in the Phoenix area. Stage 1A of the system is constructed west from Terminal 4 and passes under taxiways Sierra and Tango and ascends up to the station at Terminal 3. For passengers continuing on to Terminal 2, a walkway was constructed to make the short walk to Terminal 2. This phase includes one additional station, approximately 914.4 meters (3,000 ft) of dual-lane guideway and an additional 5 switches. There are no additional vehicles or propulsion stations in this stage of the project. This extension allows the PHX Sky Train^{TM} to serve all terminals in the near term and further reduce busses on the roadway system. The system cost for this stage was $45 million dollars and the fixed facilities cost was $195 million dollars for a total project cost of $240 million dollars. Stage 2 of the system would add an additional 4 kilometers (2.5 miles) of guideway, multiple stations, additional power substations and more than triple the current fleet of vehicles.

In addition, a 106.7 meter (350 ft) extension of the MSF yard track was included in Stage 1A and accelerated to be implemented during Stage 1 construction. The extension of the yard track allows for more efficient train movements around the yard in Stage 1. This extension gives PHX more flexibility in system operations. The spur extension provides a place to store trains, and to make or break trains without interrupting on-going operations.

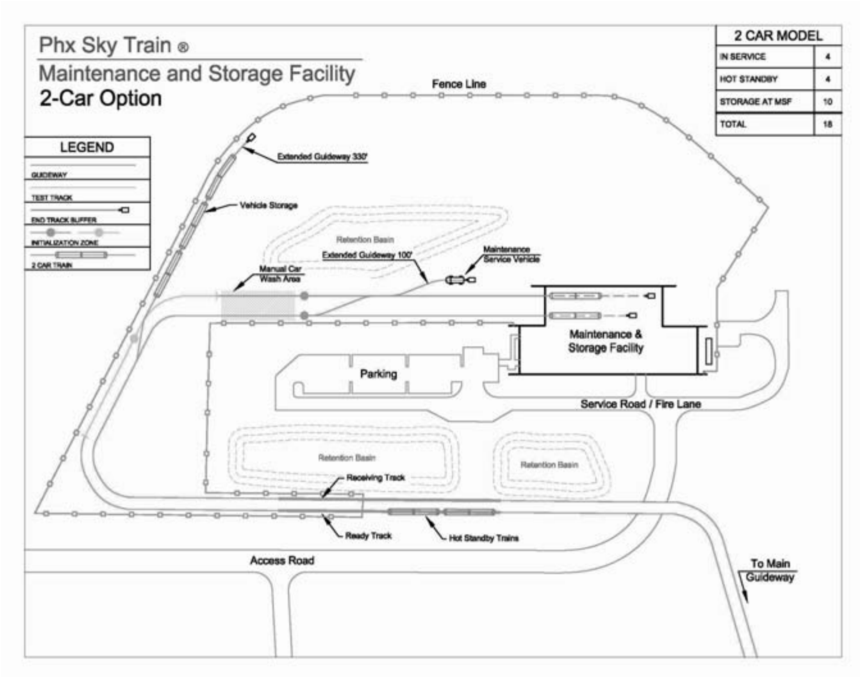

Figure 5. Stage 1 MSF Yard with Extended Storage Track (Sky Harbor International Airport)

The cut-over plan from Stage 1 to Stage 1A of the system is one of the most critical parts of the Stage 1A implementation. The extension has to be designed, constructed, installed and tested with no interruptions to Stage 1 operation as well as adhering to PHX holiday moratoriums. Much of the work, including testing, will be completed at night during the off-peak hours of the airport operations allowing only a small window of time to mobilize, work, demobilize and resume Stage 1 operations before morning.

Stage 1 and Stage 1A were designed and constructed with Stage 2 in mind. The propulsion equipment, automated train control (ATC) equipment, communications and central control were sized to accommodate the Stage 2 operations and fleet. The ATC system was design to be easily adapted for Stage 2. The MSF build was design with all the administrative offices, workshops and storage space needed for Stage 2 operations and maintenance (O&M). The maintenance area of the building incorporates “punch-out” concrete panels that will be removed to allow construction of additional maintenance bays to support Stage 2 O&M, without impact to Stage 1 maintenance operations. Further, the yard track was constructed with turn-outs for additional spur tracks in order to not impact operations during construction of the Stage 2 yard. Stage 2 will also incorporate an automated car wash facility to wash the large fleet of vehicles.

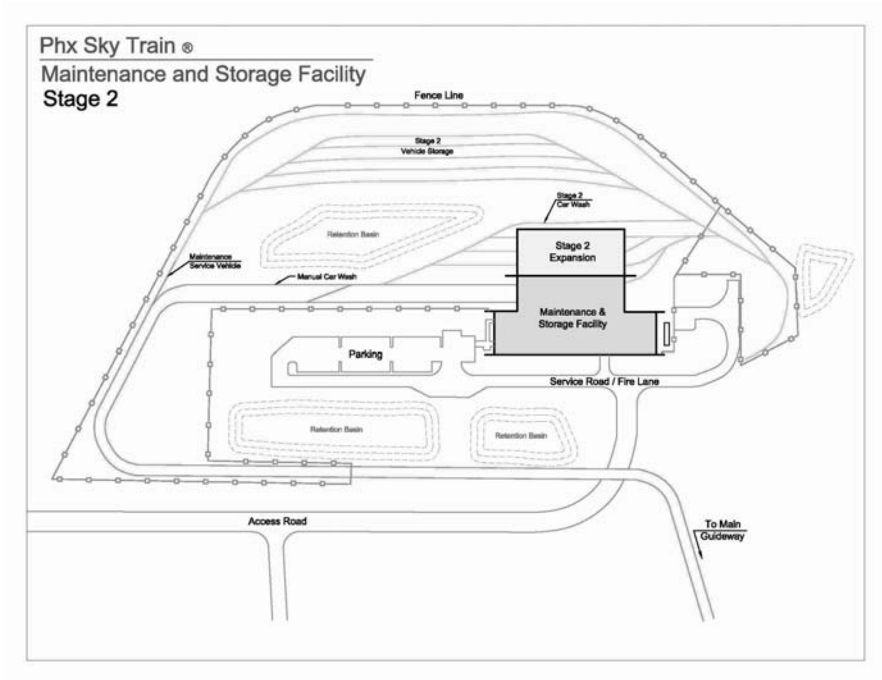

Figure 6. Stage 2 MSF and Yard (Sky Harbor International Airport)

Innovations

The ultimate goal of the PHX Sky Train™ System was improved customer service. Customer service was paramount in every aspect of the project. The vehicles were designed to operate in 2, 3 and ultimately 4-car train consists depending on the system demand. Bombardier has positioned recovery and roving technicians around the system to respond quickly to system malfunctions and provide passenger assistance. In addition, Bombardier technicians ride the system to ensure that the system is clean and operating properly.

The City, Lea+Elliott and Bombardier have worked closely with PHX first responders to incorporate their input in the design and standard operating procedures for the system. Part of this partnership was the inclusion of the Terminal 3 secondary central control. The second central control workstation resides in the Airport Communications Center, the nexus for all airport operations and dispatching. In the event of a serious airport wide emergency, Bombardier will dispatch a central control operator and supervisor to this location to operate the system under the direction of police, fire and airport executives. The secondary central control has the same functionally as the main central control facility located at the MSF.

The vehicles are wired to accommodate dynamic route maps for Stage 2 of the system so that passengers can navigate where they are on the ultimately 8 kilometer (5 mile) long system. The vehicles currently utilize on-board CCTV recording. Video is recorded and downloaded to be stored once the train comes out of service. The current vehicles and wayside equipment have been wired to accommodate live streaming video in Stage 2 of the system. The central control operators will be able to see live images of each vehicle on the system in Stage 2 of the project.

Another innovation the PHX Sky Train™ has incorporated is the passenger counting system (APC) provided by Bridge Technologies. This system was implemented as a tool to help determine service levels for the PHX Sky Train™ system. The APC system was installed in the door headers at every door opening at all three stations and will be installed at the new Terminal 3 station. The APC System has a detection system that utilizes “Time-of-Flight (TOF)” technology. For the PHX Sky Train™ the APC will use the new 500 pixel array sensor developed by iris-GmbH. The system generates a 3D-image at the opening of each doors set on the station platform, so that individual people are detected even when they board and deboard in tight groups. Each time the station doors open and close the data is collected and transmitted wirelessly to a central processing center which can then be accessed by Operations staff via the internet. Phoenix Sky Harbor International Airport is one of the first airports to use an APC of this type. The system claims to have greater than 99% accuracy. This system will help the PHX planning operations, future growth planning and ultimately enhance customer service.

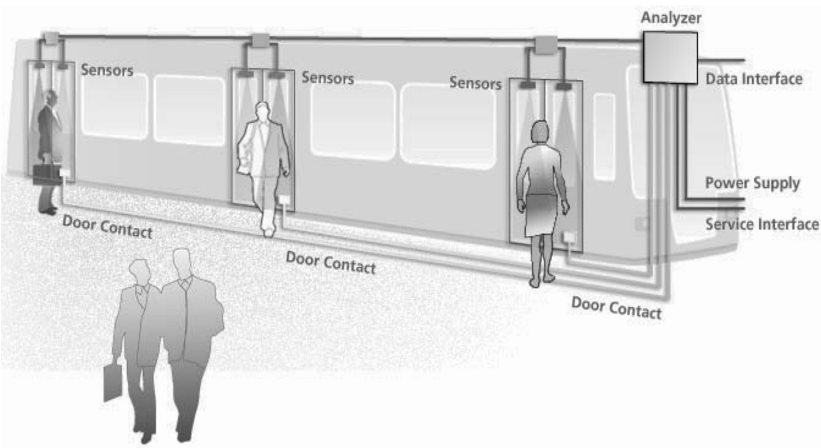

Figure 7. Passenger Counting System Graphic (Bridge Technologies)

Phoenix Sky Harbor International Airport has also deployed early bag check-in at the 44th St and East Economy Parking stations. In partnership with the airlines, the Airport has contracted with Bags, Inc., a certified third-party provider for this service. Passengers check their bags at the stations, as well as print their boarding passes prior to boarding the PHX Sky Train™. By offering this service, it not only meets a customer service need, but also increases the capacity of the system while reducing the number of bags being pulled through the terminals, thus overall improving the passenger experience.

Lessons Learned From the Project

Even the most successful projects like the PHX Sky Train™ have lessons from which we can learn. Lessons learned do not necessarily depict what went wrong with the project, but how to learn from the challenges presented in Stage 1 and make suggested changes for the future extensions of the system. The designers and City project managers have collectively analyzed design, construction and implementation of the fixed facilities and the system to find more efficient and effective means of delivering future stages of this project. The lessons learned serve as a valuable tool for the project team to use moving forward. The following are examples of lessons learned during Stage 1 of the PHX Sky Train™ system.

During design it is vitally important to bring the system supplier on-board before design has progressed too far. The system supplier provides valuable information about their unique requirements so that the fixed facilities can be sized and constructed appropriately to meet their needs. Open dialog between the designers and contractors should be strongly encouraged and coordinated. By doing this the fixed facilities designers and ultimately the fixed facility contractor understand the system construction tolerances, interfaces and unique requirements of an automated people mover. In addition, through open communication, it is much easier to manage expectations of the Owner and designers. The designers may have a design in mind, but need to understand the size and type of equipment the system supplier will be installing.

The fixed facility turnover dates should be discussed fully so that the fixed facility contractor and designer understand what constitutes a turnover of the fixed facilities. These dates should be realistic so that all parties can make the dates and avoid delays in the project. Many of the facilities can accommodate shared access, but others require that no other contractors can work during this time, however unforeseen issues can occur that can constitute in large delays if the turnover dates are scheduled critically.

During the project the schedule must be kept in mind. An integrated schedule is paramount to a successful project. A project schedule derived by the Owner that incorporates the system supplier's schedule and the fixed facility contractor's schedule is extremely valuable. The Owner, designers and contractors can see and understand first-hand the critical path and are better be able to manage the sequence of construction.

One other area is reducing the number of interfaces between contractors. For example, in Stage 1 of the PHX Sky Train™ project, the fixed facility contractor provided an opening in the station walls for the system contractor to install their barrier wall system. The fixed facility contractor provided the cladding around the door system and the column cladding within the door system. This required a tremendous amount of coordination and rework to get all the cladding to be aesthetically consistent. In Stage 1A all the column cladding and the cladding around the Bombardier door system will be supplied and installed by Bombardier.

The implementation of a construction oversight liaison between fixed facility contractor and system contractor was a void that Lea+Elliott ultimately filled. Bringing this service online sooner would help the turnover of facilities go more smoothly as well as ward off any other potential issues before they cause potential project delays or rework.

Integration with the Airports systems and facilities was another challenge to overcome during the Stage 1 portion of the project. While not uncommon in these types of projects, it was vitally important for the system contractor to understand the interfaces with airport systems such as fire alarms, telephone system, public address as well as integration with Airport Communication Center. Not only is it valuable for the system contractor, it is extremely important that the Airport understands the requirements and the system to be integrated. This will help avoid any confusion and limit the amount of rework required by both parties.

Two main reasons the implementation Stage 1 of the PHX Sky Train system was so successful was the experienced staff. Professionals working on this system had vast knowledge of delivering projects. The second reason was requiring a service proven technology. The system installed in Phoenix had been successfully installed at two other locations.

Figure 8. PHX Sky Train™ testing (Sky Harbor International Airport)

Conclusion

The PHX Sky Train™ provides Phoenix Sky Harbor International Airport with an efficient, effective, convenient and environmentally friendly transit system to move airport visitors, passengers and employees throughout the airport. The elevated train provides a seamless connection to the light rail station at 44th Street and Washington, which is now considered the new "gateway to the airport". The PHX Sky Train has reduced the number of busses and passengers utilizing the roadway thereby reducing airport roadway and curb congestion.

The PHX Sky Train™ is free to the public and operates 24 hours a day, arriving at stations during peak periods of operation every three minutes and delivering passengers to their destination in an average of five minutes. Customer service is foremost at Phoenix Sky Harbor International Airport and the PHX Sky Train™ is an important component in maintaining these standards. Given the flexibility of operations and the expandability of the PHX Sky Train™ system, the region's growth will be accommodated into the future and the train will help to maintain the airport's reputation for superior customer service.

Chicago O'Hare Airport Transit System
Sustainable Ground Transportation

Rosemarie S. Andolino[1]
Diane Woodend Jones[2] and Chris Gambla[3]

[1]Commissioner, Department of Aviation, City of Chicago; 10510 West Zemke Circle, Chicago, IL 60666; PH (773) 462-7300; email: rosemarie.andolino@cityofchicago.org

[2]Board Chairman/Principal, Lea+Elliott, Inc., 2505 North Highway 360, Grand Prairie, TX 75050; PH (972) 890-9800; email: dwjones@leaelliott.com

[3]Senior Associate, Lea+Elliott, Inc., 2140 Mulberry Drive, West Chicago, IL 60185; PH (630) 562-9407; email: cgambla@leaelliott.com

ABSTRACT

The O'Hare Airport Transit System ("the ATS") is a landside automated people mover (APM) that has been serving all four passenger terminals and Economy Parking Lot E at Chicago's O'Hare International Airport since 1993. The ATS operates 24 hours per day, seven days per week throughout Chicago's extreme weather conditions. In support of the successful O'Hare Modernization Program and the projected future growth of the airport, the ATS will be expanded, with an extension of the alignment from Economy Parking Lot E to Economy Parking Lot F, the addition of a new station at Lot F, a fleet expansion, and expansion of the existing maintenance and storage facility (MSF).

This paper will present a description of the primary drivers of the ATS expansion, which include the addition of a new runway (9C-27C) and the implementation of the new Joint Use Rental Car and Public Parking Facility in Lot F, and how the ATS is affected and contributes to each of these elements. The paper will discuss how the ATS continues its longstanding contribution to sustainable ground transportation at ORD, both historically and for the future new facilities configurations at ORD. The paper will also discuss aspects of the overall ATS expansion, including the existing north terminus of the ATS in Economy Lot E, the new station in Economy Parking Lot F that will be incorporated into the Joint Use Rental Car and Public Parking Facility, as well as expansion of the fleet and MSF to accommodate the immediate and future growth in demand.

INTRODUCTION

The O'Hare Airport Transit System (ATS) is a driverless, fully-automated, electrically-powered, landside people mover operating 24 hours a day, 365 days a year at Chicago O'Hare International Airport.

Construction of the ATS began in the fall of 1987, and the system fully opened for passenger service in May 1993. For the past 19 years, the ATS has transported millions of passengers annually between Terminals 1, 2, and 3 (T1, T2, T3), International Terminal 5 (T5), and Economy Parking Lot E, as illustrated in Figure 1.

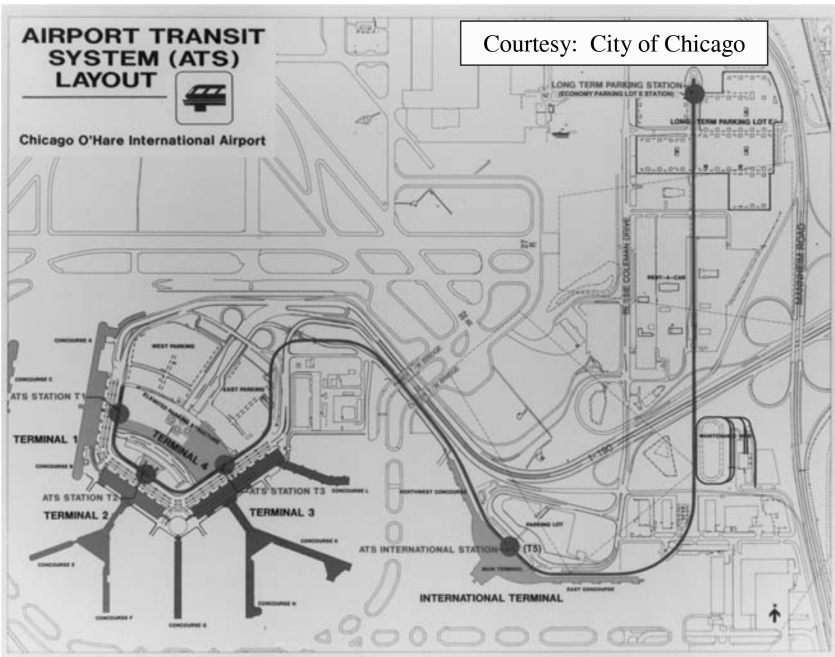

Figure 1: ORD ATS Layout

Since its inception, the ATS has significantly contributed to the Chicago Department of Aviation's environmental stewardship at the airport. As the O'Hare Modernization Program (OMP) continues today, the ATS will be expanded to serve a larger population of airport users, furthering the City of Chicago's commitment to green initiatives and to enhancing the lives of our fellow citizens at the airport.

This paper will present a description of the ATS expansion and how the ATS continues its longstanding contribution to sustainable ground transportation at O'Hare, both historically and for the future new facilities configurations at the airport.

THE ATS - A BRIEF HISTORY

In 1982 the Department of Aviation unveiled its Airport Master Plan, and shortly thereafter initiated the O'Hare Development Program (ODP). At that time, numerous shuttle buses operated between the remote parking lots and "core" terminals at the airport (T1, T2, and T3). The goals of the program were to expand the terminals, gates, and ground access systems at O'Hare. The most significant improvements of the program included the construction of International Terminal 5, as well as the ATS. In particular, the ATS was being implemented to help reduce pollution due to traffic congestion, especially around the core terminals, and was a key factor in obtaining Federal approval of the program. Upon its opening in 1993, a trip on the ATS from Parking Lot E to Terminal 1 could be made in approximately half the time of a shuttle bus operating on the same route. The shuttle buses were discontinued once the ATS began service.

At the time of the ATS opening, International Terminal 5 also opened to the public. All international passenger arrivals requiring immigration and/or customs clearance at O'Hare arrive at T5. Up to 75% of the passengers arriving at the terminal connect to a domestic flight at one of the core terminals via the ATS. Without the ATS, shuttle buses would be required on frequent headways between T5 and the other terminals, adding significant traffic congestion to the terminal access and frontage roadways.

The positive environmental impact the ATS has had at O'Hare over the past 19 years in reducing pollution and land development impacts from ground vehicles has been tremendous. During this time, the amount of fuel saved, and the reductions in NO_x and CO_2 emissions through replacement of shuttle bus and other fossil fuel-based vehicle operations with the ATS illustrate the longstanding verifiable commitment that the Chicago Department of Aviation (CDA) has to its sustainability and green initiatives. This commitment has been accelerated over the past nine years with the development and publication of CDA's industry-leading Sustainable Airport Manual, which has received national and international recognition, and is being used in the design of the ATS expansion and other projects discussed herein. However, the ATS's green footprint at O'Hare has not yet reached its full potential, and is expanding to again contribute to CDA's environmental stewardship of O'Hare in a significant way.

THE EXISTING O'HARE MODERNIZATION PROGRAM (OMP)

The O'Hare Modernization Program (OMP) is today one of the largest construction projects in the country at one of the world's busiest airports, and is managed by the Chicago Department of Aviation. The primary objective of the OMP is to reconfigure O'Hare International Airport's intersecting runways into a more modern, parallel layout. The $6.6 billion program will substantially reduce delays in all weather conditions and increase capacity at the airfield, allowing O'Hare to meet the region's aviation needs well into the future.

The modernization of O'Hare's airfield is a multi-year two phase process, and is currently nearing the end of Phase 1. The original airfield configuration (prior to the OMP) had seven runways, all of which intersected, except for one, as described in Figure 2.

The first step in the modernization process was to close Runway 18-36, extend Runway 10-28 (September 2008), build and open the far north new Runway 9L-27R (November 2008), and shorten Runway 14R-32L (May 2010). The new north runway allows the airport to accommodate three simultaneous arrival streams, while the other modernizations in this phase provide additional runway length, airfield capacity, and operational flexibility. The existing airfield configuration including these improvements is graphically described in Figure 3. Phase 1 also includes building and opening a second new runway (Future Runway 10C-28C), which is scheduled for completion during the 4th quarter of 2013.

The final step in the modernization process is to extend Runway 9R-27L, to build and open two new parallel runways (Future Runways 9C-27C and 10R-28L), and to close existing Runways 14L-32R and 14R-32L. When the OMP is complete, O'Hare will have eight runways: six east-west parallel runways and two crosswind runways, as described in Figure 4.

The development of Runway 9C-27C, and specifically Federal Aviation Administration (FAA) land use criteria for the runway protection zone (RPZ) of Future Runway 27C, will affect the continued use of the Parking Lot E ATS station. This is in part driving an expansion of the ATS, as described in the following section.

THE ATS, THE OMP, AND AIRPORT GROWTH & DEVELOPMENT

The expansion of the ATS is necessitated by: a) an increase in ridership on the system through projected growth in passenger volumes at the airport (i.e., the FAA Terminal Area Forecast projects enplanements to increase at ORD by approximately 19% by 2016, and by approximately 70% by 2030); b) the near-term implementation of a Joint Use Rental Car and Public Parking Facility in Parking Lot F; and c) the future use restriction of the Parking Lot E ATS station once Future Runway 9C-27C opens. These last two factors are discussed herein. Figure 5 presents an illustration of the airport’s northeast quadrant, which outlines the areas of these improvements.

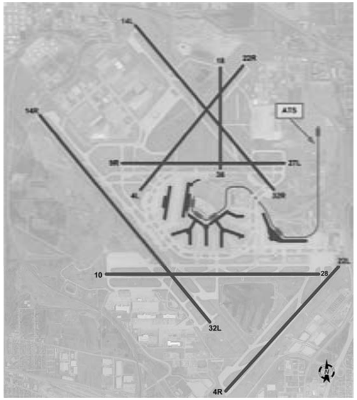

Figure 2: Pre-OMP

ORD Airfield Layout

Courtesy: City of Chicago

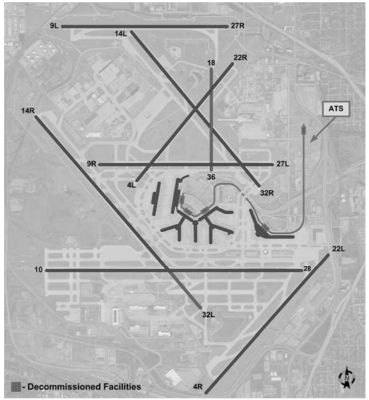

Figure 3: Existing

ORD Airfield Layout

Courtesy: City of Chicago

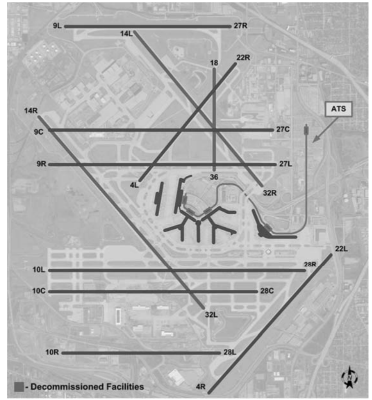

Figure 4: Future Final

ORD Airfield Layout

Courtesy: City of Chicago

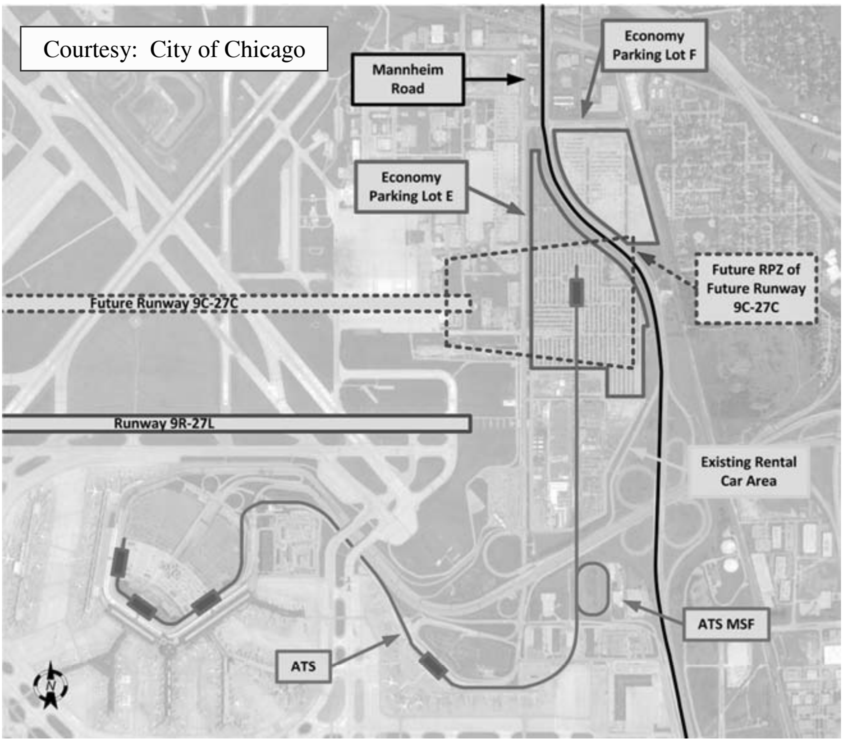

Figure 5: ORD Northeast Quadrant

The future RPZ of Future Runway 9C-27C blankets a portion of Parking Lot E, including the ATS station located there. FAA land use criteria prohibit places of public assembly in the RPZ, which will effectively render the Parking Lot E ATS station and all parking within the RPZ unusable once that runway opens. As a result, replacement economy parking spaces and a new ATS station are required outside of the future RPZ.

Concurrent with the OMP activities described above, the Chicago Department of Aviation has for a number of years explored options for consolidating rental car operations at the airport. The existing on-airport rental car area at O'Hare is located immediately south of Parking Lot E and is comprised of a number of individual secured and mostly surface lots accessible only by each rental car company (or related alliance partner(s)) and its patrons. Each of these segregated lots within the overall rental car area are individually served by branded rental car buses operated by the rental car companies on frequent headways to/from all of the terminals.

The issues discussed above will be resolved through the future implementation of the Joint Use Rental Car and Public Parking Facility (hereafter, the "joint use facility"), currently in preliminary design and scheduled to open by the end of 2016. The joint use facility will be located in Lot F immediately northeast of Parking Lot E and across Mannheim Road. The facility will generally accommodate a new ATS station, dedicated levels for consolidated rental car operations, and dedicated levels for public parking. It will also accommodate a bus shuttle center below the ATS station (relocating all hotel shuttle and regional motorcoach buses from the core area bus shuttle center), the relocated Kiss 'n' Fly area (from Lot E), and the cell phone parking lot. Dedicated walk paths to/from Metra's O'Hare Transfer station will also be provided.

The conceptual plan of the joint use facility and related developments in Parking Lots E and F is provided in Figure 6. A conceptual perspective of the development in Lot F is provided in Figure 7.

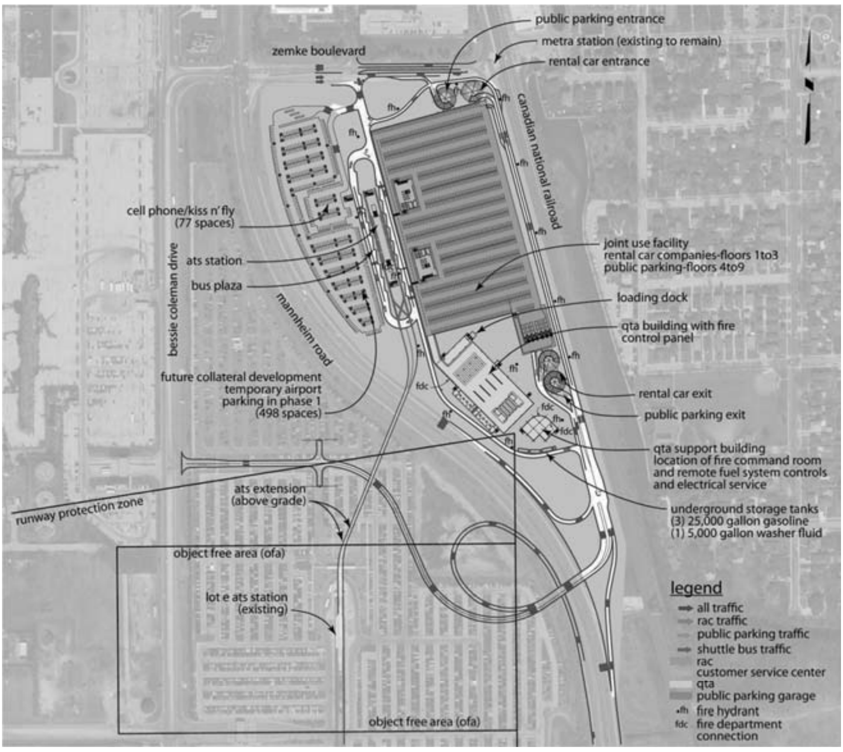

Figure 6: Conceptual Plan of Parking Lots E and F Development

Courtesy: City of Chicago

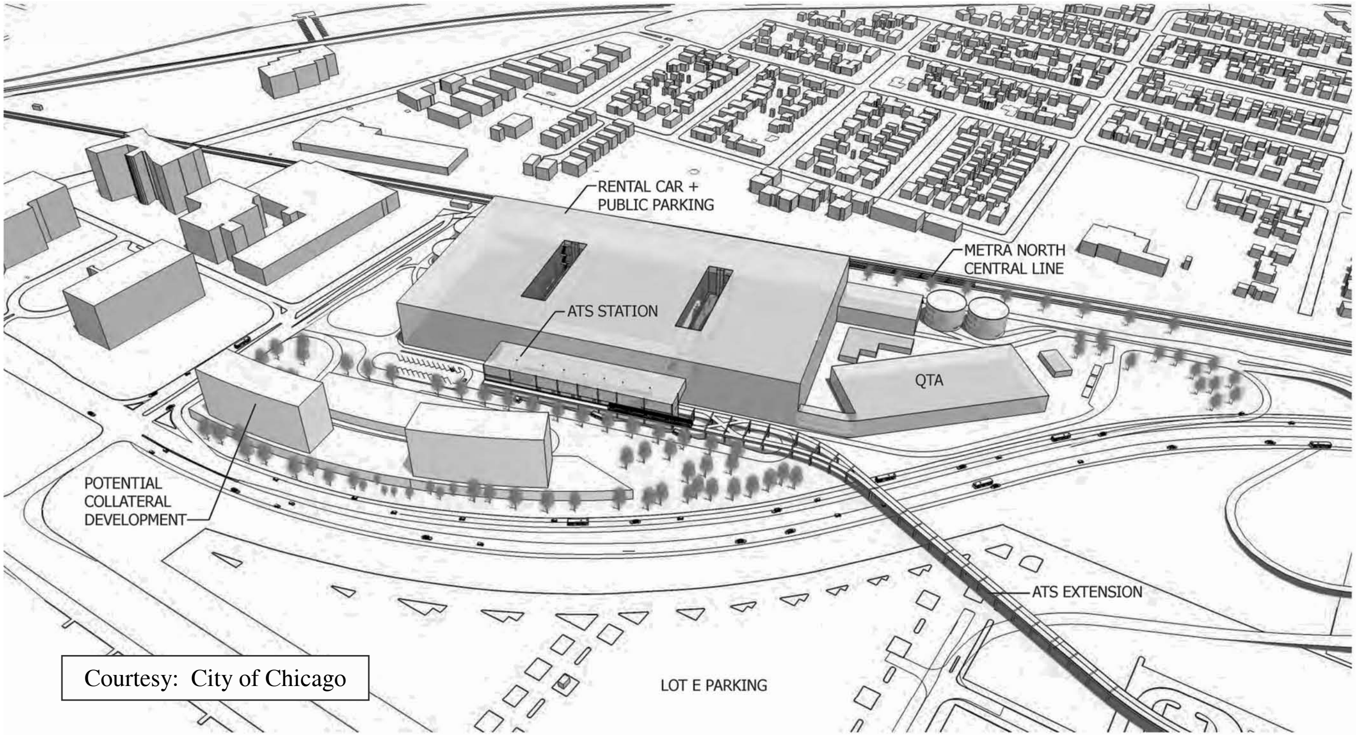

Figure 7: Conceptual Perspective of Lot F Development

THE ATS EXPANSION

The six (6) components of the ATS expansion, described in more detail in the following subsections, generally include:

- The future mainline extension from Lot E to Lot F, including the future Lot F station;
- The future building housing the Lot F facilities power substation (FPSS), uninterruptible power supply (UPS), and automatic train control (ATC) rooms;
- The future Lot E traction power substation (TPSS);
- The future additional and reconfigured guideways, expanded administrative and vehicle maintenance shop facility, additional substation, and wash/de-ice facility at the maintenance and storage facility (MSF); and
- The future expanded, additional, and/or re-configured elements of the Operating System.

Each of the facilities-related components above is being designed in accordance with CDA's Sustainable Airport Manual, v2.1, October 31, 2011, to achieve the highest green airplane rating under the manual as is feasible.

Mainline Alignment Extension and Lot F Station

The alignment extension from Lot E to Lot F will be an approximate 610 meter (2,000 foot) dual-lane guideway configuration throughout the extension length. The alignment will proceed north from the Lot E station, curve northeast while transitioning to a close-spaced guideway configuration, climb to an elevation providing at least 4.60 meters (15 feet) of clearance between the future Mannheim Road infrastructure and the bottom of the ATS structure, then after crossing Mannheim Road, curve to the northwest while the guideways flare to a wide-spaced guideway configuration until the end of the alignment at the north end of the Lot F station. Upon reaching the elevation satisfying the 4.60-meter (15-foot) clearance over the future Mannheim Road infrastructure, the top-of-rail elevation will remain the same from that point north until the end of the line. Two crossovers will be provided just south of the planned Lot F ATS station.

Emergency/maintenance walkways, either one per guideway lane or one shared by both guideway lanes, have been incorporated into the design based on whether the alignment is a wide-space section of guideway or close-spaced section of guideway.

The Lot F station and associated guideway alignment will generally be oriented northwest-southeast and accommodate a center, dual end-loaded platform, as illustrated in Figure 6. The Lot F station platform will be at the third floor elevation of the joint-use facility and allow passenger circulation up to the fourth floor of the facility, or down directly to grade into the bus shuttle center.

The guideway/station configuration and alignment have been designed to allow for future system expansion beyond the Lot F station.

Lot F FPSS, UPS, and ATC Rooms

A FPSS will be required at or near the Lot F station to power the UPS room and guideway heating on the mainline extension. A UPS room will be required at or near the Lot F station to provide power to guideway and station equipment on the mainline extension, including temporary backup power to certain equipment in the event of a loss of power from the local utility provider. An ATC room will be required at or near the Lot F station to house the vital and non-vital ATC, communications, and related system equipment for the guideway and station on the extension.

Due in part to space constraints within the Lot F station, the Lot F FPSS, UPS, and ATC rooms will likely be located in a dedicated building south of the Lot F station.

Lot E TPSS

A TPSS will be added to the system in Lot E to accommodate loads for future train consist sizes and quantities planned for operation once the extension to Lot F begins service. This TPSS will house the electrification equipment that will distribute traction power to power/guidance rails on the mainline extension.

The Lot E TPSS will be located under the existing guideways near the existing Lot E station. The primary reason for locating this TPSS at Lot E is that it is more easily served by the local utility provider than other locations. In addition, there are fewer space constraints in Lot E than in Lot F.

MSF Expansion

The MSF supports the existing 15-vehicle fleet and will need to be expanded to support the future expanded fleet of up to 45 vehicles. Expansion of the MSF east will be required to accommodate all functions and spaces to support the fleet size that will provide the ultimate capacity of the system.

The MSF expansion will include expansion of the vehicle storage area, the vehicle maintenance shop and related shop tracks, connection of the south shop to the south side of the yard loop to accommodate through-shop operations, relocation and expansion of the test track, addition of a combination wash and de-icing facility for trains, and the addition of a dedicated substation for traction power, guideway heating, and wash/de-ice facility equipment at the M&SF. The existing and conceptual expanded MSF sites are provided in Figure 8 and Figure 9.

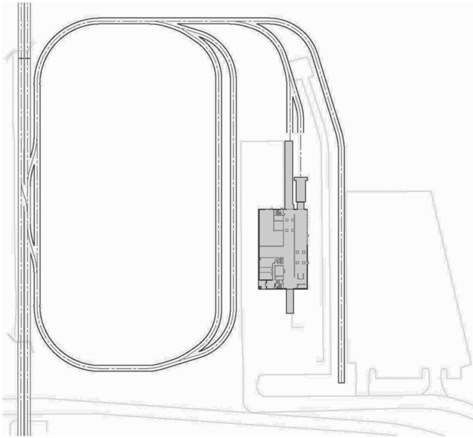

Figure 8: Existing ATS MSF Site

Courtesy: City of Chicago

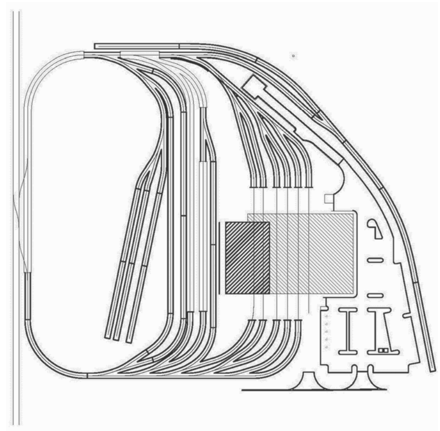

Figure 9: Conceptual Future ATS MSF Site

Courtesy: City of Chicago

Figure 10: ORD ATS

Operating System

The Operating System of the ATS (i.e., the systems elements) includes the vehicles, ATC equipment, power distribution equipment, audio and visual communications equipment, guideway/trackwork equipment, MSF equipment, and station equipment. This equipment will be provided in or on facilities implemented in support of the ATS expansion project.

THE ATS – SUSTAINABLE GROUND TRANSPORTATION AT O'HARE

With the implementation of the expanded ATS to the Lot F Joint Use Rental Car and Public Parking Facility, demand on the system will instantaneously and significantly increase, remain at such elevated levels (as compared to ridership levels thus far), and continue to increase as passenger volumes at the airport grow. This new ATS ridership demand will include all rental car customers, and all shuttle and regional motorcoach bus customers to/from off-airport hotel, parking, and car rental facilities.

The role of the ATS at the airport will thus become even more important, as it will not only require the safe and efficient movement of a greater number of passengers, but will also contribute a greater share of the airport's overall green footprint. This will be achieved by removing all branded rental car buses from the roadways, and removing all off-airport buses from the terminal areas to the joint use facility. The positive environmental impact the ATS has had over the past 19 years at

O'Hare will continue, and have an additive effect once the system is expanded, thereby dramatically increasing the amount of fuel saved, significantly increasing the reductions in emissions, improving the air quality in the core terminal area, and enhancing the lives of our fellow citizens at the airport. The ATS is a testament to sustainable ground transportation at O'Hare, historically and in years ahead.

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Note: A significant majority of the information provided in this paper is sourced from individuals currently and/or previously involved in longstanding work at O'Hare International Airport.

THE SACRAMENTO INTERNATIONAL AIRPORT APM TAKEAWAYS FROM THE EARLY, UNDER BUDGET, BIG BUILD

Jenny Baumgartner, P.E., AICP*, Brad L. Bonn**, and Harley L. Moore***

* Manager of Engineering Projects, Lea+Elliott, Inc.; 101 Montgomery Street, Suite 1750, San Francisco, CA 94104; (415) 908-6450; (415) 908-6451 (fax); jbaumgartner@leaelliott.com
** SDC Manager, Sacramento International Airport Service Delivery Center Operations and Maintenance Systems; 6900 Airport Blvd; Suite 126, Sacramento, CA 95837; (916) 648.8468 x114; (916) 877.3450 (fax); brad.l.bonn@us.transport.bombardier.com
* ** Senior Principal, Lea+Elliott, Inc.; 5200 Blue Lagoon Drive, Suite 250, Miami, FL 33126; (305) 929-8108; (305) 500-9391 (fax); hlmoore@leaelliott.com

ABSTRACT

The Sacramento International Airport (SMF) APM is a dual lane shuttle that connects the new Central Terminal B Landside and Concourse B buildings. Planning started in August 2003; preliminary design of the system and the buildings began in October 2006. The procurement process started in 2008 and resulted in a short list of four firms and technologies. The Sacramento County Airport System (SCAS) and the Sacramento County Board of Supervisors selected the APM contractor, Bombardier, in June 2008 for this design, supply, operate, maintain contract. The terminal and APM were scheduled to open in early 2012 but actually opened in October 2011. Final acceptance was gained in June 2012.

A paper about the planning, design, and procurement process was given at the ASCE APM Conference in 2009 ("The Sacramento International Airport APM" by Baumgartner and Moore). Another paper in this Conference ("Delivering the *INNOVIA* APM to Sacramento International Airport" by Brandon Kameg and Glenn Morgan) provides more information about the project and system. This paper summarizes aspects project implementation and initial operations and maintenance periods focusing on lessons learned in the process of:

1. shortening the schedule by a few months
2. dealing with two airport facility designers, two program management teams, two design-build contractors, airport and county staff, and other stakeholders and participants
3. dealing with a state regulatory agency that had approved only one APM system previously
4. helping an airport owner prepare for the operation and maintenance of a new and must-ride infrastructure element of a terminal building
5. managing the equipment, the human resources and training airport, airline, TSA and concessionaire staff needed for APM operations; including adjustments for actual ridership and timing as opposed to that estimated during the planning process.

SYSTEM DESCRIPTION

The dual lane shuttle APM is approximately 335 m (1100 ft) long, has two opposing lateral curves, and except at the stations is on a 5% grade to accommodate the station elevation difference between the two buildings (see Kameg and Morgan for more information). Figure 1 shows the SMF terminal building layout and the APM that connects the new Central Terminal B Landside and Concourse buildings. The system initially has two *INNOVIA* 100 single-car vehicles operating on the dual lane guideway (see Figure 2). The APM is designed to add one more car on each guideway when ridership warrants. The initial capacity is 2760 passengers per direction per hour (pphpd). With the expansion to four vehicles, capacity will double. Station design (length and space for platform doors), automatic train control (BOMBARDIER CITYFLO 650), power distribution, maintenance facility, and all other aspects were designed for this transition. The system operates as a dual lane shuttle during peak periods, a single lane shuttle during off-peak periods, and a single lane on-call shuttle at night. Maintenance on one vehicle and one guideway is done during the off-peak and night periods. The maintenance and control facility (MCF) is under the concourse station. The power substation is in the landside building. Deprived of the redundant primary power source, the system will run on a slightly degraded mode powered by a bank of generators that serves the terminal complex.

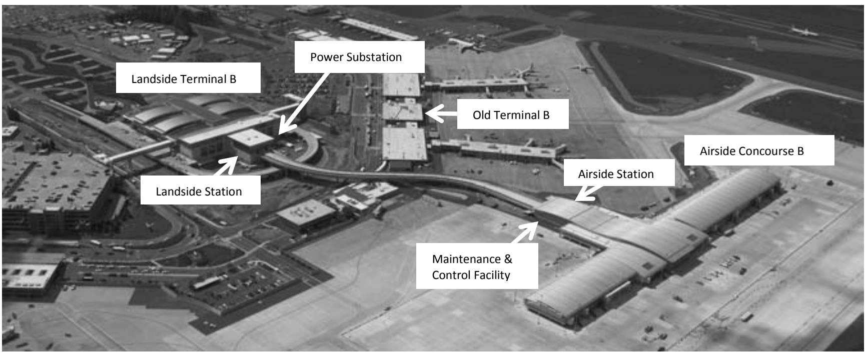

Photo courtesy of SCAS

Figure 1. Terminal B and APM Configuration

Photo courtesy of H. Moore

Figure 2. Bombardier *INNOVIA* 100 Vehicles on the Guideway

The project was undertaken for SCAS by a large project team. For design there was a lead architect for overall design and focus on the landside terminal. The associate architecture firm focused on the airside concourse. Detailed design and construction was managed by a primary design-build contractor for each of the two buildings, with the Concourse contractor also having responsibility for the APM guideway. Senior level project management subcontracted the day to day construction oversight management. Lea+Elliott was the APM consultant for SCAS and worked closely with Bombardier through the detailed design, manufacturing, construction, installation, and testing and commissioning periods.

LESSONS LEARNED

Ridership. SMF's largest carrier, Southwest Airlines, initially rejected the idea of moving from Terminal A to the new Terminal B, but changed course during. Some of the old Terminal B airlines moved to the new Terminal B; United/Continental moved to Terminal A. This mid-stream change introduced a significant increase over the initially planned ridership and peaking characteristics for the APM. As a result, capacity concerns with the single car consists are being realized years before originally expected potentially bringing earlier consideration of adding the other two cars than planned.

- Lesson. Planned conditions will change; design the APM with flexibility for expansion.

Contract. The Bombardier bid price was very close to the budget developed in the planning effort. The Bombardier contract included an option for SCAS to purchase the additional two cars at various stages of the design-supply contract and thereafter. The cost depended on the time the option was taken with the lowest cost being early in the design period and increasing as the project progressed. Although the cost at the initial decision point was quite reasonable, SCAS had to consider much more than just the APM. The APM contract came relatively early as it had been identified as a long lead time element by the program team. SCAS thus decided not to use any of its project contingency for the additional two cars; rather to reserve it for potentially greater subsequent needs on the program. Future purchase of the two additional vehicles, when they clearly will be needed, will cost at least 25% more than if purchased initially and will cause some operational disruption for installation and testing.

- Lesson. Structure the APM budgeting process to include expected options so that they can be exercised without using project contingency, or if they are in the contingency budget, identify them specifically.

When to Select the APM Contractor and Technology. This is a key question on all APM projects where the facility design and construction is done by organizations other than the APM contractor. Designing the APM facilities to the specific technology requirements would save duplication of effort and design and even some construction costs, as well as minimizing facility and system contract change orders. Typically the earlier the better, if the schedule gap between the contractor's selection and the start of manufacturing and installation is minimized or otherwise dealt with contractually. There is, however, usually a significant gap between facility design and when the APM contractor is given access to the APM facilities. Bombardier came on board relatively early in the design-build process, but considerable generic facility design had been done by the architects so that the design-build contractors could develop reasonable prices. Several considerations drove the process that SCAS used to implement the program. The first was the timing of the completion of the environmental review reports. This drove the need to start construction in a fast-tracked method to minimize program costs. SCAS's contractor procurement process required 30% design documents to be prepared and then used by the proposing design-build contractors to prepare their guaranteed maximum price.

Once the design-build contractors had been selected and mobilized, Bombardier and Lea+Elliott worked with the two architects, the two design-build contractors, and the program manager to affect the necessary APM technology-specific facility design changes. Due to the relatively advanced state of the generic designs, some necessary and many desirable changes either could not be made or took a considerable effort (including many coordination meetings) given the number of organizations in the process.

- Lesson. If the airport operator has the ability to select the APM supplier and technology early in the facilities design process, it allows incorporating the APM infrastructure, structural, and system designs into the design-build contractor's estimate and schedule, saving considerable time, effort, and cost. Develop the APM contract with multiple notices to proceed, with the earlier ones being related to the facility and system design, then plan for the gap with a delayed second notice to proceed with actual implementation.

Design Period – System Design Documentation. Considerable system design documentation is required by contract so that the owner and its representatives understand what is being provided and can do due diligence in the design reviews. It has been Lea+Elliott's experience that each APM contractor recycles many such documents from previous projects, particularly when the systems and subsystems are similar. There is much to be said for not reinventing the document, particularly if it has been found to be acceptable on a previous project. Not all documents provided by

Bombardier on this project made a complete translation from previous projects. Not just the name of the project not being changed, but often important (and sometimes detailed) design and operational and maintenance aspects. This caused such documents to be rejected, extra costs to revise and re-review the documents and concerns on the part of the owner.

- Lesson. All documentation requires a thorough internal review by the contractor to ensure that they are tailored to the specific project. It is also incumbent on the owner and its representative to do a thorough review to ensure that the design discussed in the document is appropriate for the project.

Design Period – FDCH. Lea+Elliott developed a Facilities Design Criteria Handbook (FDCH) to guide the architects with the APM facility design. Although this document covered many facility requirements, it was generic for both self-propelled and cable-propelled APMs so did not include Bombardier-specific requirements. Nor did it include many design details. More of an issue, it was often not clear that the architects and design-build contractors had adequately reviewed and used it, as many important aspects were not incorporated into their designs. When brought to their attention in design reviews, and unfortunately sometimes in construction inspections, they insisted on seeing the specific requirement in the FDCH or a code. Such specific details were not always in the FDCH, nor in local building codes (typically used by the designers but with no APM requirements) or APM/transit codes and standards (e.g., NFPA 130 and ASCE APM Standards). Arguing "good practice" or "used on many other APM projects" were often not sufficiently convincing to affect a design or construction, change.

- Lesson. The FDCH is important. It should be as complete as possible and updated as needed. It should be distributed to all designers and then discussed with them. It is not sufficient only to distribute it; discussions will ensure that they are aware of it and that any questions can be answered. All levels of initial design should be checked carefully against it and good practice by the APM consultant and architects to minimize problems and conflicts later in the design process.

Design Period – CMID. An early Bombardier deliverable was a Construction Management Interface Document (CMID). This document in effect takes the FDCH and makes it specific to the contractor's APM technology requirements as well as adds information about construction and system-facility interfaces. With so many parties involved in the design and construction, the criticality of a thorough, detailed CMID was magnified exponentially. Like the FDCH, it was not always used or accepted by the architects and building design-build contractors.

- Lesson. The APM contractor must keep this key document up to date and ensure that all requirements are understood. Timely, coordinated revision releases are imperative, as is a commitment from all parties to consider and address each requirement.

Design Period – Detailed Coordination. Design, construction, and two-way inspection coordination is always, and on this project especially, crucial, particularly with respect to the APM guideway and stations. In several cases, project design issues highlighted the need for consideration beyond the minimum requirements imposed in local building codes as well as standards such as NFPA130 and ASCE-21. Critical needs, such as access from the platforms into a misaligned train, are not necessarily called for in any of these codes and standards. Despite attempts by all at risk management relative to critical interfaces, there were hurdles ranging from the highly critical guideway rebar placement and retention during dowelling for running surface rebar connections and concrete pours, to the seemingly mundane selection of a means to secure hinged station panels behind which the APM station door operators and station communication devices are housed.

- Lesson. Extensive and coordinated shop drawing reviews and very frequent face to face communications among all relevant staff from all participants, although potentially costly and time consuming, is essential and can save costs, avoid delays and wasted efforts, and reduce problems in the long run.

Design Period – Participants. During the planning and initial design period (before the APM contractor was selected) meetings to discuss design requirements usually included the architects, owner project staff, and the APM consultant. During the detailed design period after APM and design-build contractor selection the many meetings included the architects, design-build contractors, project/construction managers, the APM contractor, and the owner's representative. Other owner staff who ultimately would be responsible to oversee system operations and maintenance and deal with higher level airport operational issues were rarely in those meetings. Such staff usually learned about the system details in the periodic Safety and Security Committee meetings. Only then were concerns raised related to overarching airport operations and the APM. By then changes to the APM and its facilities were difficult, if not precluded.

- Lesson. It is important to include those who will ultimately assume responsibility for operation and maintenance of all support facilities and functions within the airport-APM environment throughout the project so that all airport functions are considered in the design and operation of the APM. If the staff have not been exposed to APM operations, the airport operator should send the responsible staff to other airports with APMs to enhance their education.

Manufacturing. Once the APM system design was accepted by the owner and released for manufacturing, the contractor is either left almost alone with no factory inspections or has to work with frequent or constant owner representative monitoring. For the SMF project there were relatively few plant inspections until the factory acceptance testing. SCAS senior staff did make one trip to the factory and not only saw and understood the manufacturing process, but were able to discuss the project directly and in detail with the APM contractor senior staff. Both were enlightening and reassuring to the owner. Lea+Elliott's experience on some other projects is that such visits and reassurance are not always the case.

- Lesson. It is important for owner staff to visit the manufacturing facilities at least once during the manufacturing process. Such personnel typically are not technical, but such a visit will greatly assist both the owner and the contractor in understanding each other and the system being manufactured and installed. It is also good practice for the owner staff to visit the main factories of the short-listed potential suppliers to assist with contractor understanding and selection; this was done by SCAS for most factories as well as at least one operating APM of each.

Construction and Installation – Reporting and Staffing. Appropriate contractor staffing is critical in the construction and installation phase. Certainly technical management and oversight of construction and installation activities are readily recognized as necessary. What often seems overlooked is the need for skilled administrative support of record keeping and tracking. Local and state authorities and large project and construction management teams have seemingly endless requirements (many a surprise after the work starts) on projects such as this. Expecting too much from too few contractor staff can prove costly to all parties. For the SCAS project having two program management teams and two design-build contractors exacerbated this challenge.

- Lesson. Clear and complete reporting and project organization information should be included in the APM contract. This allows the APM contractor to plan and budget for appropriate local and home office staffing, timely reporting, and relatively smooth information and document flow.

Construction and Installation – Changes. Late design changes always impact the construction and installation schedule as well as create change order issues. With most completion milestones being constrained by fixed testing and commissioning milestones, late starts and/or delays due to late delivery of and APM contractor access to facilities, are crippling. Challenges encountered with the running surface construction and its interference with adjoining deck steel was a prime example of such a situation. The construction/installation schedule delays were further exacerbated on this project due to the Owner's decision to compress the overall schedule and moving service opening date up several months from the originally scheduled completion. Only with a concerted, cooperative effort, was the compressed installation and testing schedule met. Fortunately SCAS had the ability to approve change orders expeditiously which contributed to the whole project to be completed ahead of schedule.

- Lesson. Such squeezing of the APM contractor's installation, testing and commissioning activities occurs on every project and is a seemingly intractable problem. Planning for it is important, but often inadequate. The earlier such delays are identified the better the APM contractor can deal with them. Being prepared to submit change orders to increase local efforts (including subcontractors and adding a shift) is prudent, but requires skillful negotiations with the owner and others. A better solution is a reasonable overall schedule and a process to ensure the building contractors meet their schedule requirements.

Testing and Commissioning. A successful testing and commissioning program requires solid and comprehensive planning coupled with well-managed execution. All parties: the test team, observers, and approvers, must work together to a detailed program and clear procedures. Practical cooperation, rather than combative opposition, proved invaluable to providing a high quality system delivered in a manner to exceed expectations and meet the inevitable schedule compression. Sound record management of the test program is paramount. Timely submittals and approvals, consistently supported by productive discussion, are the cornerstones of gaining necessary approvals to proceed through each milestone. Careful pre-testing is also needed. Seemingly minor product modifications to subsystems or equipment that worked elsewhere before but needed "slight" changes might not work well in the new project context. Often the record test should be preceded by a less formal test so that all goes well and re-testing (with cost and schedule issues) is not required.

- Lesson. A thorough test program, with complete procedures, is required and all involved must be a part of its review and acceptance. Still, perturbations will happen and must be planned for.

Regulatory Approval. The California Public Utilities Commission (CPUC) is the Authority Having Jurisdiction (AHJ) over all fixed guideway transit systems in California. The SMF APM was only the second rubber-tired APM introduced in the state. The first was at the San Francisco International Airport (SFO). The SFO APM project began without any state required CPUC oversight; its transit responsibility was expanded to include APMs during the SFO APM testing and commissioning phase. The SMF APM project, consequently, was the first to have had CPUC involvement from the outset, and was partly a learning process for all involved. Consistent two-way communication and education were keys to the successful Application to Operate process with the CPUC. As all parties integral to operating and maintaining the APM were wading into relatively unchartered waters, maintaining open lines of communication proved to be priceless. Once again establishing partnership relations among all key parties, SCAS along with its APM consultant Lea+Elliott, Bombardier, and the CPUC, worked well for the successful completion of the CPUC safety certification process. Adherence to the CPUC prescriptive formatting requirements was simplified by CPUC staff sharing sample plans from previous steel wheel-rail transit projects. Face to face meetings, including frequent SSC meetings to which the CPUC representatives were invited, enhanced the cooperative spirit, particularly among the CPUC, SCAS, and Bombardier staff who will work together during the operating and maintenance period on annual and triennial safety reviews.

- Lesson. Following precisely the AHJ's process and working closely with AHJ representatives is key to obtaining operating approval in a timely manner. Particularly if the technology is new to the AHJ (and the owner), a cooperative and mutually educational effort pays dividends.

Owner Education. Although many large airports have APMs, this was a first for SCAS, whose staff had heretofore dealt with the typical airport operational and facility issues. The new Terminal B was a huge, multi-faceted project for airport staff and the APM was often not on their radar. Until the SSC meetings, many of the staff who were assigned responsibility for APM oversight during operations and maintenance left SCAS during construction so had to be replaced, did not known they would have that responsibility until relatively late in the program, or were too busy with running the airport or coping with other aspects of the project so did not know enough about the APM to knowledgeably undertake their new responsibilities. Further, the APM did not necessarily fit neatly into the existing airport organization.

- Lesson. It is important to educate the owner not only to the design and construction of the APM but also to the O&M requirements so that any necessary organizational changes can be made and the appropriate staff can be assigned specific responsibilities early in the process so that they can learn about the system, have input to its design and operations, and coordinate with the APM contractor throughout the project.

News Travels. Relatively early in the APM operations there was an unexpected APM shut-down for several hours. Local and Pittsburgh Bombardier staff worked hard to re-start the system which happened within a few hours, but not after airport delays and negative press articles. They and the airport staff learned difficult lessons and ultimately made some system and failure management procedural changes. That was the good news: both are better prepared for such occasional problems. But there is bad news, too. For months thereafter other airport owners asked about the problem as though it had just happened and wondered about the Bombardier product. Damage control in terms of specific problem and recovery information cannot cover everyone. There have been similar examples from other airport APMs and other APM contractors.

- Lesson. Good news (early, successful opening, on budget) might or might not get broad coverage, but bad news spreads fast and persists, particularly among airport owners. Thorough contingency and failure management planning is needed and related failure response drills should be practiced during the operational readiness period.

Teamwork Brings Success. SCAS created a large, but well coordinated team to deliver the project on budget and early. All involved with the APM worked hard and generally cooperatively within that team. Many designer and construction staff were unfamiliar with APMs and their normal practices sometimes were at odds with what was needed for the APM. The efforts of this team led to the APM opening early with the rest of the program and continued successful operation.

- Lesson. Everyone wins – or loses – together. A cooperative and communicative team effort is needed (notwithstanding that there will be bumps along the guideway) with all members working as partners but with each remembering and carrying out its roles and responsibilities.

CONCLUSIONS

While many of these lessons learned on the SMF APM project will be familiar to those in the airport APM industry, more airports are including APMs in their designs. This paper used the SMF APM project, which went quite well but still had issues, as an example to remind the "old APM hands" of such issues and their potential solutions and to educate airport owners, designers, contractors, and others to make their APM-related projects run more smoothly, whether they have considerable or no prior APM experience.

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Delivering an APM to the Sacramento County International Airport

Brandon Kameg[1] and Glenn Morgan, P.E.[2]

[1]Bombardier Transportation, Systems Division, Director Operations, Americas, 1501 Lebanon Church Road, Pittsburgh, PA 15236-1491 USA; Phone: (412) 650-6424; email: Brandon.kameg@us.transport.bombardier.com

[2]Bombardier Transportation, Systems Division, Project Director, 1501 Lebanon Church Road, Pittsburgh, PA 15236-1491 USA; Phone: (412) 655-5244; email: Glenn.morgan@us.transport.bombardier.com

Abstract

Sacramento County International Airport (SMF) is commonly referred to as the "Gateway to Northern California" with its close proximity to Lake Tahoe and Napa Valley. It is used by many major airlines to service U.S. cities and international destinations.

SMF has seen growth on average at times of 4% a year and has recently undergone the largest capital improvement project in the County's history known as the "Big Build". To support this growth, new terminal and airside concourse have been built, along with a connecting and elevated APM shuttle service.

To support the $1.04 billion SMF "Big Build" modernization program, Bombardier designed and supplied the driverless *INNOVIA* APM system as the vital dual lane link between the new concourses. The APM scope of supply includes vehicles, *BOMBARDIER CITYFLO* 650 automatic train control, power distribution, communications and station platform doors, as well as an extended O&M operation.

The new state-of-the-art airport expansion opened for passenger service the morning of October 6th, 2011. The project came in significantly ahead of schedule as well as under budget. It was a true team effort in conjunction with all of the various partners, as well as the other players associated with the works. It can be considered a model for similar projects of its kind in the current industry environment.

Introduction

In 2007, the Sacramento County Board of Supervisors gave the green light to implement its plan to modernize and expand Sacramento International Airport, building a domestic gateway serving Northern California and other major cities across the Unites States and the world. The plan called for a landside terminal, airside concourse, Automated People Mover (APM) system (connecting landside terminal with airside concourse), and parking garage.

The elements of the expansion allowed the airport to increase passenger capacity and better serve the region. In 2011, over 9 million passengers traveled through the Sacramento International Airport.

Selected as the preferred supplier of the APM System in June 2008, Bombardier designed and delivered the *INNOVIA* APM system, the vital link between two award-winning structures, the terminal building and concourse. Figure 1, Figure 2, and Figure 3 show the new terminal, APM guideway and airside concourse.

Figure 1: New Terminal – Sacramento County Airport Systetm (SCAS)

Figure 2: APM Guideway – The Vital Link - Bombardier

Figure 3: Airside Concourse - SCAS

Project Overview

The driverless system includes two *INNOVIA* APM 100 vehicles, Bombardier *CITYFLO* 650 automatic train control, power distribution system (600 Vac), communications equipment and station doors, as well as Operations and Maintenance (O&M) services for five years.

The 335 meters (1,100 feet) long elevated dual lane system operates at a maximum speed of 35 kph (22 mph) on a 5% grade and with the capability of moving 2,760 pphpd. The system was designed and safeguarded to add additional capacity when ridership increases by adding one car to each guideway. Figure 4 and Figure 5 show various system elements, such as platform screen doors and the airside station.

Figure 4: Central Control Operations (left) and Platform Screen Doors (right) - Bombardier

Figure 5: Airside Station (left) and Dual Lane Elevated Guideway (right) – Bombardier

Design

Bombardier's design kicked off at Notice to Proceed (NTP) in Pittsburgh with a strong emphasis on fixed facilities interfaces, specifically relating to configuration of the on-line maintenance facility, guideway running surface, and station platforms. The strong emphasis was a result of dealing with multiple airport designers, two program management teams, two design-build contractors, airport and county staff, and other stakeholders and participants.

Bombardier presented the preliminary system design in December 2008 and the final design in July 2009.

Build

Bombardier's APM Center of Competence, located in Pittsburgh, PA (USA), centralizes over 40 years of APM experience in a single location. As a Center of Competence, the Pittsburgh site brings together propulsion, controls, and vehicle engineering, operations and maintenance, and manufacturing expertise that allows us to deliver industry-leading systems integration worldwide.

Figure 6 provides an aerial view of our LCS facility, located at 1501 Lebanon Church Road, Pittsburgh, PA 15236. This facility has three car test tracks, where the Bombardier *INNOVIA* APM car platforms undergo dynamic testing. Two preparation and shipping buildings are located at the end of the car test tracks where the cars are prepared for shipment and loaded onto trucks for delivery to the site.

Figure 6: Aerial View of Bombardier Pittsburgh Facility - Bombardier

Sacramento Wayside Build

The Sacramento Wayside equipment was assembled in Pittsburgh in April 2010 and factory acceptance testing was completed in September 2010. Factory acceptance testing in Pittsburgh (see Figure 7) allows the engineers to simulate the actual site conditions/constraints and to debug any issues prior to arrival on-site.

Figure 7: Wayside Cabinets in Factory Acceptance Test - Bombardier

Vehicle Build

The Sacramento vehicles were assembled in Pittsburgh in the first quarter of 2011, three months ahead of schedule. The vehicles were assembled in five workstations utilizing Bombardier Operations System (BOS) lean manufacturing approach.

BOS provides all Bombardier manufacturing sites with a common operations system, bringing different tools and past initiatives under one umbrella. BOS is based on five principles that guide the way to work at Bombardier Transportation:

- Built-In Quality
- Short Lead Times
- People Involvement
- Standardization
- Continuous Improvement

Table 1 describes the vehicle top assembly process by manufacturing station in further detail.

Table 1: *INNOVIA* 100 Top Assembly – Bombardier photos

Station	Description	
Station 1	• Door System Installation • Interior Wiring and Equipment Installation • Undercar Wiring and Equipment Installation	
Station 2	• Hi-Pot Test • DITMCO Test (Point to Point Electrical Test) • Installation of ATC Equipment not installed for Hi-Pot	
Station 3	• Static tests	

Station	Description	
Station 4	• Dynamic Testing on Test Track	
Station 5	• Prep and Ship o Interior Signs and Decals o Cleaning of Car o Packaging of Shippable Items to Site o Final Quality Inspection	 

Prior to lifting the vehicles onto the guideway for testing and commissioning, the vehicles were shipped to the airport, where they were wrapped per the Owner's design and color scheme (see Figure 8). This was a combined effort between the Airport, the Design team and Bombardier.

Figure 8: Vehicle Wrap at SCAS - Bombardier

Testing & Commissioning

The *INNOVIA* 100 vehicles were lifted onto the guideway in California on March 17, 2011 (see Figure 9). Testing and Commissioning (T&C) then progressed on-site and in collaboration with the California Public Utilities Commission (CPUC) leading to the successful completion of the System Demonstration on August 24^{th}. The 30-day demonstration was completed in the minimum time frame possible, achieving 99.39% time availability compared to the required level of 98.5%. All of the above contributed to the early airport opening of October 6, 2012.

Figure 9: March 17, 2011 – Vehicle being lifted onto the Guideway - Bombardier

Challenges

Implementing APM systems has a number of challenges. The Sacramento APM has been a collaborative effort in association with a number of major suppliers in a true team effort to meet the "challenge".

- Clear requirements
- Empowerment to deliver
- Openness/communications
- One team supported via a formal partnering approach
- Trust and Open approach to problems
- Solutions/quick responses
- Best team/people for the roles

Figure 10 illustrates the running beam and guidebeam installations, which presented a number of interface challenges. These interface challenges included incorrectly installed running surface stirrups, drilling into substructure reinforcement, and misaligned guidebeam support anchor bolts. In each instance, the design team, contractors, project management, and Bombardier worked together to implement a cost effective solution.

Figure 10: Running Beam and Guidebeam Installations – Bombardier

Conclusions

Five years after the Board of Supervisors issued the green light to proceed with the “Big Build" modernization program (see Figure 11 and Figure 12), the new terminal and airside concourse opened for business ahead of schedule and under budget. In October 2011, the County Airport System celebrated the opening of the new Terminal B with a series of special events, beginning with the Experience B party on October 1, 2011, where more than 1,400 friends of the airport attended. Following this, the Airport hosted a full-day free preview for 4,500 more visitors on October 2, 2011. The first flight departed in the early morning hours of October 6, 2011.

Championed by SCAS, the overall program required close communication and collaboration, to which Bombardier was proud to be part of in conjunction with all of the partners and stakeholders**.**

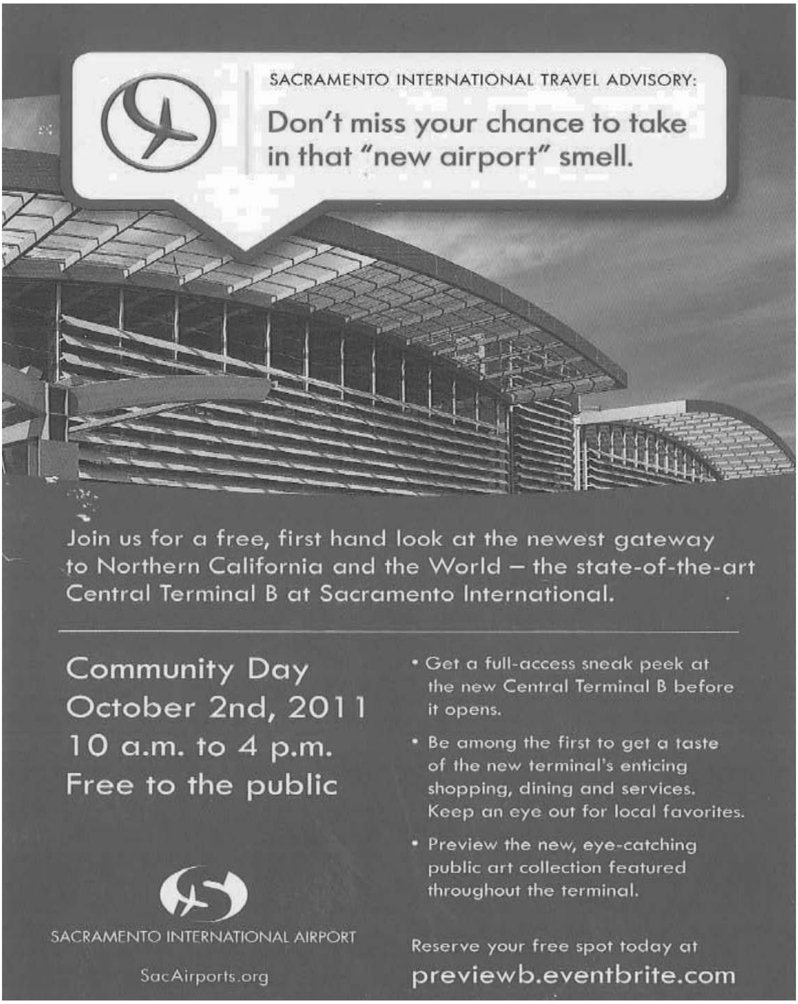

Figure 11: Sacramento International Airport Community Day Flyer - SCAS

Figure 12: Aerial View of the Airport - SCAS

Seattle Tacoma International Airport STS: APM and Airport Growing Together

David D. Tomber[1], FAIA, $AAAE_{CM}$ and Sebastian Gladney[2], P.E.

[1] Manager, Aviation Planning, Port of Seattle, 17801 Pacific Highway South, Main Terminal, Rm. A6012, Seattle, WA 98158; PH (206) 787-4368; FAX (206) 431-4496; email: tomber.d@portseattle.org

[2] Manager of Engineering Projects, Lea+Elliott, Inc., 101 Montgomery Street, Suite 1750, San Francisco, CA 94104; PH (415) 692-5920; FAX: (415) 908-6451; email: gladney@leaelliott.com

ABSTRACT

The Satellite Transit System (STS) has been an integral part of Seattle-Tacoma International Airport for almost 40 years. As the primary means of intra-airport passenger movement, including the only passenger access to the North and South Satellite concourses, the service it provides is key to the airport's past, present and future. This service has and must continue to evolve along with the airport; as the needs of the airport, airlines and passengers grow and change over time, so must the STS and its capabilities and amenities. As the Port of Seattle begins work on STS upgrades related to a new landside FIS facility and future expansion of concourses, current technology offers a range of potential advantages. This paper examines key points in the system's history, along with challenges and opportunities for its and the airport's future. Key planning areas include the location of a new landside FIS facility and how it impacts the South Loop, future expansion of concourses with the need for an APM connection, Alaska's upcoming consolidation at the North Satellite and its future expansion, connecting passengers, and the anticipated need for a landside CONRAC connection.

Introduction

As the Port of Seattle is in the early stages of a number of redevelopment and planning efforts at Seattle-Tacoma International Airport, the APM system must evolve with the Airport to continue its high level of passenger service. This paper examines the history of the Satellite Transit System (STS) and how it has grown with the airport over the last forty years, as well as introducing potential Airport and APM expansion and upgrade scenarios, each providing different challenges and opportunities for the STS.

System Overview and History

General Overview

The Seattle-Tacoma International Airport Satellite Transit System (STS) consists of automated people mover (APM) vehicles operating on three routes, as seen in Figure 2-1. The North Loop connects Concourse C, D and the North Satellite Concourse, and the South Loop connects Concourses A, C and the South Satellite Concourse. Each loop is served by two three-car trains and has a maximum capacity of approximately 4,000 passengers per hour per direction (pphpd). Both loops currently operate at headways of approximately 130 seconds. The North and South loops are the only passenger connection to their respective satellites, making this a must-ride system.

The third route is a single lane shuttle, with one car operating between Concourses A and D and connecting the two loop routes. This route has a headway of approximately 140 seconds and is capable of serving up to about 1,200 passengers per hour per direction.

All three routes are underground and within the secure area of the airport. International arrivals all occur at the South Satellite station and passengers pass through immigration and customs before boarding the train system. As arriving international passengers have not passed through TSA security, separation between groups of passengers must be maintained on this system.

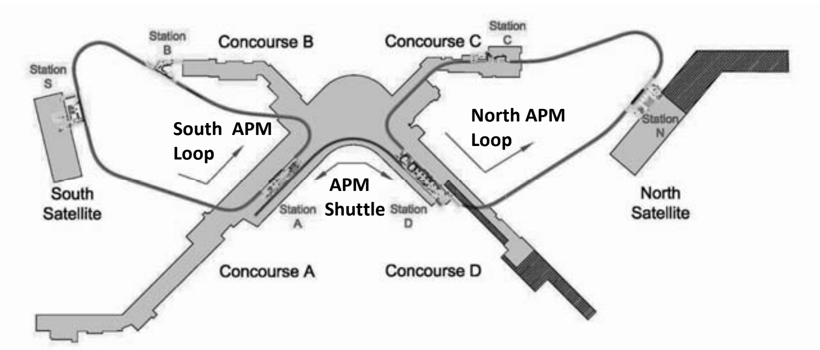

Figure 2-1: Existing Airport and STS Layout (blue) and areas of potential expansion (hatched)

Initial construction
The STS began passenger service in 1972, making it one of the oldest airport people mover systems in the United States. The fleet initially consisted of nine Westinghouse vehicles with three more added in the mid 1970s.

Replacement/Refurbishment 1999-2004
As the system approached thirty years of operation, it became clear that a major refurbishment effort was required. Due to obsolescence of 1970s era electronics and mechanical components, acquisition of replacement components was becoming prohibitively difficult.

The initial fleet was replaced by twenty-one new Adtranz/Bombardier CX-100 vehicles, modified to fit the existing tunnels, as seen in Figure 2-2. The bulk of the operating system was replaced over this five year period; the duration was partially dictated by the need to maintain system operation throughout the work to serve the North and South Satellite Concourses. Operation of the new vehicles began on the North Loop in May 2003.

Figure 2-2: Installation of New Adtranz/Bombardier CX-100 Vehicles (photo courtesy of the Port of Seattle)

In addition to vehicle replacement, a number of other major systems were upgraded or replaced, including:

- The ATC system was upgraded to a CBTC system, Bombardier's CityFlo 650
- 600V power distribution and uninterruptible power supply equipment were replaced
- Central Control workstations were replaced
- Station platform doors were replaced, including realignment for the new door locations on the replacement vehicles
- Station dynamic signage was replaced
- Wires/cables were replaced throughout the system

Upcoming Upgrades at SEA

Sea-Tac Airport Development Program

The Port of Seattle is undertaking a long-term development program that will expand capacity of the airport from 33 to 60 MAP (million annual passengers), as seen in Figure 3-1.

Major elements of the development program include:

- New landside FIS (Federal Inspection Services) Terminal, located in the expanded Concourse A
- Expansion of North and South Satellites
- Expansion of Concourses A and D
- New Airport Hotel
- Regional Light Rail Extension, as seen in Figure 3-2
- Landside APM Connection to the CONRAC

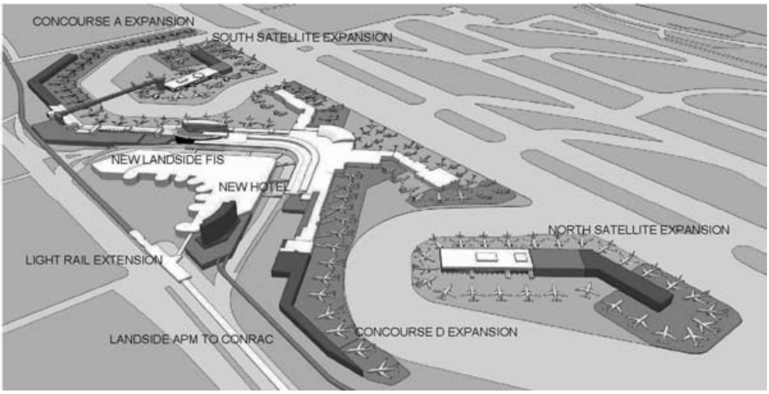

Figure 3-1: Airport Development Program


Figure 3-2: Sound Transit Light Rail Airport Station and Extension (photo courtesy of the Port of Seattle)

From a strictly APM point of view, there are two different systems, as seen in Figure 3-8. One system is the existing secure airside APM, which will need to be modified and extended to accommodate terminal concourse extensions and meet a minimum connect time standard of 70 minutes between gates. The other system is a new non-secure landside APM system connecting the main terminal to the remote consolidated rental car facility. Currently, passengers connect between the main terminal and CONRAC via a bus system.

The North Satellite currently serves 12 contact gates; the addition of three new ones represents a 25% increase in the satellite's capacity to serve aircraft. While the correlation between aircraft and passengers is not 1:1 due to variation in schedules, aircraft capacity, passenger demand, and other factors, it is likely that the North Loop of the STS system will require capacity for a similar increase in ridership. Currently, Alaska Airlines operations are spread between the North Satellite and Concourse C and D, and the North Satellite is shared with other airlines, primarily United.

The upgrades to the STS stations include electrical and mechanical systems in the NSAT and general renovation (lighting, interior finishes, wayfinding and related items) and upgrades to the communication system at all three stations. While the detailed definition of communication systems upgrades is not yet completed, it is anticipated to include, as a minimum, improved passenger signage in stations and concourse (including dynamic signage indicating expected train arrivals), replacement of existing LED signs, and upgrades to signage in vehicles. The communications upgrades may be extended to the other two lines of the STS system as well.

North Loop Demand Impacts
In late 2011 and early 2012, the Port, URS and Lea+Elliott evaluated potential APM impacts of a number of options for gate realignment and expansion, including the Alaska Airlines North Satellite consolidation and expansion included in this project. Preliminary results indicate that the existing system with two three-car trains can accommodate both present day traffic under the Alaska consolidated gate arrangement and projected traffic in ten years including the additional gates. In each of these scenarios, the peak hour load factor is estimated at 60% or less.

However, in the twenty year projections, the current two three-car trains on the North Loop fail to accommodate the projected ridership demand in some scenarios. The options in which ridership are not met are those including additional expansion of the North Satellite beyond the three gates in the current North STAR program. With additional expansion, Alaska Airlines operations at the North Satellite may increase ridership demand beyond the current capabilities of the North Loop.

APM options
This program presents a number of potential APM options for consideration. In the short term, a range of communication system improvements will be assessed for inclusion in the upgrade plans. As AAG and the Port are interested in exploring innovative ways to rethink traditional concourse layouts, the range of communication upgrades to be considered should reflect the same level of creativity. Some options will require interface with the proprietary ATC system. While the current schedule is preliminary, it is current anticipated that bids for this communications work may be solicited in 2013.

While the three-gate expansion of the North Satellite in this program is not expected to create North Loop STS capacity challenges, the longer term options for Alaska Airlines consolidation at the North Satellite might. As this program advances and gains definition, further analysis of the APM system and ridership projections may indicate the need for upgrades to the APM system, possibly including:

- An additional station at the North Satellite to serve a possible northern extension of the concourse building, along with hundreds of feet of new tunnel guideway.
- Increases to the peak operating fleet; the current two three-car trains may be replaced by two four-car trains or three three-car trains.

Federal Inspection Station Location and Expansion of Concourses
In the late 2011/early 2012 study referenced above, Lea+Elliott, URS and the Port of Seattle investigated projected APM ridership under a number of future scenarios. Along with the

Alaska Airlines Group consolidation previously discussed, the analyzed options included two other areas of focus: the location of the Federal Inspection Station (FIS) and potential expansion scenarios. This planning-level study estimated impact of these changes on APM demand and provided preliminary analysis of potential modifications to meet this demand.

Currently, the FIS location at SEA is in the South Satellite, where all of the airport's international arrivals occur. As local demand for international service increases, the FIS is approaching the capacity limits of its current location, likely requiring either a significant expansion or relocation to an area with more available space. This study examined the impacts of different airport layout and gating assumptions with projected traffic levels 10 and 20 years in the future.

Demand Impacts and APM Options

Ten Year Demand with FIS at the South Satellite

In this scenario, the South Loop ridership is expected to be slightly over the capacity of the existing two three-car trains, due to the requirement to separate international passengers who have not cleared security from other passengers. Arriving international passengers would clear FIS at the South Satellite, ride to Concourse A in dedicated APM vehicles, then either proceed through TSA security (transferring passengers) or leave the airport (arriving passengers).

In the ten year demand projection, peak hour international arrival traffic at the South Satellite is expected to exceed domestic passenger demand on the South Loop by a small margin. The current two three-car trains would not be able to serve this demand, with a peak load factor of 1.3. An increase in peak operating fleet is likely to be required, using either three three-car trains or two four-car trains. The former option would require significant train control adjustments and the latter station upgrade and renovation.

The expected North Loop demand would remain below current capacity levels.

Ten Year Demand with FIS Relocated to Concourse A

This scenario would relocate the FIS to the southern part of Concourse A and include a significant APM expansion, including roughly 2000 feet of tunnel guideway, a second Concourse A station and an expanded peak operating fleet. All arriving and transferring international passengers at the South Satellite would ride the STS to new station A2, located at the south end of Concourse A as shown in Figure 3-3.

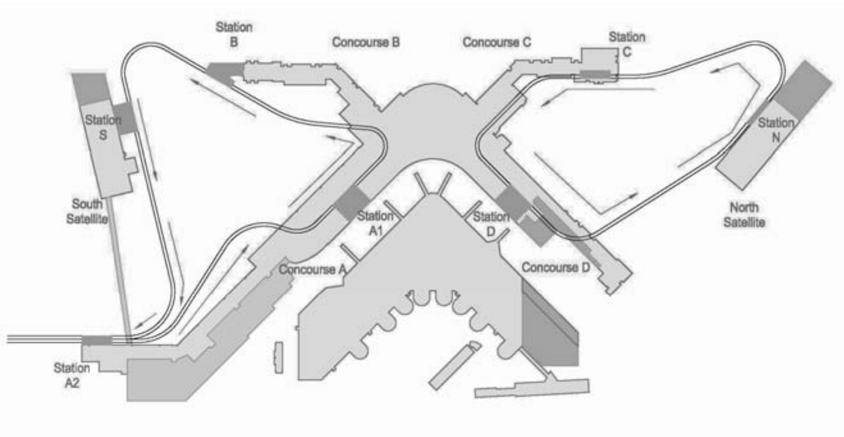

Figure 3-3: Possible North and South Loop Layout for +10 Year Demand

Arriving international passengers would then go through FIS at Concourse A and proceed to ground transportation, while transferring passengers would continue to TSA security before heading to departure gates.

Two four-car trains would be the minimum operating fleet capable of adequately serving the projected load. While the total passenger demand could be met by three three-car trains without lengthen the stations, the required group separation creates problems for this scenario. As the domestic and international passenger groups are almost the same size, each would require approximately 1.5 cars of each three-car train. While this could be accommodated with walls in the middle cars and appropriately located barriers in the station, this would likely represent only a temporary solution, as the 20 year demand is expected to require four car trains in any case.

The expected North Loop demand would remain below current capacity levels.

Twenty Year Demand with FIS at the South Satellite

The twenty year forecast scenarios analyzed include significant expansions of Concourses A, D and the North and South Satellites, as seen in Figure 3-4. This scenario locates FIS in a new southern extension of the South Satellite and adds three stations: one at the South Satellite serving international arrivals and two serving the extended Concourse A. The expanded FIS area would also accommodate TSA security for transferring international passengers, reducing the demand for sterile cars to arriving international passengers only. This scenario shows a significant increase in passenger demand on the South Loop of the STS, with a peak hour demand of nearly 5,000 passengers.

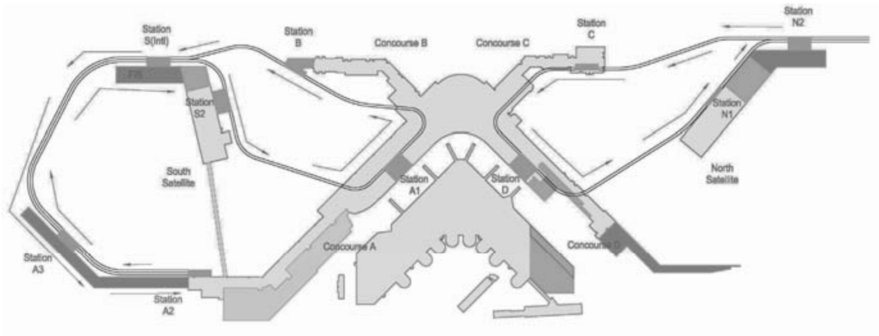

Figure 3-4: Possible North and South Loop Layout for +20 Year Demand

In order to serve the expanded concourses and projected increase in demand, major APM upgrades would be required. Along with the three new stations and thousands of feet of new tunnel guideway, a peak South Loop fleet of approximately twenty trains would be required. This fleet would most likely operate as five four-car trains, necessitating renovation and expansion of the three existing stations.

Two gating alternatives in the North Loop area of the airport were also examined: one in which Alaska Airlines flights were balanced between Concourse D and the North Satellite and one in which they were almost exclusively at the North Satellite. In the former scenario, the existing two-three car trains can accommodate peak hour demand, while the latter would require either two four-car trains or three three-car trains.

Twenty Year Demand with FIS at Concourse A

This scenario locates FIS at Concourse A, at the same location shown in the ten year demand scenario above. In this configuration, both terminating and transferring international passengers would need to be kept separate from secure passengers, increasing the size of this group.

While the mix of groups is impacted by the relocation of FIS to Concourse A, the overall demand could be met by the same guideway, station and fleet improvements anticipated for the twenty year demand with FIS at the South Satellite.

Another potential South Satellite APM guideway configuration was reviewed, one that would be a more natural extension of the 10 year layout shown in Figure 3-3. This layout, shown in Figure 3-5, is somewhat shorter and would provide improved round trip time and potentially lower costs. It would also provide a shorter trip from the South Satellite to Concourse A for the large group of arriving international passengers, though trip times for some groups of passengers would increase. However, it would likely increase the construction required in taxiway and apron areas, potentially eliminating cost advantages due to added complexity and staging challenges. The merits of these and other potential alignments remain to be analyzed in detail.

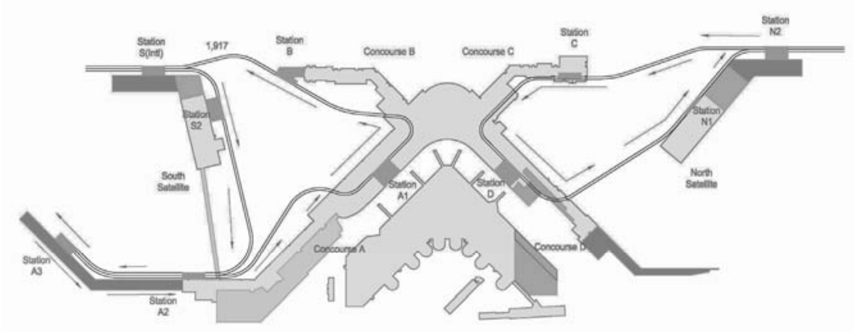

Figure 3-5: Alternate APM Layout for +20 Year Demand

Landside CONRAC APM

The Port opened a new 2.1 million square foot consolidated rental car facility in May 2012 east of the airport and slightly over a mile north of the terminal, as seen in Figure 3-6. Currently, the facility is served by buses transporting passengers between the airport and rental car facility, a trip taking about five minutes one-way. The fleet is made up of 29 CNG buses; during periods of peak demand, twenty buses are in operation. Prior to the facility's opening, rental car companies were located both in on-airport parking and off-airport, requiring shuttles. Since opening, the airport has made 3,200 parking spots available and improved traffic flow by replacing the numerous shuttles previously run by separate rental car vendors with a shared fleet.

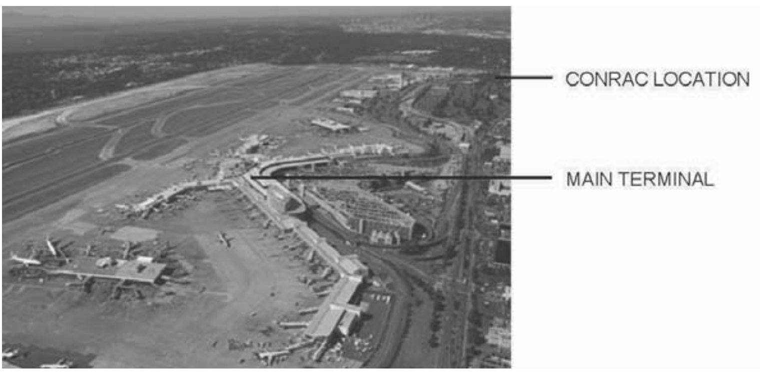

Figure 3-6: Rental Car Facility (CONRAC) Location (photo courtesy of the Port of Seattle)

Figure 3-7: New Rental Car Facility (CONRAC) (photo courtesy of the Port of Seattle)

It is estimated that approximately 16 percent of the 32 million annual origin/destination passengers at SEA will rent cars, or approximately 14,000 on an average day. This results in a peak hour demand of approximately 1,400-1,500 passengers per direction. As passenger demand and traffic increase over time, the Port anticipates the potential replacement of the bus fleet by a dedicated APM system.

APM options

In cooperation with the Port, Lea+Elliott performed a preliminary analysis of APM options connecting the terminal with the then-anticipated rental car facility in 2007 and 2008. Ridership estimates provided by the Port at at that time proved to be quite close to current data, so the conclusions reached then remain generally applicable.

A range of options were reviewed, such as:

- One Airport station at the north end of the main terminal, as shown in Figure 3-8, or two, with one at each end? In the latter scenario, the APM alignment would be above and generally follow the terminal roadway. Due largely to these options, the one-way distances of studied alignments ranged from about 1.9 to 2.6 km (1.2 to 1.6 miles).
- Landside or airside airport alignment? We prepared conceptual alignments following either the eastern or western edge of the main terminal building.
- Shuttle or pinched loop? While a dual-lane shuttle system could serve the current ridership with some capacity in reserve for future increases, adding crossovers at each end to allow pinched loop operations provides flexibility for reduced headways and increased capacity.
- Both self-propelled and cable-propelled systems would be viable options.
- Possible station(s) located at a potential remote parking facility between the Airport and rental car facility.

Depending on the options selected, one-way trip times ranged from about four to six and a half minutes, two to four cars per train, and system capacities between about 1500 and 2200 pphpd.

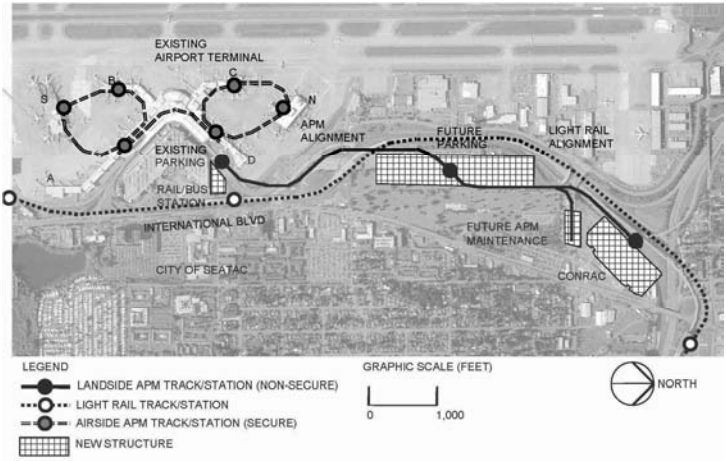

Figure 3-8: APM between Main Terminal & Rental Car Facility (CONRAC)

Next Steps

Sea-Tac Airport will soon be starting a major planning effort to update the Airport's master plan. As the Airport planning options are refined, the APM options will be modified accordingly and evaluated in greater detail. The airport development scenarios presented here imply significant changes in the airside APM and the addition of a landside system. Future planning and design efforts, with the Port, Lea+Elliott and other firms will further define the options best suited to meet the changing needs of the Airport. Short- and mid-term improvements will focus on both the secure airside System and the non-secure landside System. For the secure airside System, the focus will be on integrating an expanded North Satellite, and a future landside FIS adjacent to Concourse A to the secure airside system. For the non-secure landside System, the focus will be on integrating a multi-modal connection between the regional light rail system and a future landside APM, and creating an APM connection between the Consolidated Rental Car Facility, a future remote Parking Garage, and the existing Main Terminal.

Maintaining Reliable Service while Expanding the World's Busiest Airports.

David WT Ewing[1] P.E., M.ASCE, M.IEEE
Norman May[2] P.E., M.IEEE
John Kapala[3] M.ASCE-Standards Committee
Steve Poerschmann[4] C.M.

(1) Project Engineer, Lea+Elliott Inc., 1255 South Loop Road, College Park, GA, 30337; PH 404.216.2230; dewing@LeaElliott.com
(2) Senior Associate, Lea+Elliott Inc., 800 Vinial Street, STE B307 Pittsburgh, PA 15212; PH 412.321.4300 Fax 412.321.4900; nmay@LeaElliott.com
(3) APM Project Manager, Hartsfield Jackson Development Program, 1255 South Loop Road, Atlanta, GA. 30337; PH 404.530.5707; John.Kapala@atlanta-airport.com
(4) Aviation Transportation Systems Director, Department of Aviation, 6000 North Terminal Pkwy, Suite 4000, Atlanta GA 30320; PH 404.382.2511; Steve.Poerschmann@atlanta-airport.com

ABSTRACT

As airports continue to expand, the Automated People Mover (APM) systems which service these airports also need to be expanded. Although a plan and design which anticipate upcoming challenges are important, effective implementation of the plan in a dynamic way is critical to having a successful project. This is especially true when the expansion is taking place at the world's busiest airport and has to be done without interrupting the existing APM service.

The Hartsfield-Jackson Atlanta International Airport recently added the Maynard H. Jackson Jr. International Terminal (MHJIT) which required the expansion of the APM system. For this expansion, the installation, the testing and commissioning, and the integration with the existing system were all based on two key principles:

1. Maintain safe, secure and reliable existing APM service
2. Ensure the MHJIT APM project delivery stays on schedule and budget.

The project's challenges included the tie-in point for the new system, maintaining airport security during all phases, and coordinating work between the APM supplier and the construction contractor. This paper will give some background on the unique layout of the Atlanta Airport and the general design of the MHJIT project. It will then step through the Implementation and Integration of the Testing and Commissioning of the project, to uncover some of the unanticipated challenges and share how they were overcome.

INTRODUCTION

The Atlanta Airport has been in operation since the 1920's and expansion projects are nothing new. As expansions continue, this airport has repeatedly earned the title of the Busiest Airport in the World, now moving over 89 million passengers per year[1]. At such a high level of traffic flow and efficiency, the Airlines and other stakeholders have a major interest in continuing this level of performance. Thus, safely continuing this performance metric during this expansion was mandatory. The strong leadership from the Hartsfield Jackson Development Program (HJDP) which was created by the City of Atlanta and its Department of Aviation along with their consultants and contractors ensured that the expansion project of the Maynard H. Jackson Jr. International Terminal (MHJIT) achieved two main goals. The first was to maintain safe and reliable service and the second was for the project to stay on schedule. The focus of this narrative will be on the APM system and how those two goals were realized. This paper will navigate through the history of this project by discussing what was planned, what was implemented, and finally, the challenges faced or lessons learned.

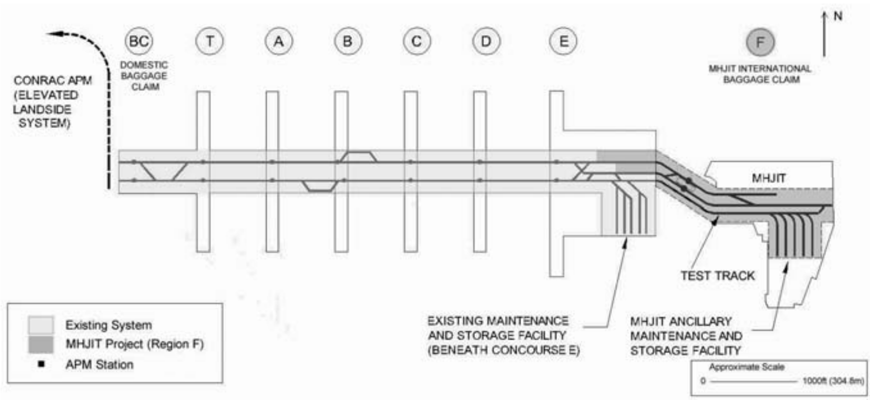

Figure 1. Atlanta Airport after MHJIT expansion

PROJECT BACKGROUND

The tie-In point for the MHJIT project was on the East end of the airport. The airport is situated on 4,700 acres[2]. There were five concourses labeled A through E sequentially from west to east. The MHJIT project added another concourse, labeled F, to the east. As shown in Figure 1, Concourse F was actually part of the International Terminal and International Baggage Claim. The international Terminal would only serve International passengers and provided a separate entrance to the airport from the Domestic Terminal. The Domestic Terminal is located west of

Concourse A and would now only serve Domestic passengers for Ticketing and Baggage claim. Since there were now going to be two portals to enter the airport, the logistics of safety and security had to be considered on all levels, including the train level.

The Atlanta airport has three different train systems that all end at the Main Domestic Terminal that is otherwise known as the Central Passenger Terminal Complex (CPTC). These systems are the public transportation system that is known as MARTA, the APM to the Rental Center that is known as the SkyTrain, and the train between the concourses that is known as the PlaneTrain. The PlaneTrain system had a fleet of 49 Bombardier CX100 Vehicles and from end station to end station the system spanned a length of over 1 mile in a dual lane Automated pinched loop system. Under the MHJIT expansion, the city of Atlanta expanded the dual lane system 1,200 ft east to the new International Terminal and procured 10 more of Bombardier's CX100 Vehicles. Before the tie-in, the PlaneTrain already moved an average of 200,000 passengers per day[2] and now the infrastructure will now be in place to increase that capacity even more.

Figure 2. Looking East, International Terminal Tie-In Point in 2009[3]

Figure 3. Looking East, International Terminal Tie-In Point in 2012[3]

PLANNING

Schedule

Although there were several schedules for the various contractors, the two main published schedules were the schedules for the APM Supplier (Bombardier) and the Prime Contractor (HMMH- Holder Manhattan Moody Hunt). Both schedules were reviewed with HJDP on a weekly basis. Some of these meetings included both the Prime Contractor and APM Supplier and some of them were more targeted meetings with select groups. The more targeted meetings with the city and the Prime Contractor or APM Supplier proved to be very valuable in zooming in on specific parts of the schedule. These two main schedules were also in a format which HJDP's scheduler used, to integrate and improve the review process. HJDP's ability to integrate and overlap the schedules was an important tool which allowed the leadership to anticipate any upcoming issues. The major milestones for the integrated schedules provided a great overview to keep items on track. Shown below are some of the major milestones achieved as it relates to the APM system:

1. December 2007: Note To Proceed (NTP)

2. November 2010: Modified Alternate Turn back placed in Revenue Service (later added to the schedule)
3. March 2011: North Track turn back placed in Revenue Service
4. June 2011: Completion of Train Control Upgrade of the Existing System
5. July 2011: South Track turn back in Revenue Service
6. May 2012: Full System in Operation

For the more critical phases of the project, a more detailed schedule was created. In the case of the tie-in to the existing system, flow charts and phased drawings also supplemented the schedule. This level of planning and coordination began at least a year before implementation. In planning for this tie-in, there were two items which were given the most attention; maintaining system operation, safety and security.

Maintain System Operation

To ensure that system operation was not affected, the boundaries for verifying the area under construction were established with various site walks with the APM Supplier, APM Operations, Prime Contractor, HJDP and its consultants. These boundaries took into account the safe stopping distance for the train, protecting all of the conduits and equipment which were currently in use, and limiting dust and debris from entering the system. The site walks used spray-paint to physically mark the demolition areas, fence lines, and conduits/equipment to be removed to eliminate the potential of error.

APM Operations also had certain requirements for any work in the areas under operation. This required advance notification and supervision from their personnel. Coordination with the APM Operations team was important because even though the system was not in passenger service for a 4 hour window every night, sometimes access to the area was limited due to scheduled routine maintenance activities.

Since the construction was going to be at the turn back point for the train, it was important to allow the redundancy in the system to maintain the system reliability. This was accomplished by turning over parts of the new system for passenger service in phases instead of all at once. The North Track was turned over to part of the new construction to allow for demolition.

Security and Safety

The established requirements for safety and security were integral to the schedule and finalizing the demolition demarcation. The fence at the system integration boundaries had certain height criteria and guards were also placed to secure any entrance/exit gates. There were also specific access request requirements so the contractors would need to provide advance notice to perform work in those areas. During construction and testing there were three main levels of security. There was a security level to gain access to the construction site, one for access to the areas which overlapped in the airport's secure side, and one for access to areas under the control of the APM supplier. During testing, the highest level of access, known as Security Identification Display Area (SIDA), required all personnel to have a SIDA badge and security training.

IMPLEMENTATION

Phased Access

A very large component to a successful schedule was the flexibility of all parties involved. The Phased Access approach, as shown in Figure 4, is an excellent example of that. The initial plan was for the Prime Contractor to be completely out of the AGTS level so that Bombardier could start their work, unimpeded. As the original plan and schedule evolved, a Phased turn-over approach was realized. For this phased turn-over approach, the Prime Contractor worked on completing their scope starting from the east end of the system and moving west towards the tie-in point.

An advantage to this approach was the efficiency in resolving Quality Control deficiencies. The APM Supplier and Prime Contractor were able to work together to resolve any deficiencies in manageable sizes while the specific sub-contractor was still available and on-site. Although this provided rapid resolution to issues as they were discovered, it also increased the traffic of the various contractors in those areas which were already turned over. Such an increase in traffic always raises the potential for damage to the finished product. There were some instances of damage, but in general the advantages of a more aggressive schedule far outweighed the disadvantage of having to do touch-up work.

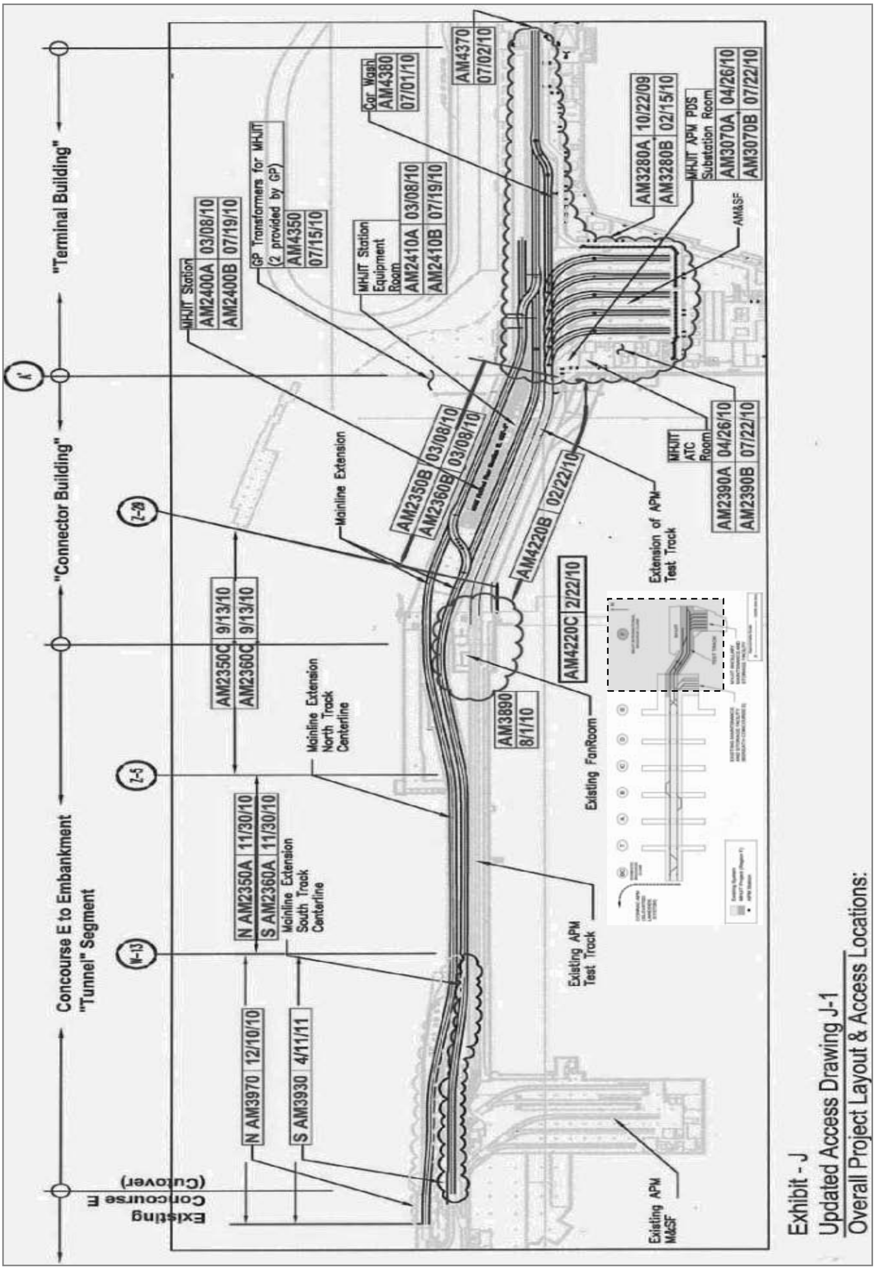

Figure 4. Phased Approach of turnover areas from the Prime Contractor to APM Supplier

Phased Tie-In

Since maintaining system operation was such a big part of the project criteria, phasing the tie-in to the existing system proved to be the best approach to reduce any impact to the existing train operations. Considering that the expansion and tie-in was taking place at the turn back of the existing system, it was important to be error free in the cut-over, else there would be significant impact to system operations. There were three main sequences of activities or milestones which were tied in on the train level. Achieving the first two milestones was critical because there was not a back-up turn back mode while it was under construction.

1. **North Track In Passenger Service**
   The North Track had to first be placed in passenger service because it created the least impact to the normal operation. The North Track was already used as the primary turn back for the system, so for the tie-in, the turn back was simply extended into the new turned over area. As the North Track tie-in was under construction, as an intermediate step, a temporary turn back route on the South Track was programmed into the APM's Controls. This mode affected the train movement in the maintenance area so this temporary mode was limited to four to five months in operation. After the North Track's extended turn back was tested, the appropriate security borders had to be established since that part of the system would now be considered secure. Figure 5 shows the North Track in passenger service.

2. **South Track In Passenger Service**
   Placing the South track in passenger service proved to be a little more of a challenge considering that a switch needed to be added. But with the expertise of the APM Supplier they were able to work with the Prime Contractor to get this track constructed and tied-in in less than four months. Similar to the North Track tie-in, the security borders had to be re-established before placing the South Track in passenger service.

3. **Full Test Track In Operation**

The Test Track was one of the last sections to be tied-in, since it did not have a direct impact on passenger service. The APM Operations and Maintenance (O&M) team was very cooperative and creative throughout these various construction activities to maintain and operate the system with all the construction and integration restrictions in place.

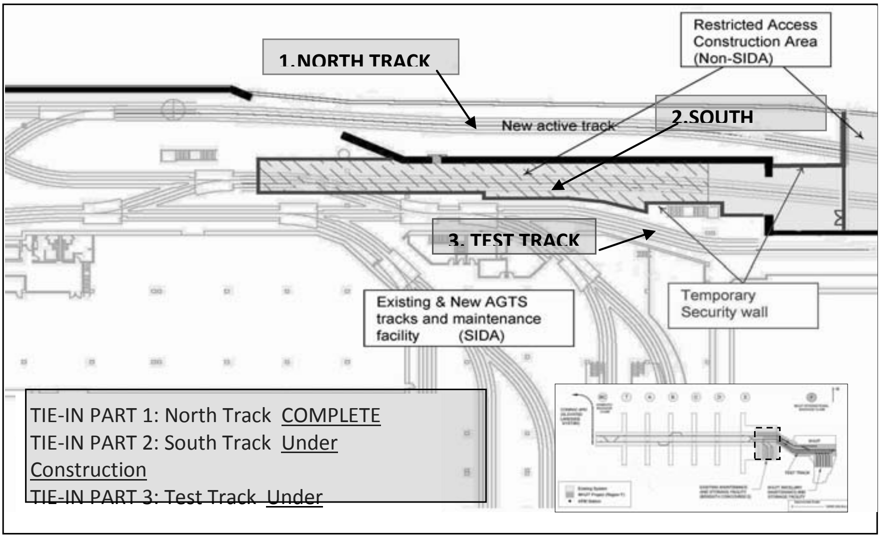

Figure 5. Train Level System Tie-In Sequence with the North Track in Service

APM Testing and Commissioning

Part of the process of tying in each part of the system was Testing and Commissioning. The Lea+Elliott adopted criteria documents required the Supplier to layout this detailed test plan information at least five months after the NTP. A more general Preliminary Master Project plan was due fifteen days after NTP. The criteria document listed the items which should be explicitly tested and some items were left to the Supplier's discretion on whether full testing was necessary. There were two major phases of testing, Factory Testing and Site Testing. The tests which were pre-determined to be Factory Tests varied depending on the subsystem. The APM Supplier's testing plan was more heavily weighted towards Factory Testing than towards Site Testing. This was feasible for this project mainly because the supplier used mostly proven and trusted designs. Those designs which were under question were tested as Qualification Tests at the factory. As a result of the established confidence in the design, much of the site testing was spent functionally testing the subsystems and integrating the tests.

There were four major stages of site testing for five major subsystems. The four stages in order of operation were Post Installation Check-Out (PICO), Static, Dynamic, and System Integrated Tests. These tests were performed for the five major subsystems Civil/Wayside, Station, PDS/UPS, Vehicle and Central Control.

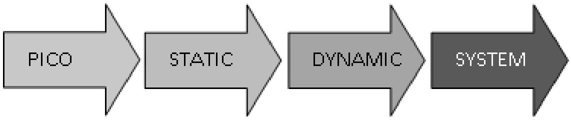

Figure 6. Four Stages of Testing

Stage 1: PICO tests were typically performed by the Supplier and their Subcontractors and were generally not witnessed by the city. Although there was not always a city's witness present, documentation was required for all stages of testing.
Stage 2: Static tests generally ensured that the mechanical devices and controls were operating as expected.
Stage 3: Dynamic tests incorporated full testing of that subsystem under full power and controls
Stage 4: System Integration tests will then incorporate that subsystem into the full system.

Part of the documentation process which was really helpful throughout each stage, was that the test procedure included the list of applicable reference drawings. This is highly recommended, because during testing, we were able to quickly perform any additional verifications and trouble shooting that was necessary. Also since the references were categorized by subsystem, it made the particular reference easily accessible.

At least the first two stages were performed for each of the five major subsystems. There was some overlap in the different subsystems. In those cases, some of the inspection items or stages were verified more than once to avoid any gaps in the testing.

The Civil/Wayside Subsystem was one of the first subsystems tested and it comprised of the civil structure and everything that physically connected to it. This included leveling tests for the running plinths, switch installation and operation, signal rail and track circuit installation. Eventually tests for the signal levels in the wayside boxes were finally checked.

Some of the other subsystems were tested concurrently as the phased work continued and some were tested in parallel. Shown below is an overall flow chart of how the remaining subsystems were sequenced.

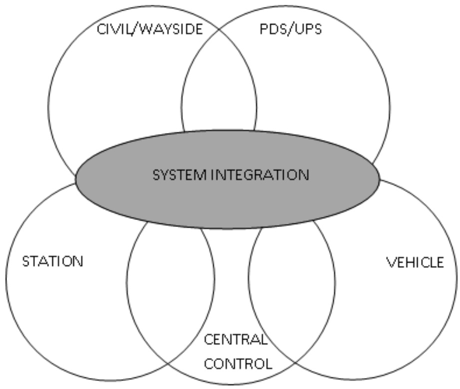

Figure 7. Venn Diagram of Overlapping Subsystem Testing

PROJECT CHALLENGES

Schedule

Before developing the four stages of testing, there are two potential pitfalls we tried to avoid when testing was condensed to a more aggressive schedule. First, the temptation is to skip part of the four stages of testing, but that often creates more problems during integration testing and system operation. Discrepancies, which could have been discovered and resolved during an earlier stage of testing, can eventually impede progress by forcing more resources from the Supplier and their subcontractors to troubleshoot the issue. In addition, more resources from the city's side would be needed to witness the rescheduled test.

The second pitfall to avoid tends to occur when the momentum and pressure of the site installation and testing increases. As the energy increases there is always a hesitation to slow down for documentation. Considering that rarely the same team finishes a project as the ones who started it, resolving poorly documented or un-documented discrepancies can later drain resources in closing out a project or even troubleshooting issues that arise. Avoiding these pitfalls by following the stages of testing and properly documenting, worked well to set the pace for a successful project.

Shown in Figure 8 is a general timeline of all four phases of testing for each subsystem. The dates represent when most of the testing was done and does not include any punch-list or new items. *Since the Central Control Software was mostly in place under a previous project, the integration for this subsystem was seamless except for a couple unique issues.

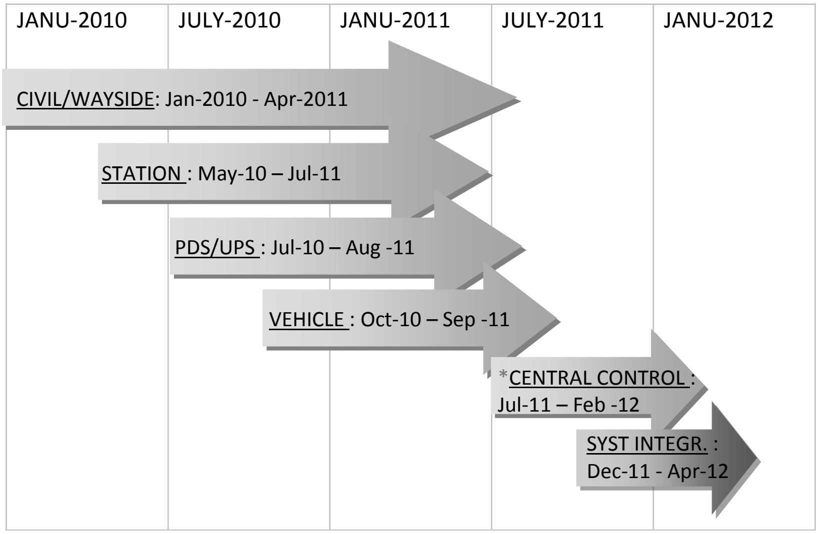

Figure 8. General dates for MHJIT Testing by Category

Quality

Another challenge was maintaining a high quality level with various organizations involved. There were several areas during the construction phase which required interfacing between the Prime Contractor and the APM Supplier. In preparation for this interface, Design Construction Interface Documents were created by the supplier to ease this transition. In general, interfacing between various entities will have an associated cost especially when the organizations are not sub-contractors or in partnership with the other involved organizations. Much of the cost occurs during interfacing when there is a disagreement in scope or responsibility and the involved entities are at an impasse. Although there is contract language to limit lost time when the responsible party was in question, the city's leadership and its consultants were critical in quickly clearing up discrepancies.

Two areas where this challenge was realized are with the running surface and the station doors or station barrier walls. Since the Prime Contractor provided the running surface for the Supplier, there were sometimes disagreements on whether or not the Prime Contractor satisfied the criteria of the Supplier as presented in the Design Interface Documents. This challenge was overcome by having the quality control personnel of the Prime Contractor and the Supplier work together several times a week to ensure the criteria was satisfied. The advantage of both entities working closely together during the phased turn-over was that the quality improved as the installations progressed. Another option in avoiding this situation is for the

Supplier to use one of their own subcontractors who is experienced with their installation criteria.

The other challenge was with the phased turnover of the station doors or barrier walls. Some of the inspection activities for the station doors were performed while various contracting groups still had access to the area. Although some areas were successfully inspected without any major issues, discrepancies eventually surfaced. The phased turn-over of this area did create some additional touch-up work, partially due to the various contractors that moved in and out of that area after the station doors and the barrier walls were installed. This was an important reminder that there must be strict requirements to protect any areas when they are turned over to another contractor.

Train Control

Since the train control subsystem is essential to train operation, this could have been a big challenge without proper planning. Most of the Central Control upgrade to the existing thirty year old system took place in a project which preceded the MHJIT project. This proved to be very advantageous in completing MHJIT on time because it had the most potential to slow down the project. It's potential for affecting the schedule was mainly because it was the only subsystem which was completely new to the Atlanta site. If one is planning a similar expansion, if the central control update can be done as a preliminary project it is strongly advised. There were several advantages to performing this upgrade first. Most of the troubleshooting for the central upgrade was completed early and had little to no impact on the MHJIT schedule. It also proved to provide seamless integration once the MHJIT equipment was available to test. The seamless transition was also a cost savings for the supplier in mobilization costs for the central upgrade team. The same installation and testing team was involved for both projects, so they were able to quickly address discrepancies as they surfaced.

CONCLUSIONS

With all of the Challenges faced during this project the highly dedicated team of personnel was able to achieve the goals to minimize system interference and minimize the impact to the schedule. Many would agree that the expertise of those involved, continuous planning, coordination and flexibility made this project a success. As the inevitable expansion to the airport continues, the next expansion team can build on this winning approach and continue the legacy of successful expansion at the busiest airport in the world.

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Evaluation of passenger satisfaction with the Heathrow PRT system

P.H. Bly,[1] J.C. Hammersley[2], M.V. Lowson[2]

Summary

The ULTra PRT system has been in operation at Heathrow airport since April 2011. A survey of passenger satisfaction was carried out in May 2011. The results for this survey demonstrate very favorable passenger response to the new system. Scores for every aspect of the system are positive, in the majority of cases very positive. Overall scores for questions related to the overall service and vehicle are between good and excellent. Scores for access issues, notably the stations, are also positive but at a lower level. Overall 96% of all passengers rated the service good or excellent. The highest score was given to image, an average 4.82 on a 5 point scale. Surprisingly, the second highest score was given to the perception of personal safety. This is encouraging for PRT since it might be thought that passengers would be concerned about the lack of a driver. The lowest score is for ease of finding the Terminal 5 station. However the survey was undertaken before wayfinding signs had been installed. Comparative results for the transfer bus show a significant improvement in overall scores. 94% of all passengers surveyed perceived PRT to be better than bus transfer, the remaining 6% said they were equal. No passenger preferred the bus. The results demonstrate that PRT is now ready for serious consideration as part of an integrated transport system for airports.

1 Introduction

PRT is now in operation at London's Heathrow Airport, linking the Business Car Park to the new Terminal 5, operating for 22 hours each day. Measured availability is 99.7%. BAA, the owner of the airport, constructed the system as a pilot, to demonstrate its practicality and, depending on its success, BAA may consider expanding PRT more widely across the airport. This first system is essentially a shuttle system, which cannot fully demonstrate the advantages of PRT as a network where passengers can travel directly from any point to any other point on the network, without intermediate stops, and with little or no waiting. Nevertheless it will demonstrate the technical operation and reliability of the system and, most importantly for the owner, BAA, the service level it offers to passengers. Thus it is not intended that the Pilot Scheme will of itself be economically justified, but it is intended to be the start of a larger scale PRT system which will, after the Pilot phase, continue to serve passengers traveling between the business car park and Terminal 5. The design of the Pilot system must, therefore, be as detailed and functional as the larger network. Experience of the

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[1] Consultant

[2] Ultra Global PRT Ltd, Bristol, UK

construction and operation of this Pilot will provide a basis for judging the merits of future applications of PRT.

The previous transfer system was a midi-bus service which took passengers between the car park and Terminal 5 prior to operation of PRT. Such bus services are used widely within the airport to transport passengers between the various car parks and the Terminal buildings, and also to link the different Terminals, car hire centers, hotels, staff workplaces, and various other centers of activity. Passengers using the transfer bus system were surveyed in March 2009. This survey was administered to PRT users in May 2011, shortly after the service began public operation.

This paper describes the PRT passenger survey, and its findings. Section 2 describes briefly the Heathrow PRT system, Section 3 the survey methodology, and Section 4 the respondents, where there were minor differences in their characteristics. Section 5 describes the distribution and average scores achieved for each of the 21 questions pertaining to passenger's perceptions of the PRT service, categorized into questions concerning access at the car park end, the vehicle itself, access at the Terminal 5 end, and the service overall. Section 6 concerns the two additional questions added to this survey, which were specific to PRT. A discussion Section 7 includes a brief comparison between the PRT and bus surveys.

2 The Heathrow Pilot PRT Scheme

The Heathrow Airport Pilot PRT Scheme has been commissioned and financed by the airport owner BAA. This followed an extended period of analysis of alternatives to provide the key landside transport needs of the airport. BAA concluded that all existing forms of public transport were unsuited to meeting their key requirements, on the grounds of cost or inflexibility or both, and that the best transport solution to meet their future needs was a PRT network.

The scheme carries passengers arriving at the Business Car Park to the new Terminal 5 Building, which opened in March 2008. The PRT network has 3.8 kms of dedicated guideway, collecting passengers from two two-berth stations in the car park, transporting them along a dual-guideway mainline section which skirts the perimeter of the airport, and terminating in a four-berth station on the second floor of the multi-storey short-term car park alongside Terminal 5, as shown in Figure 1.

The system is served by 21 small four-seat battery-electric vehicles, controlled automatically. Except where there are sudden large peaks in arrivals, passengers find a vehicle already waiting to collect them at the stations, and there is little or no waiting. The scheme is intended as proof of concept.

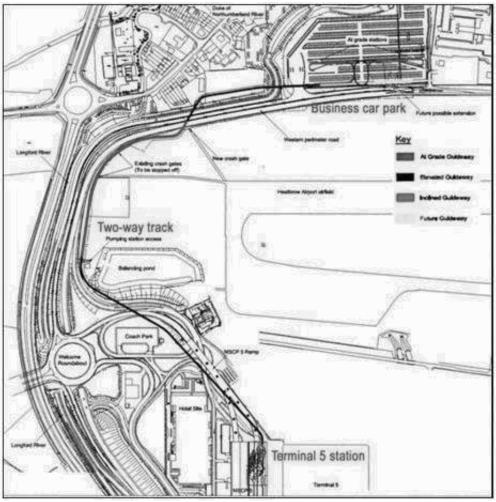


Figure 1. The PRT routing between the Business Car Park and Terminal 5

It is important to understand that, because the PRT system is a pilot to demonstrate proof of concept, some aspects of its location are unavoidably sub-optimal. Had the system been designed as an integral element of the airport the Terminal 5 station would have been installed closer to the Terminal building itself, either within the building (the PRT vehicles are battery electric and produce no exhaust emissions and very little noise) or placed along the exterior wall of the building, rather than on the second floor of the multi-storey car park, where connection to the Departure level, or from the Arrivals level, is via lifts or stairs. Thus in this after-fit, access to PRT could be considered worse than access to the buses. It is also the case that in this application the run time from car park to terminal, and return, is essentially the same for both bus and PRT, so passengers have gained travel time benefit mainly from the significant reduction in waiting time, rather than in-journey time. This gain in waiting time is significant, however, with 80% of passengers having no wait for a PRT vehicle. Across the airport PRT would be considerably quicker than bus since buses have to negotiate traffic signals, intersections and traffic congestion, while many bus services also stop at intermediate destinations. PRT, by contrast, runs non-stop from origin station to destination, though in some cases the routing might be less direct than by road. In this initial application, PRT operates essentially as a shuttle service, and consequently most of the guideway is two-way track. In a wider network the guideway would be designed as interconnected one-way loops, and vehicles would be able to navigate directly from any point on the network to any other, travelling automatically and safely across intervening junctions, and bypassing intermediate stations.

There are two stations in the Business Car Park, each with two berths. If the car park is full the mean walking distance to the nearest station is about 60 meters. From the car park PRT runs as shown in Figure 1 to a station on the second floor of the multi-storey car park alongside the Terminal 5 building, from where passengers walk across a level bridge into the mezzanine level of the airport. The departure level is on the fifth floor above this, and arrivals on the ground floor below. The station on the second floor of the multi-storey (short-term) car park at

Terminal 5 has four berths. The bus service, by contrast, dropped passengers at the Departure level, and picked passengers up at Arrivals level.

The PRT system first began operating a simulated revenue service in September 2010. BAA were unwilling to permit public operation until they were confident that the system could operate without any failures, and it was subjected to an extensive commissioning period to ensure that it was fully reliable, and met all its operating targets. In the autumn of 2010 and winter 2010-11 the system carried airport employees and numbers of visitors who came to examine the new system, and operated for extended periods in exactly the same way as for public operation. There were, inevitably, teething problems and equipment failures, though there were few problems with the operation of the PRT system itself; mostly problems affected components which might form a part of any conventional transport system, such as touch-screens and door sensors. Sequentially, minor problems were eliminated and in April 2011 the system began full public operation.

As noted above, if PRT were to be incorporated into the design of the Terminal it would deliver passengers directly into the building, and could in principle drop passengers at Departure level and pick them up at Arrivals level, though this would necessitate considerable additional length of track to accommodate the change in level. The mean run time from either car park station to the T5 station is 5.0 minutes, very similar to that for the buses. The buses ran at a mean headway of 8.9 minutes, with a variability which corresponds to a mean waiting time of 5.2 minutes for randomly (Poisson) arriving passengers. For most PRT passengers there is no waiting at all, since most find a vehicle waiting for them in the station, though occasionally their selection of the destination on the tough-sensitive panel will call one up from another station or the depot. The mean passenger waiting time has been measured at 0.3 minutes. The buses did however offer an advantage over PRT at the Business Car Park of dropping passengers on request as they travelled around the car park, so that the mean walking distance on return was less than on the outer journey, though these stops delayed the journey for passengers left on the bus.

3 The survey

The survey was carried out on three consecutive days from May 18th to 20th 2011. The Questionnaire is exactly the same as that administered to the transfer bus passengers, but with the addition of two questions specific to PRT, dealing with how PRT compares with the bus service, and how much passengers might be willing to pay for PRT in an urban context. These questions were added after the main questions to ensure that they could not bias the answers to the main questions.

Figure 2. The passenger survey

Supervisors met passengers as they boarded vehicles at Terminal 5, explained the reason for the survey, and gave them the questionnaire form Passengers filled in the form as they travelled to the car park station, where other staff collected the forms and provided any assistance needed.

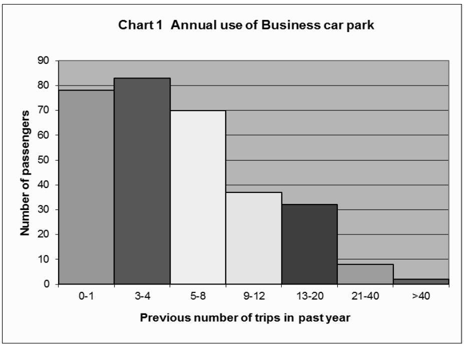
Most of the questions required the respondents to assess various aspects of the service on a five point scale, from 1 = Extremely poor to 5 = Excellent. In all, attitudes were sought on 18 aspects, plus the two additional questions noted above. The survey also asked whether the respondent would recommend the car park service to a friend or colleague, using a 10-point scale.

4 The respondents

Usable returns were obtained from 314 respondents. Not surprisingly, given the nature of the car park, the overwhelming majority, 289 in 294, were travelling on business (20 passengers failed to reply to this question - indeed 20 passengers failed to fill in the reverse side of the questionnaire sheet, and only completed the first 14 questions). Of the rest, 4 were travelling on package holidays and one to stay in their own house abroad. The sample of non-business travelers is too small to make meaningful distinctions between the scoring for different travel purposes.

88% of the respondents were male and only 12% female, reflecting a very strong bias in business travel, as was the case in the bus survey. Average rankings were similar for both males and females for most of the aspects surveyed, and in what follows differences between the sexes will be mentioned only where they are appreciable or of potential interest.

Respondents were asked how many times they had used the Business Car Park in the last year. This response is not comparable with the bus passenger survey, since in that survey the car park had been open for only slightly less than one year. As Chart 1 shows, some users were frequent travelers from Terminal 5: 42 had travelled more than 12 times from the Business Car Park. The surveyed trip was the first or second time of use for 78 respondents.



Passengers were not asked whether they had used the PRT system before, but it had been open for such a short time that very few would have had the opportunity.

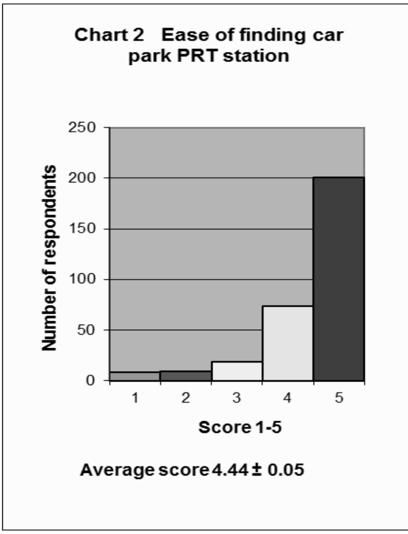
5 Survey results

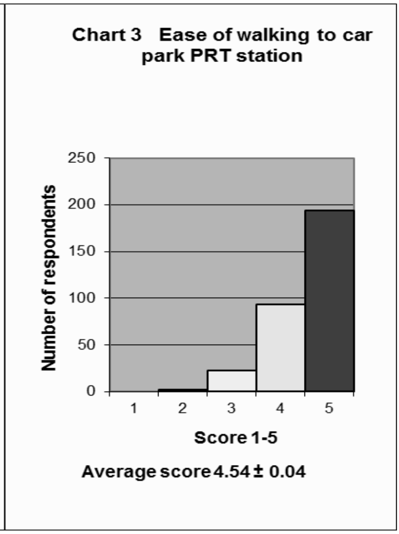
5.1 The Business Car Park

"How would you rate the ease of finding the PRT station in the car park?"

In the Business Car Park the two PRT stations are located towards the Perimeter road edge of the car park, and have sculpted wing-shaped canopies which are readily visible from any point in the car park (see Figure 3).

Figure 3 Station in Car Park





This ease of finding the station is reflected in the high markings given in answer to the question, as Chart 2 shows. The standard deviations shown are those on the means. The sample size was designed to achieve discrimination between mean scores of ±0.1 and this was generally bettered. The Heathrow stations are designed to be iconic, but in general PRT stations in a car park need be hardly more elaborate than bus stops. There were, however, a number of passengers who marked this aspect low, perhaps because they did not realize that the very attractive station structures could be the transfer stations, when they were used to simple bus shelters.

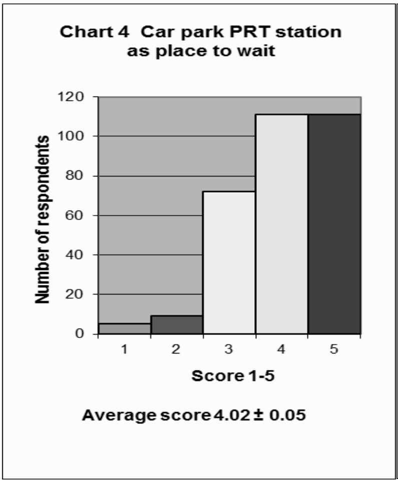
"How would you rate the ease of walking to the PRT station from your car?"

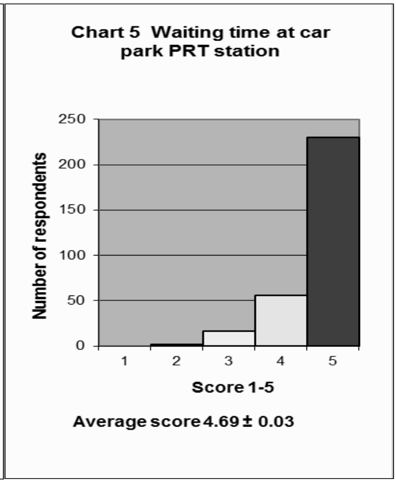
Similarly, as Chart 3 shows, travelers found no difficulty walking to the PRT station, since the mean walking distance is only about 50 meters. It is the case, however, that unlike the transfer bus stops, which can be located anywhere in the car park where it is suitable for the bus to pass, PRT stations have to be located where feasible because the guideway must be segregated, and this could increase the mean access distance over a bus service.

"How would you rate the PRT station in this car park as a place to wait?"

The car park stations scored fairly highly as places to wait, though perhaps not as highly as might be hoped given the very striking architectural statement they make (Chart 4). They are well protected from the weather, though they do involve passengers interacting with a touch-screen to call the vehicle, an action not required with the transfer buses. In this small-scale pilot the screen is rather redundant, since the only available destination is Terminal 5, but in a larger network passengers will have to choose from a list of destinations. In practice, most passengers did not have to wait there, since they could immediately board a waiting vehicle, and would have little time to consider the attractiveness of the station as a place to wait.

Nevertheless, 31 passengers gave the stations a mark of 1 or 2, indicating positive dissatisfaction with the stations. This may be due to the stations being not fully enclosed. Also a small minority of passengers appeared to expect seats, despite waiting times being very low.





"How would you rate the amount of time you had to wait at the PRT station?"

This question achieved a remarkably high mark (Chart 5), with only 5 passengers rating the waiting time as less than "good", and 20 rating it "good", i.e. 3. 241 gave it 5 marks. Given that the average waiting time across the survey was 19 seconds, and only 6% of passengers waited more than a minute, this is not surprising.

Walking through the car park to the station is in the open air, and Question 14 asked for a rating of the **weather at the time**. 76% of respondents marked the weather at 5 or 4, and 24% at 1 or 2. Although poor weather did depress the ratings slightly the effect was not statistically significant, as:

	Good weather (4&5)	**Poor weather (1&2)**
Ease of walking to car park station	4.56±0.04	4.45±0.08
PRT station as place to wait	4.04±0.06	3.96±0.11
Waiting time at stop	4.72 ±0.04	4.62 ±0.08

In general, though, poor weather depressed the rankings slightly across all aspects, but only in the cases of personal space, personal safety and information was the difference statistically significant. This is clearly not an effect of the weather on the particular aspect, but simply that good weather encourages people to take a more optimistic view of life in general.

There were no significant differences between the way **women** viewed the car park end of the system from the scores given by **men**. Women rated walking to the station at 4.68±0.21, the station as a place to wait at 3.94±0.17, and the waiting time at 4.68±0.10, compared with 4.50±0.04, 3.99±0.06 and 4.70±0.04 respectively for men. Interest in this question arises because women might feel more vulnerable walking and waiting in a car park, but one potential strength of PRT is that, since waiting time is so short, vulnerability, even at night, is minimized. But in any case, the airport car parks are very secure places.

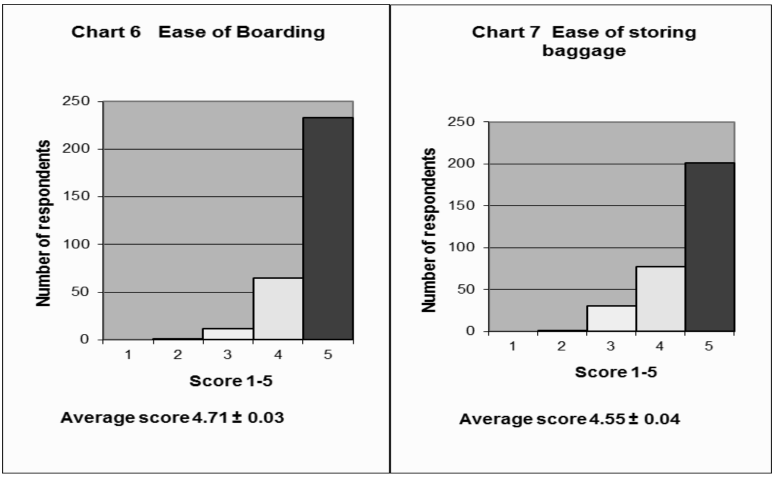
5.2 The PRT vehicles

Five of the questions related to aspects of the PRT vehicles or "pods" themselves. First, getting on the vehicle:

"How would you rate the ease of boarding the vehicle?"
"How would you rate the ease of storing your baggage once on board?"

As Charts 6 and 7 show, few passengers found difficulty with either aspect. Entering the vehicles is rather easier than entering a car, though it is necessary to bend the head a little when passing through the door. Unlike the transfer bus, there is no special rack for storing baggage, but there is plenty of space between the opposing bench seats to place baggage on the floor, and no lifting of bags into racks is required. It is the case, though, that this is a business car park, and many passengers have only light baggage.

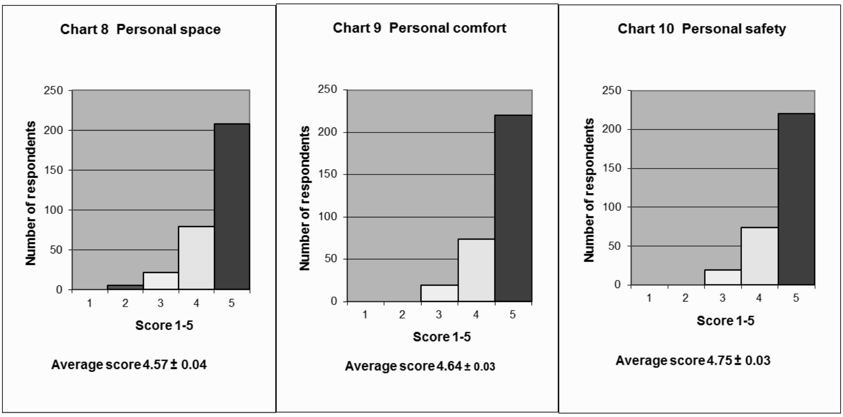
Women found no more difficulty than men, with scores of 4.79 and 4.47 for boarding and baggage respectively, compared with 4.69 and 4.54 for men.



"How would you rate the amount of personal space in the vehicle?"
"How would you rate your personal comfort whilst in the vehicle?"

These two aspects are closely related, and the scores are very similar (Charts 8 and 9), though there are rather more low scores for space than for comfort, which may represent the distribution of physical size of the passengers. Roughly two thirds of passengers marked these aspects at 5 out of 5, so clearly they were very impressed by the vehicles. It may be the similarity to a private car which is so appealing.

Women find the vehicle less spacious than men, but more comfortable, at 4.35±0.16 and 4.74±0.10 respectively, compared with 4.57±0.04 and 4.61±0.04, but these differences are not statistically significant.



Lastly passengers were asked how safe they felt:

"How would you rate your personal safety whilst in the vehicle?"

It is remarkable that this question achieved the second highest score in the survey, after image. This is an entirely new mode of transport, it is driverless, and most of the guideway is elevated and on a gradient. Yet passengers clearly felt extremely safe. The question is compound, since safety encompasses both freedom from accident on the system, and freedom from assault and it is not possible to say how these components were judged. The finding is very important for future designs of PRT networks, whether airport based or for urban transport. Women give a slightly lower score than men, at 4.59±0.12 compared with 4.76±0.03, but the difference is not significant.

5.3 The Terminal 5 station

Three questions concerned access at the Terminal 5 end, and the survey was completed as passengers accessed the service at Terminal 5 and travelled to the car park. As noted previously, the T5 station is not at an optimum location, because the PRT system was designed as a pilot and introduced after completion of Terminal 5, when the easiest place to construct it was within the multi-storey car park alongside the Terminal building. Passengers have to take a lift to the Departures floor, where there is a bridge across to the Terminal building. For a PRT system designed as an integral part of a Terminal it would be possible to bring the vehicles into stations directly at Departure and Arrival levels, and close to the relevant check-in desks.

"How would you rate the ease of finding the PRT station at Terminal 5?"

As Chart 11 shows, this is an aspect that is rated very low, and the score of 2.51 is far below the scores achieved for all the other aspects. This is primarily because at the time of the wayfinding signs pointing to the PRT station had not yet been installed in Terminal 5, although the rather circuitous route to the station might not have scored highly even if the signs had been in place. Nevertheless, many passengers had no idea where to go, had to ask, and were clearly irritated. It is interesting, though, that even given the high praise passengers are giving to the system as a whole this aspect, which deserves to score badly, is singled out for a low marking, and this instills confidence that the survey is correctly identifying passenger attitudes. The wayfinding signs were installed shortly after the survey, so the scoring now would be very different.

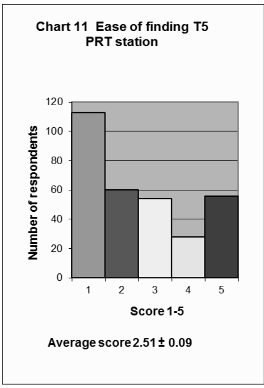
"How would you rate the PRT station at Terminal 5 as a place to wait?"

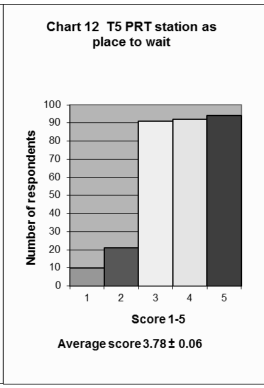
This question received the second lowest score of the survey, probably in part because the difficulty of finding the station was fresh in the mind. Although the station is well-designed, with modern glass screening of the concourse from the berths, and glass doors which opened synchronously in the station and on the vehicle, the low roof and approach alongside the second floor of the multi-storey car park might give the impression of a place rather squeezed into a corner of a workaday car park. Also on windy days there is a noticeable draft though the station. The transfer bus stop, alongside a roadway, fared even worse, however.

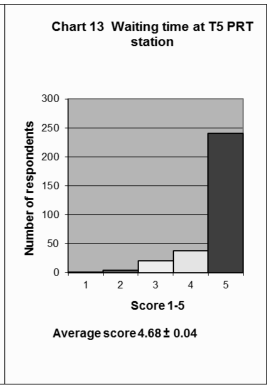
Just as for the car park station, passengers were asked about their waiting time:

"How would you rate the amount of time you had to wait at the station?"

Despite passengers' unhappiness with the directions to the T5 station, and their relative indifference to the station itself (though note that 3.78 still shows good satisfaction with the station), they appreciated the very short waiting times, or lack of waiting altogether, which PRT achieves. Waiting time at the station is marked almost exactly the same as at the business car park station, which again suggests a high degree of consistency in the survey, since the two questions were well separated in the questionnaire.







5.4 The Service

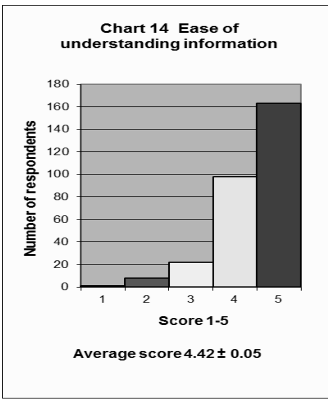
The remaining questions in the survey were concerned with the PRT service overall.

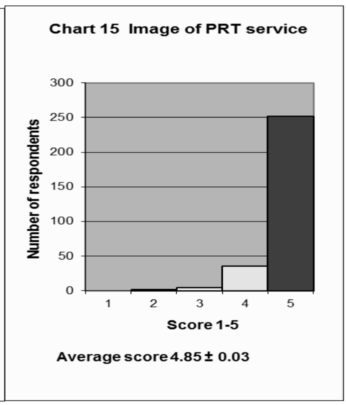
"How would you rate the information about using PRT as being easy to use?"

This is a crucial question for PRT, since while everyone knows how to use a bus (at least, when it is free), PRT is a mode which is entirely different from the conventional modes with which people are familiar and it is essential to provide information which makes the service easy to use. In reality, there is nothing complicated about calling and using PRT, but it is likely that passengers using it for the first time will be unsure what to do. As Chart 14 shows, however, passengers rated the information provided highly, and indeed the system can be seen to work smoothly, with passengers handling destination selection, boarding and alighting without difficulty. Only one passenger gave a mark of 1, and 8 marked the information at 2.

"How would you rate the PRT vehicle (the "Pod) in terms of having a modern image for the airport?"

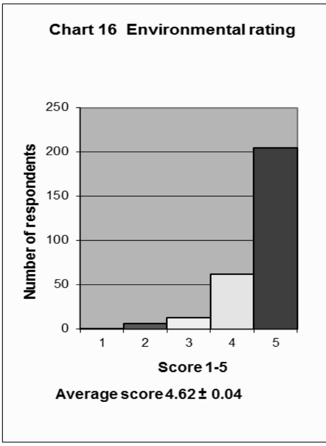
It comes as no surprise that the image of the PRT system should be scored the highest of all the questions (Chart 15), though it will be nonetheless gratifying for BAA. Eighty six percent of passengers marked it at 5 for its modernity, presumably because it was regarded as very advanced technology. In terms of its automated operating system this is true, of course, but both guideway and vehicles are in fact based on tried and tested technologies, with many component parts supplied from the automotive industry. It is the whole ensemble which comes together to give most people who see the system the impression that this is a transport system taken from the future.

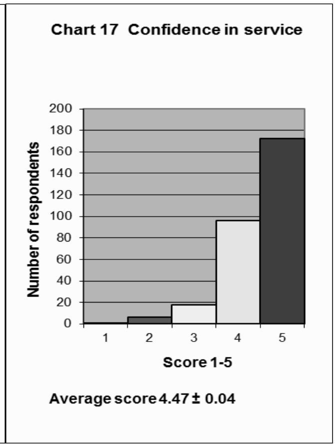




"How would you rate the PRT vehicle for being environmentally friendly?"

Passengers rated the environmental friendliness of PRT very highly, though they had no way of knowing the precise details of its energy use or emissions. It was obvious, though, that the vehicle was electric (though most passengers would not be able to say whether it was battery-electric or track-powered). They would guess that the vehicle had no emissions at the vehicle, and probably emissions from the electricity generating station would not be considered. The vehicle was clean and quiet, and was not powered by an internal combustion engine, and that was enough to justify the very high marking.

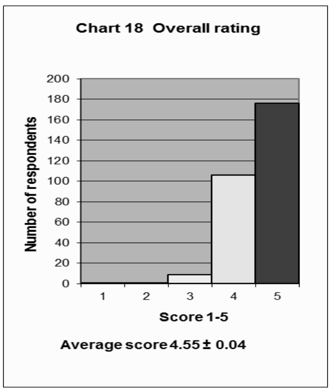




"How would you rate your degree of confidence in the PRT service as a means of travelling between the car park and the Terminal?"

As Chart 17 shows, this question is marked very highly, even though hardly any of the passengers would have had the opportunity to use the service more than once. It will be the case, however, that for almost all the respondents to the questionnaire the service operated smoothly and with little delay, since the reliability of the service since it began public operation has been very high (99.7% of passengers were served without any problem in the system). This marking reflects passenger's pleasure and satisfaction with the PRT service in general, rather than any wider knowledge of the service's reliability.

"How would you rate your overall experience of the PRT service?"



This aspect might be expected to be strongly related to the previous question, and as Chart 18 shows the score is very similar. 96% of passengers scored the system at 5 or 4. Only one passenger marked this at 1, and one passenger at 2, and in both cases they gave the lowest marks to their Terminal 5 station experience: it may be they were particularly frustrated by the temporary lack of signing, and marked most other aspects relatively lowly.

"Would you recommend using this car park to a friend?"

This question was asked for BAA's own purposes, and clearly relates to use of the car park as a whole, but it provides an additional measure of the extent to which PRT might improve the image of the car park. The average score, on a 10-point scale this time, is 8.95±0.10. It is not clear how this might be interpreted in terms of the proportion of users who would definitely recommend the car park in a yes/no answer, but it suggests that the great majority of users are very satisfied with the overall car park arrangements, in a situation where they are paying a premium price (though for most the cost will be paid by employers). Given that the markings shown above are so high for aspects connected with the PRT transport, the very high willingness to recommend the car park must in large part be due to the PRT service.

6 Questions specific to PRT

Now we pass onto the two additional questions which were added to the PRT questionnaire after those questions which had been asked in the Transfer Bus survey. These were located in this way to ensure that they could not bias answers to the questions which were asked of both bus and PRT passengers, where the treatment had to be exactly comparable.

"If you have previously used the Transfer Bus system at Heathrow, how do you rate the PRT system against the bus transfer?"

As we have seen, many of the passengers were regular users of the Terminal 5 business car park, and although for the vast majority the PRT survey occurred on the first occasion when they used PRT, they would be very familiar with the previous transfer bus service.

Passengers were asked to tick one box according to whether they thought the PRT service was better than, worse than, or much the same as the previous transfer bus service. The replies were:

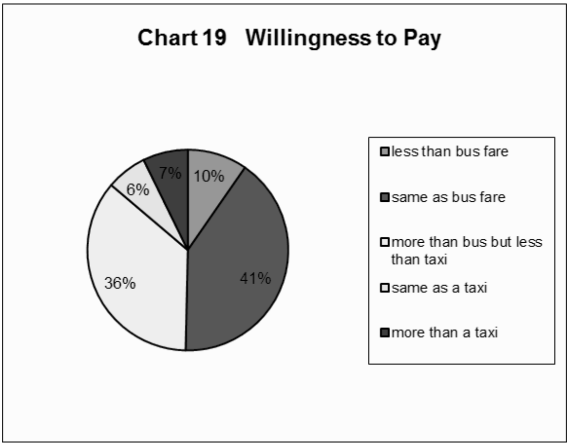
259 passengers thought PRT better than bus
14 passengers thought PRT and bus were "much the same"
0 passengers thought bus was better than PRT

There is an overwhelming vote here for PRT over bus for this local service. But it should be noted that current PRT networks only cover short areas. In the great majority of practical applications links to a bus or other service is required to deliver a full transport capability. In this regard, other studies have shown that such PRT links can increase the use of conventional transport service by 100% or more.

"Suppose a PRT system were available in your home town and could take you from home into the town centre. What is the most you would you be prepared to pay to use it?"

Willingness to pay is an important question in consideration of PRT. It is, however, difficult to obtain an unbiased opinion, and while it was sensible to examine the question at this opportunity interpretation of the answers is subject to obvious caveats. The business car park at Terminal 5 is fairly expensive, as car parks are at most UK airports, but the transfer from the car park to the Terminal is included in the fee and not charged separately. Questions about money may therefore be answered with some reservation, since passengers might consider that their answers could be used in decisions about car park charges and how to charge for transport. On the whole, such fears are likely to reduce the amount passengers say they are willing to pay, rather than increase it.

As Chart 19 shows, the largest number of passengers opted for paying "much the same as the bus fare", though almost as many were willing to pay more than for bus, but less than for taxi. A few enthusiasts were willing to pay as much as, or more than, a taxi fare. Curiously though, 28 passengers said they were not willing to pay as much as a bus fare, despite the fact that no passenger had judged PRT to be worse than bus, and 23 out of the 28 had said that PRT was better than bus. This lack of consistency is presumably due to an unwillingness to give the airport any basis for charging more for the car park, or for the PRT service separately. In reality, there is no intention to charge for the PRT service.



7 Discussion

This is the "After" survey of a two-stage comparison, so it is possible to draw conclusions from a comparison of the PRT passenger survey with an earlier transfer bus passenger survey. Figure 4 summarizes the average scores given to the various aspects for both PRT and from the earlier bus survey. It is clear that the great majority of the passengers surveyed rate the new PRT service remarkably highly. In all aspects concerning the vehicle or the service, the margin by which the PRT scores exceed the bus scores is highly statistically significant.

Looking first at the PRT results, the dissatisfaction with the lack of wayfinding information to the Terminal 5 station at the time is clear to see, and to a lesser extent with the location of the station as a place to wait. Otherwise, every aspect surveyed achieved an average score of 4 or above, and eleven out of the seventeen aspects scored above 4.5. Moreover, the problem with the T5 station signing was soon corrected, but this, and aspects of access at both ends of the PRT system, are not attributes of PRT itself. The twelve aspects which are specific to PRT itself have an average score of 4.57±0.04, compared to 3.23± 0.06 for the bus.

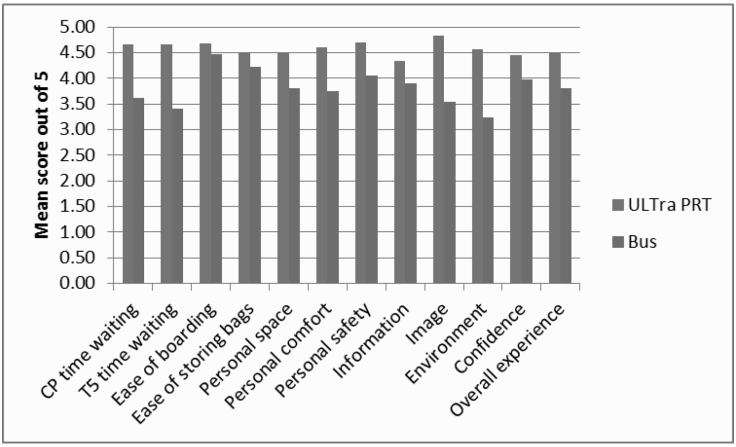


Figure 4: Summary of passenger scores for the twelve aspects specific to PRT

The two additional questions which were specifically aimed at the PRT service showed that the overwhelming majority of passengers thought the PRT service better than the previous transfer bus service (which had been scored as being generally satisfactory), and no-one thought it worse, but only a bare 50% said they were willing to pay more for PRT than for a bus service. This inconsistency between the high regard for the PRT service and a lack of willingness to pay for it is presumably due to an understandable reluctance to give any grounds for increasing the car park charges or charging for PRT separately. Asking people how much they are willing to pay is always contentious, and in the end how much the market is likely to bear depends on the degree to which PRT provides a superior service to its competitors.

Both this survey, and the transfer bus survey, were completed very successfully, and there is no reason to doubt that the scoring faithfully reflects the perceptions of passengers. Indeed the PRT results are virtually identical with a pilot survey carried out a few months before using Terminal 5 staff.

More recent informal results have been obtained by noting the comments provided freely by passengers to their friends using “Twitter”. Although this sample is self–selected, the results are uniformly enthusiastic. Comments include: super cool, fun!, I love these things, best airport transfer devices ever, really impressive.

8 Conclusions

A passenger survey has been completed on the newly operational PRT system at Heathrow airport. The results demonstrate very high levels of passenger satisfaction with PRT for nearly all aspects of the service. Key features were

1) 96% of all passengers rated the service good or excellent
2) Passengers perceived the system to have high safety, a crucial aspect of passenger acceptance for an automatic system
3) The only significant negative response was to station wayfinding at the Terminal end, which was a temporary issue, corrected shortly after the survey.

The results demonstrate that PRT is now ready for serious consideration as part of an integrated transport system.

Acknowledgement

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MIRAGE/TREASURE ISLAND AUTOMATED PEOPLE MOVER: SAFE OPERATIONS FOR 19+ YEARS

J. David Mori, P.E., President[1] and Antonio Garcia[2]

[1]Jakes Associates, Inc., 1940 The Alameda, Suite 200, San Jose, California, 95126, USA. PH: (408) 249-7200; FAX: (408) 249-7296, E-mail: jakes@jakesassociates.com, Website: www.jakesassociates.com

[2]Clark County Department of Development Services, Building Division, 4701 W. Russell Rd., Las Vegas, NV 89118 PH: (702) 455-8091; FAX: (702) 221-0630, E-mail: acg@clarkcountynv.gov

Abstract

The Mirage/Treasure Island (Mirage/TI) Automated People Mover system is a fully automated elevated transit system designed to provide transportation along a single lane, elevated guideway structure. The system operates between Treasure Island Hotel/Casino and the Mirage Hotel/Casino. Having been initially commissioned for passenger service in 1994, the system is beginning its third decade of operational life.

JAI, working on behalf of Clark County as an approved third-party, has been extensively involved with the engineering development, safety monitoring, evaluation, inspection and audit of this system. Due to the efforts, consistent approach, and effective management by the operation and maintenance team, JAI is pleased to report that the system continues to operate within functional compliance with the original approved Clark County and OEM requirements and parameters.

This paper summarizes significant findings, conclusions, and 'lessons learned' through safety audit activities over the last decade. Also included is a discussion of O&M 'best practices' for this and other similar APM systems in Las Vegas developed over the last two decades.

Introduction

The Mirage APM system is based upon the VSL cable drawn technology platform which is offered in the current market by Schwager Davis, Inc. (SDI). Further, it is the fourth commercial installation of such technology, worldwide. The last nineteen (19) years of successful operation have clearly been the result of proactive, proficient maintenance activities combined with close collaboration with key major subsystem suppliers (such as Frey AG Stans for controls and drives). In addition and in collaboration with Clark County, operations and maintenance staff have initiated several procedures beyond those found in the factory manuals designed to further enhance system operations and safety (such as routine monitoring of station gate closing force).

Applicable system standards and codes include (not exhaustive):

- ANSI B77.1
- NFPA 70
- CFR, Title 49
- Clark County ATS Ordinance
- Other

It should be noted that the Mirage APM was engineered and installed (1993) prior to the adoption of ASCE APM and Clark County ATS Ordinance standards. However, several aspects of the ASCE APM standards have been integrated into system operation and maintenance to the greatest extent possible. Figure 1: "Mirage/TI APM Vehicle" shows the Mirage People Mover vehicle. Figure 2: "Mirage/TI APM Guideway" shows the Mirage People Mover guideway support structure. Figure 3: "Mirage/TI APM System Alignment" shows the overall system alignment.

Figure 1. Mirage/TI APM Vehicle.

Figure 2. Mirage/TI APM Guideway.

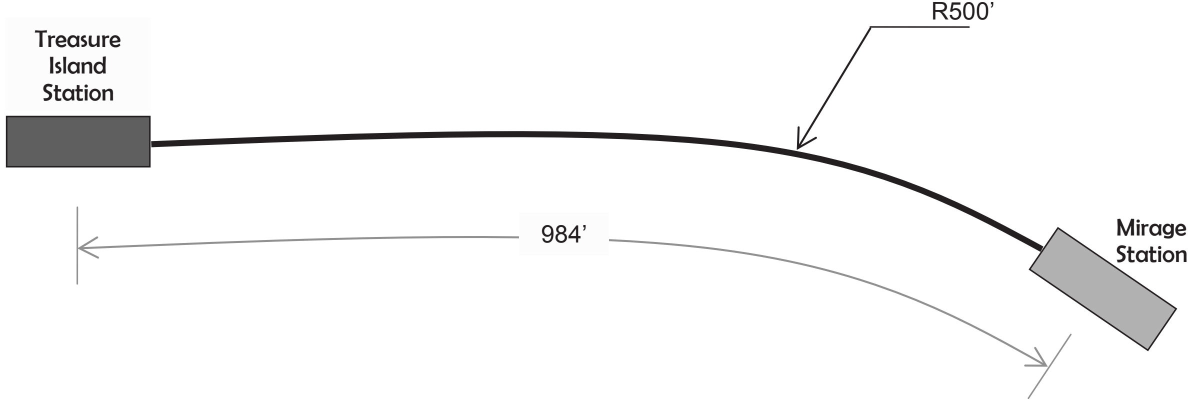


Figure 3. Mirage/TI APM System Alignment.

Customer Experience and Lessons Learned

From the inception of system design, the Mirage/TI APM system has focused upon a design philosophy of simplicity. The vehicle permanent grip system to the cable offers a simplistic design approach requiring no special tools, parts, or fasteners. The drive and bull/return wheel systems are extremely compact and designed for optimum durability. To emphasize this feature, a planetary drive reduction assembly is directly affixed to the common bull wheel drive shaft and driven by common automotive, elastomeric ‘V’-belts. To date, none of these ‘V’-belts have been replaced.

Despite this simplicity, system safety assurances and subsystems are substantially similar to more modern APM systems. For example, overtravel switches rigidly mounted on the guideway insure the vehicles will not overrun a station facility. Simple tachogenerators mounted on the primary driveshaft monitor and provide redundancy for system travel speed. Sensitive edge detectors integrated within vehicle door assemblies allow for door recoil in the event of a doorway blockage. Virtually all maintenance operations can be accomplished quickly.

In terms of lessons learned, several system design features could have been further enhanced. For example, vehicle system load and guidewheel tires were originally specified from the low volume industrial equipment market. Problems have persisted in terms of not being able to secure replacement tires and equipment which quickly became obsolete after the system was originally installed. A more efficient approach originally would have been to design key elements (such as tires) around standard automotive components and sizes thereby insuring a higher likelihood of future spare and replacement parts availability.

Several major subsystems have been either added or upgraded over the last two decades. For example, an innovative and simplistic emergency train retrieval system (as supplied by Leitner-POMA) has been added for emergency train recovery. Powered by the hotel back-up power generator, this unique system provides reliable passenger safety operable by maintenance technicians within minutes. Figure 4: “Mirage/TI APM Emergency Retrieval System” graphically illustrates this unique system.

In addition, Mirage added an enhanced service and emergency braking system (as supplied by Doppelmayr) to the primary drive bull wheel thereby enhancing system operation and safety. The original system became obsolete in terms of securing spare parts and service.

At the time of its original review and commissioning, a Clark County Amusement/Transportation System Ordinance was not yet in place and so certain industry design processes were not performed nor required. Shortly after it was commissioned and in the absence of the now available ASCE 21 APM Standards Parts 2, 3, and 4, the ASTM F-24 amusement industry standards were adopted along with

ASCE APM Standard Part 1 and NFPA 130. Now, ASCE 21 APM Standards Parts 1-4 have been adopted along with a more recent NFPA 130 Standard. All future new system applications for a Clark County Permit will be reviewed under more stringent requirements.

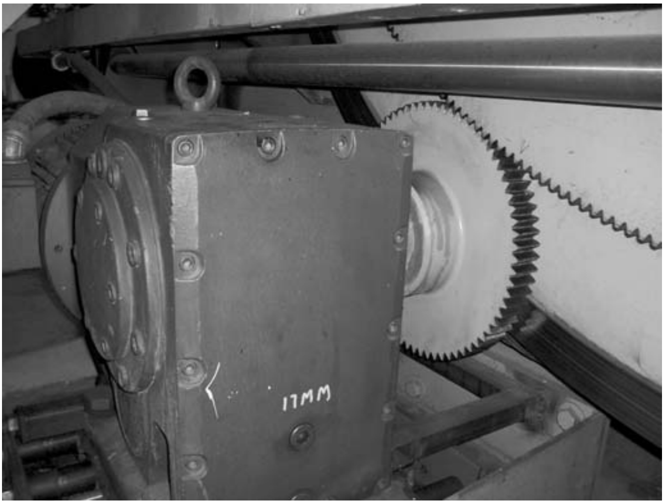


Figure 4. Mirage/TI APM Emergency Retrieval System.

Under the past Clark County ordinance, among many other standard requirements, a ride analysis for the original system, per section 5.1 of ASTM F 2291-05 (Standard for the Design of Amusement Rides and Devices) was not required. The ride-analysis must now include, among other applicable ASTM and Clark County required items, the following:

a. A Patron Containment Analysis.

b. A Clearance Envelope Analysis - Analysis shall include platform-to-cabin, cabin-to-structures, and wheel-to-support structures, building, or loading platform clearances.

c. A System Safety Plan per Mil-STD 882 or equivalent.

d. A Failure Mode and Effects Analysis/Failure Mode and Effects Criticality Analysis (to include Preliminary Hazard and System Hazard lists) or other equivalent.

e. An Emergency Response Plan - Documented listing of the identified safety issues and the means used to mitigate each one.

f. Passenger Evacuation - Per Section 22.16.190 of the ATS Code (added new Paragraph 5.1.1.4 to ASTM 2291-05); the ride analysis shall address passenger evacuation and shall provide an egress platform, stairway, walkway, elevator, scissor lift, ladder or other acceptable means to safely evacuate passengers from all positions during an unscheduled cessation.

Given the above, certain features such as the original emergency retrieval system or emergency guideway evacuation procedures would no longer be acceptable. Additionally, per NFPA 130, the required twice-a-year drills are now strictly required to be performed and documented.

Proactive Operations and Maintenance Is Critical

From the beginning of system operation, the Mirage/TI APM system has set a benchmark for operations and maintenance efficiency. Unlike other APM systems currently in operation in Las Vegas, the Mirage/TI APM has not experienced a period of supplier provided operations and maintenance. In effect per VSL operations and maintenance manual requirements, the Mirage technical staff created and established a maintenance and preventative maintenance philosophy including staff training. The lesson learned was that subsequent operations and maintenance staff had to re-engineer several elements of the system in terms of operations and maintenance to adequately insure satisfactory operation.

The system operations and maintenance team has continued this maintenance philosophy in full cooperation and collaboration with Clark County. Through trial and error (in effect, lessons learned), Mirage has taken system safety and inspection a step further by establishing additional operating logs designed to monitor sheave wear rates, tire inflation pressures and temperatures, and other on a daily or weekly basis. Again keeping with the philosophy of preventative maintenance, these proactive steps have worked to insure further system safety.

Collaborative Relationship with System and Subsystem Suppliers

For newer APM systems, the value of overall system supplier support during the lifecycle of an APM system and its positive impact on safety and operational efficiency cannot be overstated. However, in the case of the Mirage/TI APM system, major *subsupplier* technical support has proven invaluable and available continuously from the beginning of system operation. This has extended from remote communication system support to physical, on-site supplier technician support.

This feature has been clearly demonstrated by Frey AG Stans (the original provider of the drive and control systems for the Mirage/TI APM system). Each year, an experienced Frey AG Stans technician conducts an onsite complete ‘tune-up’ of the entire drive and control systems. All system circuitry (based upon 1993 vintage relay-logic design) and components are fully tested and evaluated. System performance is both qualified and quantified. The efficiency of this service has further been enhanced over the last two decades as the dispatched Frey AG Stans field engineer who conducts the annual 'tune-up' is also the original system design engineer.

Incremental Operations and Maintenance (O&M) Improvements

As stated, the Mirage/TI APM system serves as the fourth commercial installation of the VSL cable drawn technology. Over the last nineteen years, various system design improvements as also integrated into more recent system installations have further both enhanced safety and operational efficiency. New O&M logs have been added to enhance system efficiency and improve overall system safety. Subsupplier support has proven invaluable in overall reliability.

Conclusion

The Mirage/Treasure Island APM system has operated extremely well over the last decades utilizing modest, low technology equipment (by modern standards). Several hardware upgrades have been integrated primarily to further enhance safety performance characteristics of the system. Other major upgrades concerning the operations and maintenance process and record keeping have further made the system safer and more reliable. With continued diligence by the customer, O&M staff, and others, the Mirage/Treasure Island APM system is poised to serve at least another 19 years with safe and reliable operation.

Aerial Transit Link – New York City

Jim Fletcher, P.E.[1] and Mike Deiparine, P.E.[2]

[1]Engineering Specialties Group, 8501 Turnpike Drive, Suite 106, Westminster, CO 80031; Direct (303) 482-3182; Mobile (303) 589-2250; jimf@engineeringspecialtiesgroup.com; F-ASCE.
[2]Engineering Specialties Group, 8501 Turnpike Drive, Suite 106, Westminster, CO 80031; Direct (303) 482-3184; Mobile (303) 589-6761; miked@engineeringspecialtiesgroup.com

ABSTRACT
Beginning 1976 an aerial transit link was constructed to provide service for commuters between Roosevelt Island located in the East River and Manhattan at 60th and 2nd. In 2008 the Roosevelt Island Operating Corporation (RIOC) decided to modernize the system so as to be able to provide continuous automated service seven days per week, 365 days per year. Since this presentation will provide details of the planning, design, procurement, construction and operation of the only true urban, aerial cable transportation system in North America, it will provide both transit design professionals and system operators with how a system of this type can be integrated into the larger scheme of a transit network.

The paper will detail how aerial cable systems can provide continuous service given the unique needs of the operation and maintenance of these types of systems; how to develop a system selection process for urban aerial cable systems; the difficulties of constructing aerial systems in a congested urban environment and over a river; and the costs associated with these types of transit.

Those attending this presentation will better understand how aerial cable systems can provide unique, cost effective transit solutions for communities that exhibit difficult geographical constraints "islanded" in a larger urban setting.

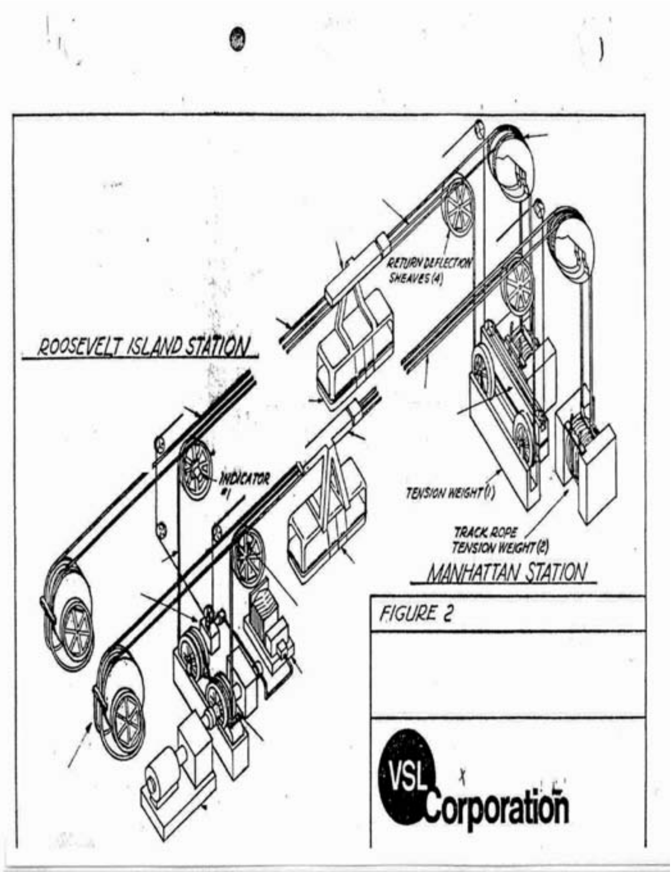
INTRODUCTION AND HISTORY

The New York State Legislature created the Roosevelt Island Operating Corporation (RIOC), a New York State Public Benefit Corporations, in 1984 to take over development and operations of Roosevelt Island. RIOC is the first independent entity to be solely dedicated to the operations and development of Roosevelt Island. The first RIOC Board and President were appointed by the Governor in 1986.

RIOC was preceded by the New York State Urban Development Corporation (UDC), the State entity that turned the City's Welfare Island, as Roosevelt Island was previously known, into one of the only urban "new communities" under the federal "Great Society" programs of the 1960s and early 1970s. Development of this "new" community was authorized by the 99-year ground lease and accompanying General Development Plan (GDP) entered into in 1969, by New York City and New York State.

Figure 1 – Google Earth

The Roosevelt Island Tramway (Tram) was commissioned in 1976. The term Tramway is often used to describe systems of this type even though Ropeway is more universal. The original Tram system equipment was supplied by Von Roll Ltd located in Berne, Switzerland through their American partner VSL Corporation. The Tram installation was a bi-cable system of the double reversible type with two carriers traveling back and forth between terminals on two stationary paths. Each path consisted of two stationary track ropes whereby the carriages supporting the cabins traveled along the path in a controlled motion propelled by a moving haul rope. Each carriage was counter balanced and connected to a concrete counterweight by a counter rope. The counterweight was located at the Manhattan terminal and the haul rope drive machinery was located at the Roosevelt Island terminal. The original system is schematically shown in the following Figure 2.



Both of the Tram carriages were equipped with automatic brakes (track brakes) that acted directly on the track rope to bring the carriers to a full stop in case of a haul or counter rope failure. Each track rope path was tensioned in the Manhattan terminal with a concrete block weighing approximately 296,000 pounds. Each track rope path consisted of two track ropes that were each 45.5 mm in diameter with an actual breaking strength of 504,980 pounds. The haul rope diameter was 41 mm and the counter rope diameter was 36 mm.

Picture 1- Original Tram-Queensboro Bridge (59th Street) Looking West (ESG)

The total length of the Tram is 3,095 feet. Its profile uses three intermediate towers, two on the Manhattan side of the East River and one on the Roosevelt Island side. The largest free span of the Tram is over the East River with a length of 1,189 feet. The Tram's theoretical capacity is 1,500 passengers per hour per direction with a cabin capacity of 125 passengers plus the attendant. The design speed of 1,440 feet per minute provided a travel time of 210 seconds. However, the system generally operated at a reduced speed and with fewer passengers than was theoretically possible.

Before the March 1, 2010 shut down for initiation of the modernization program, the Tram had been in operation for thirty-four years, had carried approximately 40,000,000 passengers in 120 trips per day during the week and 100 trips per day during the weekend for an approximate total of 2,000,000 trips. The short length of the tramway subjected a number of the components to more stress cycles per unit of time as evidenced by the total number of trips.

Picture 2 - Roosevelt Island Station Original Tram-Queensboro Bridge Looking East (ESG)

Over the years, the Tram has been given a number of major inspections and overhauls. Starting in 2005, discussions had taken place as to how to upgrade major sub-systems of the Tram or how to modernize the Tram as a whole. The sub-systems that had been considered for updating or replacement included the carrier comprised of the cabin, the hanger and the carriage; the supporting ropes (track ropes); and the track rope support system at the Manhattan Station. In addition the electronic control system had had two major updates most recently adding a second motor controller in the summer of 2006. Also in the summer of 2006, the auxiliary power system including the hydraulic pumps and controls were replaced.

The Roosevelt Island Operating Corporation (RIOC) approved in 2006 a comprehensive study to determine how to upgrade or modify the tram so as to provide for service during the next 25 years.

PLANNING FOR THE NEW SYSTEM

During the planning for the modernization of the Tram, a major consideration was how to maintain or improve the Tram's availability to the community of Roosevelt Island. Originally the Tram was planned as a temporary solution to increasing the efficiency of movement of island residents between the island and Manhattan. Eventually a subway stop would be provided on the Island. In 1989 when the subway was finally completed, the Tram had become so popular with the local residents that each time consideration was given to removing the Tram, public outcry prevented such from happening. A major consideration in the planning of the modernized tram was how to increase its availability such that major long term shut downs for maintenance did not happen.

Financing Constraints

In the 1990's the Island started to change character from a small community. Several high rise condominium and apartment complexes were developed and became popular since they could provide much more economical living than people experienced in Manhattan. The use of the Tram increased as residents saw it as more comfortable and less intimidating than going some 100 feet into the ground to ride the subway. By 2005 the Tram was transporting approximately 2,000,000 persons annually which were generating a significant positive cash flow after operating expenses when the single ride fare was increased to $2.00 and when the fare was integrated with the New York Transit System automatic ticket checking. Given the above, financing for a new system was limited. In 2006, the State of New York agreed to provide a direct grant of $15,000,000 to RIOC for the modernization of the Tram.

Ridership

In the period from 2006 through 2009, the Tram generally made four trips per hour throughout its operating day, except for high demand times when it made eight trips per hour. This high demand time was Monday through Friday from 7-10 am and 3-8 pm. The tram operated for 20 hours per day from Sunday through Thursday and for an additional 1.5 hours on Friday and Saturday. In a typical week, this schedule equated to 844 trips. Best estimates are that on a typical day the tramway served roughly 4,000 one-way riders. Put another way, the tramway provided a round trip for one out of every six employees or residents on the island.

In 2007 during the planning, no long range tramway ridership study existed and there was little formal data which could be used to make a detailed, comprehensive prediction of future tramway demand. However, some reasonable estimation was made, based on the Island occupancy. With the growth of the residential units of Southtown, RIOC anticipated that the resident count on the island would increase to 15,000. It was somewhat unclear exactly when this would occur, but it was expected to be within the near-term as the remaining five Southtown buildings were completed and occupied (the fourth was completed, but not occupied). This represented roughly a 50% increase in the resident population with the completion and occupancy of Southtown.

In approximate terms, the tramway ridership could be estimated to increase proportionately with either the residency or with the combined residency and employee count. This presented an increase of approximately 35-50% in ridership. Much less quantifiable was the effect on ridership of the additional east side north-south subway line. The opening of the subway line which runs north and south on the east side of Manhattan, near 2nd Avenue will provide easy access to much of Manhattan through a transfer from the Tram. This is expected to increase the ridership of the Tram by some amount.

Based on the planned residential development, the expected impact of convenient access to Upper East Side transit and the general increase in New York population, it is estimated that the Tram will see a near-term increase of approximately 50% in ridership. Since the life of the modernized Tram is on the order of 25 years, it is difficult to estimate what the ultimate ridership may be, but it is undoubtedly much larger than today's. Further it should be expected from the commuter nature of the morning west bound peak times that rush hour demand on the Tram will intensify as the population grows on Roosevelt Island. As the community and population grow, it should also be expected that while the evening east bound demand will intensify, the duration of the evening heavy demand will increase. Whatever the actual ridership numbers may be, the expectation from the commuting public is that the Tram will be highly available and that it will serve them reliably.

<u>Political Issues</u>

In 2005 the RIOC was governed by a nine member Board of Directors (BOD) appointed by the Governor of the State of New York. In addition RIOC has a full slate of full time operating officers. Some of the Board Members were residents of the Island. Often the political makeup of the Board along with resident concerns made the planning of the new Tram difficult, lengthy and convoluted. In April of 2006 when the Tram experienced an operating delay that necessitated the emergency evacuation of both of the cabins between the stations, the BOD begun a detailed planning process for modernization of the Tram. The technical considerations and planning with recommendations were completed by March of 2007, but the procurement process was not completed until November of 2008.

<u>Technical Considerations</u>

The Tram due to updating of Codes and Standards presented some issues. The Tram is regulated by the Tramway Division, Department of Labor, State of New York. The applicable standard is Code Rule 38 of the State of New York which is based on the American National Standard Institute (ANSI) B77.1 for Passenger Ropeways, Safety Requirements. The deficient areas are listed below:

1. The vertical clearance over 2nd Avenue in Manhattan
2. Carrier swing clearance at the towers
3. Track cable deropement supervision
4. Terminal hauling rope sheave retention
5. Tower fall protection
6. Haul rope and track rope entanglement
7. Carrier fatigue and inspection
8. Track Cable brake design

In addition to these specific Code Rule 38 deficiencies, there were several significant, costly maintenance issues that would need to be addressed in the near term.

Track Ropes

The existing track ropes for the Tram were scheduled for routine slipping in 2009. Slipping is a necessary maintenance process where the track ropes are moved to relocate areas of the rope which experience high fatigue stresses. The amount of rope remaining on the storage bollards was not adequate to slip all four of the track ropes. Accordingly, rather than slipping the ropes, they needed to be replaced by 2009.

Track Rope Roller Chains (Track Rope Supporting Structure in Manhattan)

In addition to the track ropes, their supporting roller chains at the Manhattan Terminal were experiencing high wear and were a significant maintenance item.

Hanger (Device connection the Cabin to Carriage Rollers)

The cabin hangers were the original equipment supplied with the Tram with over 30 years of service. Because of their age and the dynamic nature of their loading, their remaining life was a concern. Studies found that certain portions of the hanger could not be inspected for fatigue.

Cabins

Like the hangers, the cabins had served the tramway since its commissioning over 30 years ago. Their fatigue life was also unknown, and there was no program in place to determine and monitor their condition. In addition there had been some observed corrosion in the cabin support structure.

Gearbox

The existing gearbox was a custom part with no known model or standard parts. Design drawings and detailed specification on the gearbox were not available. Based on anecdotal information and the physical size of the gearbox elements it was believed that the gearbox had been provided with a high service factor. Maintenance personnel had not seen any indications of gear cracking, shaving, fatigue or other modes of failure. While there was no indication of an impending gearbox failure, one would create a significant Tram outage. While no real estimate of time could be made, it was reasonable to expect that a failure of the gearbox could result in a Tram service interruption of several months. As a result, the gearbox presented a significant concern for a modernization program designed to provide another 25 years or more of highly reliable Tram service.

Rescue System

As was evident on April 18, 2006, the current arrangement for evacuation of cabins was tedious. If it became necessary to remove passengers from the cabin with the rescue system, the maintenance personnel must first mobilize the rescue cabins. This required that the rescue cabin be hoisted to the track ropes, attached to the separate rescue haul rope and adjusted for height. Under good conditions and with adequate personnel approximately 3 hours were required to mobilize the rescue system. After the rescue cabins were mobilized, the passengers could be returned to the station in groups of 10-15 every half hour to an hour. Unless evacuation was possible by other means (such as ground-based operations) this process must be repeated for each primary cabin as the rescue system cannot be used on both cabins simultaneously. While this process provided a reasonably safe means for returning passengers to the terminals, it required a great deal of time and effort under the best of conditions.

Alternatives for Modernization

Replace Critical Subsystems

The preeminent alternative for any alternatives analysis is to do nothing. In the case of the Roosevelt Island Tramway, doing nothing was not a legitimate option. However, the spirit of this alternative was to make the minimal changes, perform preventative and corrective maintenance, but to make no dramatic changes to the existing design. For the Tram this required the replacement of the track ropes, replacement of the cabin hangers, replacement of the cabins and replacement of the track rope roller chains. The rescue system was to remain.

This was the lowest cost alternative and it was the baseline alternative. Assuming that the replacement components could be timed so that they are all available on site at once, it was estimated that the system would be out of operation for approximately 8 weeks. This alternative did not provide a high level of confidence for an additional 25 years of service. Including facility and system costs, the estimated cost of this alternative was $4.9 million.

Replace Existing with Similar Systems

The next alternative was to replace the system as it existed with approximately the same arrangement, but with current accepted technologies. This alternative essentially called for installing a new tramway but reusing the existing facilities. The existing motors and drives would be replaced with new AC components. A new gearbox and drive train would likely be installed. The rescue tram would be modified or replaced to facilitate its mobilization and operation, but the general premise of a separate rescue tramway would remain.

The profile of the existing system would change very little, if at all. Because of the horizontal clearance issues, this system would likely need to be built with a track rope brake. This alternative could be reasonably expected to provide another 25 years of service, or more. It was expected that the system would be inoperable for approximately 6 months. It was estimated that this alternative would cost $12.4 million including both system and facility costs.

Rebuild with Major Redundant Components

This alternative is one step beyond the previous alternative. It amounts to installing a new but similar tramway, doing so with accepted technologies and designing additional redundancy into the system. The additional redundancy would be designed to provide a high level of availability and to provide a modern integrated rescue approach. The additional redundancy would be achieved by installing multiple elements such two gearboxes, two AC drives and two AC motors in a way that they could be readily put into service.

Like the previous alternative, the system profile would not change appreciably. Because of horizontal clearances, this alternative would require a track rope brake. The machinery room would change to provide additional redundant components. The towers and terminal structures would need only minor modifications with the exception of the facility upgrades intended to extend their lives.

This alternative could reasonably be expected to provide another 25 years, or more, of service. It was expected that the system would be out of operation for approximately 7 months. This alternative was expected to cost $15.0 million including both system and facility costs.

Dual Shuttle System

The most complete of the alternatives considered was that of replacing the tramway system with a Dual Shuttle system. Fundamentally this means having two tramways side by side, which operate independently from each other except that they share towers, terminals and operations personnel. This arrangement allows the greatest flexibility in operations and maintenance scheduling. One system may be shut down for maintenance while the other system continues to operate and serve passengers.

This would eliminate the need for maintenance shutdowns which can be quite inconvenient for regular tramway passengers. It would also allow for nearly uninterrupted, 24-hour service since routine maintenance could be performed on alternating systems on alternating dates. For example, routine maintenance could be performed during off-peak hours on System 1 on Mondays, Wednesdays and Fridays while System 2 served passengers for those times. Then on Sundays, Tuesdays and Thursdays the same routine maintenance could be performed on System 2 during off-peak hours while System 1 satisfies passenger demand during those times.

Since the Dual Shuttle system would require that additional elements be in service, another challenge of the Dual Shuttle solution was that the space requirements were larger than those for the existing system. As this turned out to be the selected, this constraint was overcome within the exterior configuration of the existing stations.

A Dual Shuttle System was expected to be the highest cost alternative. Such a replacement could reasonably be expected to provide at least another 25 years of service and at the highest availability level of the alternatives evaluated. It was estimated that the system would be out of operation for approximately 7 months. The estimated cost of this alternative was $17.7 million in system and facility costs.

Preferred Alternative

Based on the expected increase in demand and on the increasing expectations of high availability, it was recommended that RIOC pursue a course of replacing the existing tramway with a Dual Shuttle System. This arrangement offered the greatest long term access to the tramway. In addition to the Dual Shuttle System, it was recommended to use a system which included an integrated rescue design philosophy, excluded a track rope brake and eliminated the track rope counterweight.

Summary

The following Table provides a summary of the planning process.

Alternative and Description	Probable Cost	Estimated Outage
Replace Critical Subsystems – Replace those items that must be replaced to continue operations, specifically track ropes, track rope roller chains, hangers and cabins. Additional major maintenance items should be expected, with additional system down time and additional cost, which cannot reasonably be estimated.	$4.9 million	8 weeks

Replace with Similar System – Fundamentally, replace the system with current technology. In addition to the track ropes and roller chains, some of the major subsystems to be replaced would be motors, drives, gearbox, cabins and hangers.	$12.4 million	6 months
Rebuild with Major Redundant Components – This alternative is similar to the previous alternative with the addition of service ready backup elements such as a gearbox, motor and drive.	$15.0 million	7 months
Dual Shuttle System – This alternative amounts to installing two adjacent tramways which run parallel, operate independently but share towers, terminals and operations personnel. It offers the greatest flexibility and the best prospect for a high level of service for many years into the future.	$17.7 million	7 months

DESIGN CONSTRAINTS

In modernizing the Tram there were three primary design constraints that occurred because of budget limitations. They were:

Alignment

The alignment was significantly constrained by the fact it penetrated a very dense urban landscape as shown in Picture 3. The system approximately paralleled the Queensboro Bridge also known as the 59th Street Bridge. In Picture 3 two of the three towers are visible with the third tower located on the Island near the Roosevelt Island station as previously shown in Picture 2.

Picture 3 – Manhattan Station 2nd Avenue & 60th Street Looking East (ESG)

The longest span approximately 1200 feet traverses the West channel of the East River. The modernized tram had to consider clearances for a future high rise building located at 60th Street and York.

Existing Infrastructure

The financial feasibility of the entire modernization program based on a dual shuttle system required that the stations and towers be reused in their original locations with minor modifications. The original design of the infrastructure was completed by Lev Zetlin Associates, Inc.

Towers

The towers as originally designed utilized ASTM A588 COR-TEN® B a weathering steel. Since rolled shapes could not be obtained the members were built-up W sections with full penetration connections between the flanges and the webs. End connections were bolted. The typical fabrication is shown in Picture 4. When the towers were analyzed only minor modifications were required to the existing members for the addition loadings considering fatigue. To accommodate the new mechanical equipment at the top of the tower significant additions were made to the tower head as shown in Picture 5. The new tower head was more extensive to accommodate two independant systems.

Picture 4 – Original Tower (ESG)

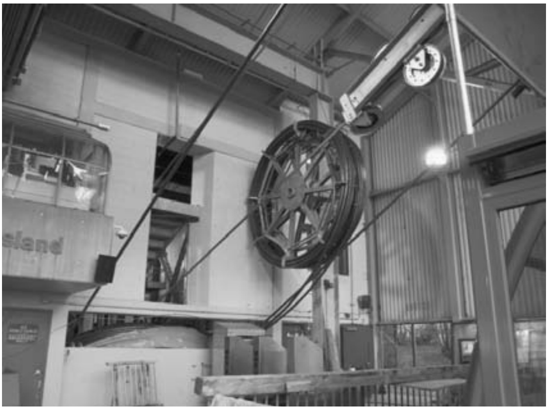
Picture 5 – New Tower (ESG)

The foundations consisted of a concrete cap encapsulating a single cassion drilled into bedrock with anchor bolts connecting the tower to cap. The foundations were also determined to be adequate for the new loadings.

Stations

Roosevelt Island

The Roosevelt Island Station as shown in Picture 2 was originally designed and constructed as a structural steel frame with moment resisting braced frames resting on a concrete box foundation. The condition assessment report detailed a number of corrosion and deterioration issues that were not critical to modernization of the Tram, but would need to be addressed in the near term to maintain the integrity of the structural system. The concrete shear walls that form the basement of the original tram that housed the power motive equipment were utilized for the modernized tram. Electrical room enclosures, a concrete machine room deck and concrete anchorages were added all of which provide additional lateral support. See Picture 6 for the new machine room.



Picture 6 – New Machine Room Enclosure (ESG)

Manhattan

The Manhattan Station had originally been designed to have a multi-story complex above, therefore load carrying capacity of the primary structural system including the pit containing the tensioning concrete blocks for the ropes proved to be sufficient for the modernized system. This station is located at the intersection of 2nd Avenue and 60 Street is as shown in Picture 7.

Picture 7 - Manhattan Station Looking Southwest (ESG)

The condition assessment report indicated that concrete deterioration would need to be repaired by sandblasting and filling cracks with epoxy. The structural steel roof support structure would need to be sandblasted and painted.

The estimate of probable cost for rehabilitation of the infrastructure not including architectural upgrades and enhancements was $900,000 in 2007.

PROCUREMENT PROCESS

Due to consolidation in the ropeway manufacturing business over the last 30 years, there were only two companies that had the capability to supply the new systems. Therefore the procurement process had to consider this limited capability and needed to be flexible in order to accommodate both of the manufacturers. The two companies were Doppelmayr/Garaventa Group with headquarters in Wolfurt, Austria which has production facilities and sales and service locations in over 33 countries of the world and to date has built more than 14,300 installations in over 87 countries; and the Leitner Group with headquarters in Sterzing, Italy whose history goes back to the late 1800's and has over 70 sales, service and production facilities worldwide.

Preliminary meetings took place with the suppliers in late 2007 for the purpose of providing them with the overall plan for the modernization of the tramway and to discuss significant issues and constraints. Emphasis was placed on minimizing the actual downtime for the Tram during construction and the importance of accommodating the existing infrastructure. Difficulties of constructing in the dense urban environment surrounding the Tram were detailed.

Preliminary drafts of the procurement documents were circulated to both companies in early 2008 and comments were received and considered in the development of the final documents.

Formal requests for proposals were issued on June 25, 2008. The request was for a design, build, operate and maintain (DBOM) proposal by September 2, 2008. The design-build agreement (DB) called for completion of the work with the modernized tram being placed into passenger service by January 31, 2010. The operations-maintenance (O&M) agreement was for five years after completion of the DB work.

The DB contract was awarded to Pomagalski, S.A. (POMA), a Leitner Group member located in Grenoble, France. The O&M contract was awarded to Leitner Poma of American located in Grand Junction, Colorado. The DB contract was executed on November, 25, 2008 and stipulated that the Tram out-of-service date would begin on July 6, 2009 and not exceed 186 days with substantial completion on January 8, 2010. The total DB price was $15.9 million including all infrastructure modifications with the exception of architectural upgrades. The O&M contract totaled $17 million for 5 years approximately $3.4 million per year.

CONSTRUCTION HIGHLIGHTS

Due to delays in design, construction planning and permitting, the out-of-service period did not begin until March 1, 2010 almost eight months later than anticipated. The modernized tram was commissioned and accepted tested in October and November of 2010 and was placed into passenger service in early December 1, 2010. Thus the tram was out-of-service for a total of 275 days which exceeded the original plan of 186 days.

Permitting and acceptance was handled by two separate governmental entities. For the system equipment the New York State Department of Labor (NYDOL) was the authority and for the existing building infrastructure modifications up to the primary electrical disconnect, the New York City Department of Buildings was the authority. The DB contract was managed by Liro Engineers of New York City working for RIOC. RIOC's engineer was the staff of the Engineering Specialties Group (ESG) of Westminster, Colorado.

POMA employed subcontractors for the design of building and tower modifications; for erection of the new tower heads; for the construction building modifications and for the installation of power distribution systems. The cabins as shown in Picture 8 were designed and supplied by Sigma a POMA subsidiary.

Picture 8 – Independent Operation (ESG)

The construction schedule was constrained primarily by the installation of the new tower heads for the towers located in Manhattan. This was due to the fact that New York Department of Transportation would only allow street closures for limited hours during weekend nights. Construction at the top of the towers was protected as shown in Picture 9.

Picture 9 – Tower Top Construction Protection (ESG)

Construction access and staging was extremely limited for the Manhattan station because of an adjacent park and the amount of traffic that was experienced at this intersection as shown in Picture 10.

Picture 10 – Manhattan Station Looking West (ESG)

Staging had to be done within the footprint of the station and material deliveries were off loaded to the North of the station on 60th Street. Installation of the ropes or cables also presented the construction team with challenges due to the environment. As shown in Pictures 11 and 12 the number of ropes, the amount of tension required to keep them high enough and the problems with going over a major river and street complex provided unique installations for the rope specialists.

Picture 11 – Rope Rigging (ESG)

At the top of the towers in the final configuration there are four supporting track ropes each of which is 56 mm in diameter with three layers of full lock coil construction.

In addition there are four hauling or towing ropes with two pairs each forming a vertical loop between stations. These hauling ropes are 48 mm in diameter with a 6 strand by 36 galvanized wire constructions with the strands support by internal solid plastic core. Additional rigging ropes are required to facilitate installation of the final ropes.

Picture 12 – Rope Installation Detail (ESG)

OPERATIONS

Operation for passenger service for the modernized tram began on December 1, 2010 even though substantial completion had not been provided by RIOC. Prior to operations all operating permits had been granted by the NYDOL after a successful acceptance program. The operating schedule is as shown in following:

Monday - Thursday

06:00 to 10:00 Dual Track Scheduled 10 min intervals per track
10:00 to 14:00 Single Track Scheduled 15 min intervals
14:00 to 20:00 Dual Track Scheduled 10 min intervals per track
20:00 to 02:00 Single Track Demand
02:00 to 06:00 System down for Maintenance

Friday

06:00 to 10:00 Dual Track Scheduled 10 min intervals per track
10:00 to 14:00 Single Track Scheduled 15 min intervals
14:00 to 20:00 Dual Track Scheduled 10 min intervals per track
20:00 to 03:30 Single Track Demand
03:30 to 06:00 System down for Maintenance

Saturday

06:00 to 20:00 Single Track Scheduled 15 min intervals
20:00 to 03:30 Single Track Demand
03:30 to 06:00 System down for Maintenance

Sunday

06:00 to 20:00 Single Track Scheduled 15 min intervals
20:00 to 02:00 Single Track Demand
02:00 to 06:00 System down for Maintenance


Picture 13 – Cabin Approaching the Island Station (ESG)

The Island patrons after not having the tram for more than nine months while relying on the subway and bus connections to Manhattan fully accepted the modernized tram and ridership returned to its pre-construction norm of approximately 167,000 passengers per month. For the operating year of 2011 the patronage totaled 2, 100,000.

The O&M Agreement required that the Tram system meet or exceed the following cumulative 3 month performance requirements:

Service Reliability (MTBFs) 44 hours minimum

Service Maintainability (MTTRs) 0.333 hours maximum

Service Availability (As) 0.9925

All performance definitions listed above are based on the ASCE Standards for Automated People Movers. The Tram has met or exceeded these performance requirements since it was placed into service.

BENEFITS AND LIMITATIONS

The obvious benefit of the Tram system is that it provides an economical transportation solution in a constrain environment with minimal impacts per passenger transported. Currently in 2012 the monthly transport of passengers is averaging 200,000 per month. The net revenue per passenger is $2.00 for a total annual operating revenue of $4,800,000. The O&M contact annual cost is $3,400,000 thus returning $1,400,000 or 7% return on investment in the modernization program based on total project cost of $20,000,000 including project management and engineering.

The Tram has had a high availability and will continue to have such due to design redundancies including backup generators. History has shown that the Tram is the most likely system to be operating during any environmental condition that is experienced in New York.

Based on a comparative analysis for different modes of transportation (Fletcher 2011), it has been shown that ropeway offer superior safety history when compared to other means of transit as shown in Tables 1 and 2.

Table 1 – Fatality Rate per Million Passengers

	FATALITIES	PASS (x10E6)	RATE	PERIOD
Ropeways	21	18,196	0.001154	1960-2010
Airlines	3277	19,180	0.170100	1960-2010
Transit	5681	176,400	0.032210	1990-2010

Table 2 – Fatality Rate per 100 Million Passenger Miles

	FATALITIES	PASS MI (x10E8)	RATE	PERIOD
Ropeways	21	127.4	0.1648	1960-2010
Airlines	1482	107,170	0.0138	1991-2010
Transit	5681	8,308	0.6840	1990-2010

The primary limitation is the fact that is system is capacity limited to 1500 passenger per hour per direction. Given utilization rates based on peak and non peak hours, it is estimated that the system would be limited to less than 360,000 passengers per month which is an increase above the current monthly rate (200,000) of 80%. Based on projected development from Cornell's new campus on the Island there is potential to see a significant increase in ridership, but it may be such that the overall efficiency of the system can be increased by leveling the peak demands.

Picture 14 – Roosevelt Island Offers Attractive Development (ESG)

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APM History in Canada

William J. Sproule[1]

[1] Professor, Michigan Technological University, Department of Civil and Environmental Engineering, Houghton, Michigan, USA; 906-487-2568; wsproule@mtu.edu

ABSTRACT

In 1971, the Premier of Ontario, William Davis stated that "cities were built for people and not cars" as he announced that the Toronto Spadina Expressway plan would be stopped and that the government would help develop new mass transit systems. During the following year plans were announced for new transit networks, known as *GO-Urban*, in Toronto, Hamilton, and Ottawa in which intermediate capacity AGT systems were to be used. Several systems were evaluated, one was selected, and plans were put in place to build a test track in Toronto. A government crown corporation, the Urban Transportation Development Corporation (UDTC), would lead this undertaking. Although the GO-Urban project was abandoned, UDTC AGT systems were build in Scarborough (a Toronto suburb), Vancouver (the SkyTrain), and downtown Detroit (DPM) in the 1980s. In the late 1980s, the UDTC was sold to Lavalin and then in the early 1990s, the company was bought by Bombardier to be part of their transportation division. Through several acquisitions, the transportation division has since become one of the largest suppliers of rail equipment in the world.

This paper traces the history and development of APMs in Canada and includes descriptions of the Scarborough RT (Rapid Transit) and Vancouver SkyTrain, as well as systems at the Toronto Zoo, the Toronto International Airport, Expo'67 (Montreal), and Expo'86 (Vancouver), and people mover studies in Niagara Falls.

A CHANGE IN TRANSPORTATION IN ONTARIO

In the 1950s, Toronto was experiencing growth in its suburbs like many cities in the United States. Suburbs grew along existing highway corridors as the metropolitan area expanded east and west, and then northward along the provincial freeway network. In order to plan for this urban sprawl phenomenon, an extensive network of freeways was identified in the city's long range transportation plan in 1959. As construction of this network started, the mood of citizens changed and by the mid-1960s there was a growing awareness of the impacts of urban freeways on the development of our city cores in the United States and Canada as people fled to the suburbs and they commuted to the downtowns on new freeways. Eventually downtown businesses began to move to the suburbs and abandon downtowns. One of the controversial freeway corridors in Toronto ran through a densely settled neighborhood north the

University of Toronto. While the opposition to this project was growing, planner Jane Jacobs moved to Toronto after having successfully rallied groups to cancel the construction of the Lower Manhattan Expressway in New York City. Applying the same formula in Toronto, Jacobs helped local groups in a campaign to oppose the Spadina Expressway project.

In 1971, Ontario Premier William Davis announced that he was cancelling provincial funding and support for the Spadina Expressway. He said that "Cities were built for people and not cars. If we are building a transportation system to serve the automobile, the Spadina Expressway would be a good place to start. But if we are building a transportation system to serve people, the Spadina Expressway is a good place to stop." The Toronto freeway plan was dead and construction of the Spadina Expressway ended shortly after and other planned freeways were never built. Instead of freeways, Davis and his government outlined the *GO-Urban* plan which called for the development of networks using advanced transit systems in Toronto, Hamilton, and Ottawa. The idea was to select a system with low capital costs that would be cost effective in low-density areas where traditional heavy rail rapid transit systems would be too expensive to build and operate. Designed to have a capacity between buses and heavy rail systems, the new system was referred to as an "Intermediate Capacity Transit System (ICTS)". Automated guideway transit systems (AGT) that were being developed and promoted in the United States in the late 1960s seemed to be the right solution.

Practically every company working on an AGT or developing an AGT concept at that time submitted a proposal. The first review reduced the list to fourteen designs and then it was further reduced to eight formal proposals. Some were PRT systems, while others were more traditional rapid transit systems. Three of the eight ran on rubber wheels, four were air cushion vehicles, and one used magnetically levitated vehicles. After a year-long selection process, the German Krauss-Maffei Transurban magnetically levitated system with linear induction motors was announced as the preferred system in May 1973. Krauss-Maffei agreed to do all vehicle construction and testing in Ontario, and plans were announced to build a test-track on the grounds on the Canadian National Exhibition (CNE) in Toronto. A newly-created crown corporation, Ontario Transportation Development Corporation (OTDC) would oversee testing, construction, and North American sales. A crown corporation is a company in which the government is the primary shareholder. A photograph of the Krauss-Maffei Transurban vehicle is shown in Figure 1.

A NEW DIRECTION

In late 1974, Krauss-Maffei announce that they were forced to withdraw from the project as development funding from the German government had been eliminated and some technical problems related to switching trains would require extensive redesign. Ontario was not willing to assume the Krauss-Maffei development funding but instead decided to develop a new system. In 1975, the OTDC announced a consortium of companies to continue the development of ICTS.

Figure 1 – Krauss-Maffei Transurban vehicle *(Government of Ontario)*

The company name was changed to the "Urban Transportation Development Corporation" (UTDC) and a dedicated test facility was built in Millhaven, near Kingston, Ontario. The Transit Development Centre included a 1.9 km (6000 feet) oval test track with at-grade, elevated and ramped sections, and an automatic control center. During the next three years, several prototype vehicles were developed and tested.

Looking for a site to demonstrate the system, the government focused on an extension of the Toronto Transit Commission's (TTC) Bloor-Danforth subway line. The TTC was planning to build a streetcar line that would extend from the Kennedy station to the Scarborough City Centre, a low density route passing through an industrial area. Construction had already begun when the provincial government asked them to switch to the new ICTS. The TTC was reluctant but the government threatened to withdraw funding for the project. An agreement was reached and the Scarborough RT project proceeded with the ICTS. Studies were also undertaken in Hamilton and Ottawa, and then Vancouver expressed an interest in the system.

As early as 1978 the city had been planning a transportation themed show for its 1986 centennial, and in 1980 they won the rights to host a world's fair titled "Expo'86". Vancouver was more spread out than Toronto so the traditional heavy rail rapid transit system was not cost effective and an intermediate capacity transit system seemed like an ideal solution. The UTDC was interested in showcasing their ICTS and Expo'86 and Vancouver planners supported a solution that could be open in time for the exposition. A deal was quickly arranged that would be attractive for all with funding from provincial and federal governments. The system would be called "SkyTrain" and it would serve the Vancouver area and the Expo'86 site.

Following a review of automated guideway transit in the United States in the mid 1970s, the US DOT Urban Mass Transportation Administration (UMTA) announced the Downtown People Mover (DPM) program and several cities submitted proposals.

In 1981 as the Reagan administration came into office, the federal government decided to reduce its role in research, development, and support of AGT systems, however three committed DPM projects continued and were completed in Miami (Metromover, 1986), Detroit (Detroit People Mover, 1987), and Jacksonville (Automated Skyway Express, 1989). During the selection process for the Detroit DPM, the UTDC responded to a “Buy America” provision and opened a Detroit office with the result that they were judged as the preferred system.

Construction was underway on three UTDC projects – Scarborough (Toronto), Vancouver, and Detroit. The Scarborough RT opened in March 1985, the Vancouver SkyTrain opened in December 1985, and service began on the Detroit People Mover in July 1987.

ANOTHER NEW DIRECTION

In the early 1970s, the OTDC as part of their mandate to develop new transit systems took over some initial work by the Toronto Transit Commission (TTC) and Hawker Siddeley Canada, a rail equipment manufacturer, to develop a new streetcar (Canadian Light Rail Vehicle - CLRV) using a Swiss design. The TTC placed an order with the OTDC for 200 new vehicles who in turn subcontracted with Hawker Siddeley Canada. Hawker Siddeley was also manufacturing commuter rail and heavy rail passenger cars. A few years later, an Articulated Light Rail Vehicle (ALRV) was also developed. In the early 1980s, Hawker Siddeley Canada sold a portion of their rail equipment manufacturing division to UDTC to create a new company, Can-Car Rail, and as a result, in addition to ICTS, the UDTC now had a portfolio that included a wide range of transit equipment products.

The sales of new ICTS systems did not materialize, and the government began to worry about the continued success of the UTDC. The formation of the Can-Car Rail was promising but concerns of a government rail equipment manufacturing company were troubling. In 1986, the Ontario government sold UTDC to Lavalin, a large Montreal based engineering company, but following a period of investments unrelated to their core engineering business, Lavalin’s bankers pressured them to sell to its chief rival, SNC. Lavalin announced its intent to sell its stake in UDTC and several companies expressed an interest but before a transaction was completed the company went bankrupt. As part of the bankruptcy, UDTC was returned to the Ontario government who quickly sold it to Bombardier in 1991. Bombardier was a Canadian company who got its start as a snowmobile manufacturer and entered the transit equipment business when they were successful in a bid to build vehicles for the Montreal Metro transit system. SNC purchased the engineering parts of the company and became SNC-Lavalin while other parts of the business were sold to other firms.

Bombardier rebranded UDTC products under their growing Bombardier Transportation name and became more aggressive in marketing the product line. In 2001 Bombardier acquired ADtranz, a successor of the Westinghouse Transportation Systems Division, and other companies and with continued growth Bombardier has become one of the world’s largest suppliers of rail equipment. The original ICTS vehicles were redesigned with more seating, greater capacity, and an updated look, and were introduced as "Advanced Rapid Transit (ART)". The Bombardier ART system was selected for the New York Kennedy Airport Air Train project, new lines on the Vancouver SkyTrain network, and several other new systems throughout the world. Many of these systems have been described in papers and presentations at this and other APM and transit conferences. A photograph of a Bombardier ART vehicle at a Vancouver SkyTrain station is shown in Figure 2.

Figure 2 – Bombardier Advanced Rapid Transit (ART) vehicle at a Vancouver SkyTrain Station (*Bombardier Transportation*)

APM SYSTEMS IN CANADA

Although much of the focus on APMs in Canada was the work lead by the Ontario government there have been several other developments. The following is a brief description of APM systems in Canada. Three systems were built and dismantled, three systems were built and are still in operation, and an AGT system for Niagara Falls has been the subject of extensive planning studies but it has not been built. Figure 3 shows photographs of vehicles on the six systems.

(a) Expo'67 Minirail *(photo by author)*
(operating in front of USA Pavilion)

(b) Toronto Zoo Domain Ride
(Metropolitan Toronto Zoo)

(c) Scarborough RT *(UDTC)*

(d) Original Vancouver SkyTrain *(UDTC)*

(d) Expo'86 Monorail
(photo by author)

(f) Toronto (Pearson) International Airport
LINK Train *(DCC Doppelmayr)*

Figure 3 – APM Systems in Canada

Expo'67

Expo'67 was the world's fair that was held in Montreal from April to October 1967. It was Canada's main celebration during its centennial year in which over 62 nations and numerous companies participated with the theme "Man and His World /Terre des

Hommes". A geodesic dome designed by Buckminster Fuller was the U.S. pavilion and was one of feature buildings on the site. Several sites were considered in the planning of the fair but a site in the St. Lawrence River was selected that involved creating new islands and enlarging Ile Sainte-Helene. A site specific transit system, known as the Montreal Expo Express, was built with a connection to the Montreal Metro subway system. An automated minirail system, developed by a small family owned Swiss firm Habegger Limited, was built on the site and operated through several buildings. There were actually three routes and the largest was a 6.8 km (4.2 mile) loop with four stations (Blue Line). After Expo'67 closed, the system continued to operate for the Man and his World exposition until 1971.

Toronto Zoo

In 1976 an automated guideway system (AGT), known as the Toronto Zoo Domain Ride, began operating between domains or sections of the new Toronto Zoo in Scarborough, Ontario (northeast Toronto). In addition to being a quick way to travel between sections of the zoo, the ride provided the only way to view several animals that were not accessible to visitors on walking paths. The system had three stations and was 5.6 kilometers (3.5 miles) in length. It was developed by Bendix-Dashaveyor with rubber tired vehicles operating on an elevated concrete guideway in which trains operated clockwise on a one-way loop alignment. Although it had capabilities for full automation, on-board drivers would provide commentary and identify animals to passengers during a ride. Despite the popularity of the system, funding for its maintenance and repair was limited and the system was allowed to deteriorate. In 1991, nine people were injured when a train crashed into a second train that had stopped between stations and then in 1994, another crash occurred on the system and 27 passengers were injured. The system was shutdown and following an investigation and studies to determine the costs to rehabilitate the system it was judged too expensive. Over the next few years the system was scrapped and portions of the elevated guideway were removed.

Scarborough RT

The Scarborough RT (Toronto) opened in 1985 using the intermediate capacity transit system (ICTS) developed by the Urban Transportation Development Corporation (UTDC). The line has six stations and it is 7.0 km (4.3 miles) in length and is operated by the Toronto Transit Commission as part of their network. Passengers must transfer from the Bloor-Danforth subway line at the Kennedy Station to the RT (meaning "Rapid Transit") to continue travel to the Scarborough Town Centre and the McCowan Station. The vehicles are driven by linear induction motors with steel-wheels on steel tracks and can be fully automated, however due to union opposition and public perception, operators are used. In practice the trains drive themselves and the operator monitors their operations and controls the doors. The fleet is aging and several studies have been undertaken for acquiring new vehicles and retrofitting the line. Several proposals ranging from extending the existing line with new RT equipment to conversion and rebuilding of the line to use light rail transit vehicles are being evaluated.

Vancouver SkyTrain

Construction of the Vancouver SkyTrain began in 1982 and revenue service started in late 1985 in time for Expo'86. The SkyTrain uses the ICTS technology developed by the UTDC with full automation and linear induction motors. The original line had 20 stations and connected downtown Vancouver (Waterfront Station) with Surrey, a length of 28.9 km (17.3 miles). Trains operate on exclusive tracks and mostly on elevated guideways which provide spectacular views of the city. The system has been extended and today there are 47 stations on three lines for a total length of 68.7 km (42.7 miles). The original line (now known as the Expo Line) and the Millennium Line are operated by the British Columbia Rapid Transit Company under contract from TransLink (originally BC Transit), a regional government transportation agency. The Millennium Line serves North Burnaby and East Vancouver. The Canada Line was built as a public-private partnership by a consortium led by SNC-Lavalin (now known as ProTransBC) in which they helped fund the project and will operate for 35 years in cooperation with TransLink. The Canada Line begins in downtown Vancouver and continues south to Richmond with a branch to the Vancouver International Airport. Construction of a fourth line and retrofitting of the Expo line are now underway.

Expo'86

Expo'86 was held in Vancouver from May to October 1986 on the north shore of False Creek and coincided with Vancouver's centennial. It also marked the 100 year anniversary of the completion of the transcontinental railway across Canada. The theme of Transportation and Communication led to several transportation exhibits including a monorail, a gondola system, water taxis, a high speed surface transport system from Japan, the French Soule people mover system, and the Sky Train. The monorail was a Von Roll Seilbahnen AG Mark II system that would shuttle passengers on the site and through buildings and when the fair closed, it was disassembled and installed at Alton Towers in the United Kingdom.

Toronto (Pearson) International Airport

In 2006 an automated people mover system opened at Toronto (Pearson) International Airport in Mississauga, Ontario (northwest Toronto). The LINK Train connects Terminals 1 and 3 and a reduced rate parking garage on the airport site. The free service uses two trains of six cars each built by the Austrian company DCC Doppelmayr Cable Car GmbH. It is a cable driven system in which each train operates independently in shuttle mode on two parallel tracks. The elevated guideway consists of a steel tube truss and is 1.47 km (0.9 miles) in length. The travel time on a shuttle is three minutes. Plans are underway to build an express rail system that will connect Toronto Pearson Airport with downtown Toronto for the 2015 Pan American Games and the airport station will be on the LINK Train system.

Niagara Falls People Mover Studies

Niagara Falls is one of Canada's most popular tourist attractions and over the years several studies of visitor transit systems have been undertaken to reduce parking needs and traffic congestion near the falls viewing areas and enhance visitor experiences. Since the mid-1980s the Niagara Parks Commission has operated buses during the main tourist season and they have helped alleviate traffic congestion but there are capacity limitations. In the early 1990s a new local tourism committee was formed and lobbied for a study to assess the feasibility of an automated people mover system to serve the falls viewing area, downtown, and other attractions in the area, and transport expected increased visitors. A 1996 Niagara Falls People Mover Feasibility Study was completed and identified several route alignments, station locations, possible people mover technologies, and cost estimates. The economic and environmental benefits of such a system were also quantified. Environmental Assessment studies have been undertaken and several options for financing a system, including design-build-operate, have been explored but the project has yet to proceed to the construction phase.

CONCLUSION

When the Ontario Premier William Davis announced that he was cancelling provincial funding and support for the Spadina Expressway in Toronto it marked a new direction for advanced transit systems in Canada. The formation of a government crown corporation and the development of a new intermediate capacity system was an exciting outcome that would lead to automated transit systems in Scarborough (RT), Vancouver (SkyTrain), and Detroit (DPM) in the mid 1980s. However, sales did not materialize as hoped and the Ontario government sold the crown corporation, and it eventually would be acquired by the Canadian company Bombardier as part of its growing transportation division. Today Bombardier is one of the world's largest suppliers of rail equipment. Although there have been only six APM systems in Canada and only three are operational today, the vision of the Ontario government in the 1970s to develop ICTS and its eventual sale to Bombardier have placed Canada among the leaders in APM development and applications throughout the world.

Automated Light Metro for Honolulu

Mike Bogonovich, BSME [1]

[1] Infraconsult LLC, Rail Systems Engineer, 6900 E. Camelback Road, Suite 800, Scottsdale, AZ 85251 Ph. (480) 272-6497; Fax: (480) 272-7815 ;Bogonovich@infraconsultllc.com; Website: www.infraconsultllc.com

Abstract

Generally, the system performance is one of the key aspects for the success of the project. Since an Automated Light Metro (ALM) can be designed to act much like an APM on a larger scale, defining such expectations such as top speed and distance between stations etc. is critical to the success of the project. Also, federal requirements such as ADA and Buy America must be accomplished within the system performance requirements.

Guideway equipment, like substations and switches, take more room than its APM counterpart. Also, locations are limited by existing intrastucture which causes one to make compromises in such things affecting system performance. Many times, in elevated systems such as the Honolulu ALM, extreme or unusual elevation changes can not be avoided due to existing utilities or other transportation networks such as buses and planes.

Generally, interfaces to other organizations such as fire and police may be more involved and time consuming to implement. In elevated systems, coordination with street running equipment such as traffic signaling are more simplistic involving system operations but have to be dealt with eventually during construction.

The contract packaging for Honolulu ALM is very unique and worth noting in detail. The success of the project lies squarely on the shoulders of the train and system supplier known as the Core System Contractor (CSC). The CSC is packaged in such as way as to provide all the vital systems such as Fare Collection, Signaling, Traction Power, Station Equipment, Operations Central Control and Maintenance Storage Facility fitout. Other contractors are involved to build stations and guideway with ultimately the CSC taking over the entire infrastructure to maintain and operate for a fixed price and set number of years.

The specification for a typical ALM system such as Honolulu involved writing a specification which would not limit the Proposers in the ALM arena and focusing on the possibility of a later add on of the system without issues of proprietary designs and obsolescence of equipment. Usually, due to the number of contractor and

designers on the project providing station, facilities and guideway design, a 30% complete design was offered during the request for proposal process. This design also must not limit the Proposers in the local area. In addition, what makes it even more challenging in Honolulu's case was there was only a city organization and not an existing authority such as a Metro or an Airport Authority to lay down exiting standards for design and construction. All this was developed during the procurement, design and construction phases.

System Performance

Generally the system performance is one of the key aspects for the success of the project. The following will summarize the process Honolulu followed to develop an ideal system for Oahu.

Technology Alternatives

A variety of alternative transit technologies were identified for the evaluation. These included conventional bus, guided bus, light rail transit (LRT), personal rapid transit (PRT), people movers, monorail, magnetic levitation (MAGLEV), rapid rail, commuter rail. The bus and rail modes operate in a number of different urban environments, including the following:

- Low-Speed in Mixed Traffic,
- Low/Medium-Speed in Limited Mixed Traffic,
- Medium-Speed in exclusive right-of-way, and
- High-Speed in exclusive right-of-way.

While the two mixed traffic types of service operate at-grade, the two exclusive right-of-way types of service can operate on elevated structure, at-grade, and/or in a tunnel.

Overview* of *Technologies Considered

A brief overview of the functional characteristics of each technology that was considered in the corridor is provided below.

<u>Conventional Bus</u>

This technology category consists of conventional buses that include standard buses, which are12 meters (40 feet) in length, or articulated vehicles, which are 18 meters (60 feet) in length. A bus provides its own power from an onboard power plant (such as a diesel engine or diesel electric hybrid) or obtains electric power from overhead catenary wires (trolley bus). Conventional buses are sometimes used in a Bus Rapid Transit (BRT) operating mode.

THE BUS
City and County of Honolulu
http://www.TheBus.com

Guided Bus

The guided bus technology is similar to a conventional bus but it also includes features that allow for operations with guidance for precision docking or reduced guideway width operations. Examples range in length from 12 to 24 meters (40 to 80 feet). Guidance can be provided in a variety of ways, including a slot in the pavement, side guidance, embedded magnets, or stripes on the pavement. As with a conventional bus, a guided bus can be used in a BRT operating mode.

O-Bahn Busway in Adelaide, Australia

Light Rail Transit (LRT)

The steel rail-based technology category has 18 to 27 meter (60 to 90 foot) long vehicles that can be combined into multi-vehicle trains. Most examples include articulation to improve maneuverability. Versions of this technology that are sometimes narrower and have shorter sections between articulations may be termed Streetcar Trams. Power is usually obtained from overhead catenary wires (required for mixed traffic operations), but third rail applications also exist. Onboard diesel-electric power plants also exist on Diesel Multiple Units configured for light-rail-type applications.

Baltimore Light Rail Vehicle
Courtesy of Bombardier

Personal Rapid Transit (PRT)

PRT is a technology that is intended to operate directly between a passenger's origin and destination with short headways between vehicles. The mode envisions using a large number of automated, small vehicles (two to ten passengers) on an exclusive, separated guideway. One small system is operating today in Morgantown, West Virginia, and several other concepts are under development.

West Virginia University
Courtesy of Jon Bell

People Movers

This technology has a wide range of vehicle lengths. For the Honolulu application only medium-length vehicles of about 12 meters (40 feet) in length are considered. These vehicles operate in an automatic, driverless mode on rubber tires that can be combined into short, multi-vehicle trains. Power is obtained from a third rail or current collection system.

Houston APM
Courtesy of Bombardier

Monorail

This is a technology that features trains that straddle an elevated guideway beam with rubber load and guide tires running along the beam beneath the cars. Both large and medium-sized versions of these trains exist. Large versions feature wider, longer and higher vehicles. Power is obtained from a third rail or current collection system.

Las Vegas Monorail
Courtesy of Bombardier

Magnetic Levitation

This is a technology that uses magnetic force to support the vehicle above guide rails and linear induction motors to propel them. Power is obtained from a third rail. As related to other MAGLEV applications, the technology under consideration in this study is "low speed MAGLEV" which has a top speed of about 80 to 100 kilometers per hour (50 to 62 miles per hour).

China Low-Speed MAGLEV
Courtesy of Transrapid International

Rapid Rail Transit

This is a steel rail-based technology category that features vehicles 15 to 23 meters (50 to 75 feet) in length, without articulations, that can be combined into long trains operating at high speeds. Medium and large versions of these vehicles also exist with the difference being the individual vehicle lengths. Power is usually obtained from a third rail.

Red Line (Los Angeles Metro)
Courtesy of AnsaldoBreda

Commuter Rail

This is a rail technology with trains consisting of one or more non-powered passenger cars pulled by a locomotive. The locomotive is typically a diesel-electric. Station spacing is typically four or more miles apart. The trains are compatible with freight rail trains (track gauge) and typically operate in mixed-rail traffic over track owned by others.

Technology Screening

All potential technologies were assessed in a screening process against criteria derived from the stated goals and objectives. Listed below are some of those objectives:

- Technical maturity: The technologies to be selected for combining with specific alignments must minimize risk from technical, schedule and cost perspectives. Technical maturity is measured in terms of operating service years, number of operating applications and reliability of operating systems. This criterion supports the goals of cost-effectiveness and feasibility by providing an indication of the cost certainty and schedule risk.

- Line capacity: Selected technologies must have the capacity to accommodate the travel demand for the planning horizon of year 2030. At this stage of the project a detailed travel-demand estimate has not been produced; however, from earlier work in the corridor it is assumed that a minimum threshold of between 3,000 and 5,000 pphpd will have to be accommodated by the technology. Capacity will be measured for a technology's minimum and maximum train length. This criterion relates to the goal of mobility by identifying whether the projected number of transit riders in the corridor can be accommodated by a given technology.

- Performance: Because of the distances between various activity centers being connected by the project, technologies should achieve relatively fast travel times. Higher operating speeds will result in faster travel times which, in turn, will promote system use. This criterion relates to the goal of improved mobility.

- Maneuverability: Technologies must be able to physically operate within the corridor. Maneuverability relates to the right-of-way requirements for a technology given its performance capabilities and constraints with regard to the geometry of proposed alignments. This is measured in terms of a technology's achievable minimum curve radius for the horizontal alignment and by the maximum grade for the vertical alignment. This criterion was derived from the goal of feasibility. In order for the technology to be feasible, it must be able to maneuver through the corridor within the natural and man-made constraints and work within the potential alignment elevations so it will not limit the alignment options.

- Costs/Affordability - The selected technologies should be cost-effective given the type of service (mixed traffic versus exclusive ROW) they provide. Costs are considered in terms of general annualized capital costs, O&M costs, cost variability (technologies' ability to be at-grade as well as elevated) and the cost of extension (supplier competition for system extensions). This criterion provides an indication of the technologies' ability to be both cost-effective and financially feasible.

- Environmental- The resulting exhaust and noise emissions generated by the technology should be acceptable within the corridor. This criterion measures the technologies' ability to have minimum community or environmental impact.

- Safety - Technologies must meet local and national life/safety requirements. The transit operations should be inherently safe or the design of the system can accommodate safety concerns in a cost-effective manner. This is measured in terms of right-of-way exclusivity. This criterion relates to the technologies' ability to have minimum community or environmental impact.

- Supplier Competition - A sufficient number of suppliers of the technology need to be available to foster price competition on the project to obtain a cost-effective system. This criterion provides one indication of the potential cost-effectiveness of a technology.

- Implementation Time - This criterion considers the relative time for planning, design, permitting/funding and construction of the system. This criterion relates to the accomplishment of the goal of being feasible in terms of political and public acceptance of the implementation time.

- Accessibility - Selected technologies must comply with the Americans with Disabilities Act requirements. Vehicle boarding ease is another measure within this criterion and considers whether "level-boarding" occurs with a given technology. This criterion relates to how well a technology will allow the project to achieve the goal of equity by allowing equal access to the technology for disabled users.

Independent Selection Panel

In 2008 a five member panel made the selection of the technology based on the screen process and alternatives analysis. The system characteristics that were identified by the alternatives analysis were used by the Independent Selection Panel to evaluate the available technology. The following parameters were used to determine the system to be used by HART:

- System Characteristics

  -Required train service speed of 55 mph
  -Must be able to navigate through 150 ft. radius horizontal curves within the maintenance facility, 400 ft. radius horizontal curves on the mainline (elevated structure)
  -Maximum grade of 6%
  -Stations lengths will not exceed 300 ft.
  -Line capacity - 9,000 passengers per hour
  -End to end trip time in the range of 40 minutes
  -Emergency evacuation in all areas of the system
  -3rd Rail or equivalent (no overhead contact system)
  -Fully automatic train operations
  - Low noise and vibration requirements
  -ADA compliance at all stations

- Vehicle Characteristics

  -Electric propulsion
  -High floor
  -Dynamic and regenerative braking
  -Fire performance to National Fire prevention Association (NFPA) 130
  -High reliability/high availability
  -Minimum vehicle life of 30 years
  -Ergonomic design to accommodate US 5th percentile female to 95th percentile male
  -Attractive appearance
  -ADA compliant

- Functionality of the Proposed System

  -Special guideway requirements
  -Maintenance facility requirements

-Proprietary components or subsystems that restrict or limit competition
-Interoperability of the system to accommodate different manufacturers in the future
-Availability of long term engineering and maintenance support
-Representative costs for similar systems
-The technological maturity of the proposed system

Also, a working group determined fully driverless was needed to meet the objectives of the project. Where trains are completely unstaffed having fewer people on the payroll has financial advantages as staff represent a significant part of the cost of running a transport system.

The working group also sited other advantages of not requiring staff to be available to drive the trains include the ability to provide far more frequent services at quiet times (such as evenings and weekends) when passenger levels are lower and the revenue earned would not justify the costs of employing a full complement of train drivers, and the ability of train operators to vary the service frequency to meet a sudden unexpected demand - such as to instantly put extra trains into service when torrential rain interrupts an outdoor event and everyone decides to go home at 5 pm instead of 7 pm. The working group also mentioned in their report that some automated systems still carry staff on their trains, if only to operate the doors and generally reassure nervous passengers that there is someone 'onboard' who can take control in the (unlikely) event of a fault; others are fully driverless. However even these may have staff at busier stations and all have operations watching the platforms, etc,. via closed circuit television systems. Automation offers financial savings in both energy and wear & tear costs because trains are driven to an optimum specification - instead of according to each motorman's style. For the same reasons rush-hour services can be slightly more frequent as the automatic train control system can allow trains to travel at closer intervals.

Guideway & Station Equipment Concerns

Guideway

In order to keep the elevated guideway substructure and superstructure as simple as possible the traction power is located at ground level (see Figure 2-1 Figure 2-2). Also, equipment for third rail electrification in the track switches is contained in these Traction Power System Substations (TPSS) site locations.

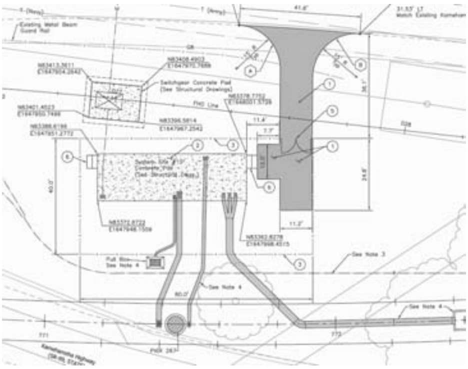


Figure 2-1 - Typical Site Plan for TPSS
Courtesy of HART

Figure 2-2 - Typical TPSS
Courtesy of HART

Station

Typically systems such as this require signaling and communication houses along the guideway. On the Light Metro for Honolulu it was determined to have rooms in the stations to accommodate such equipment. Listed below is a typical Station design and a Train Control & Communications Room (TCCR) layout (see Figure 2-3 and 2-4).

Figure 2-3 - Typical Elevated Station
Courtesy of HART

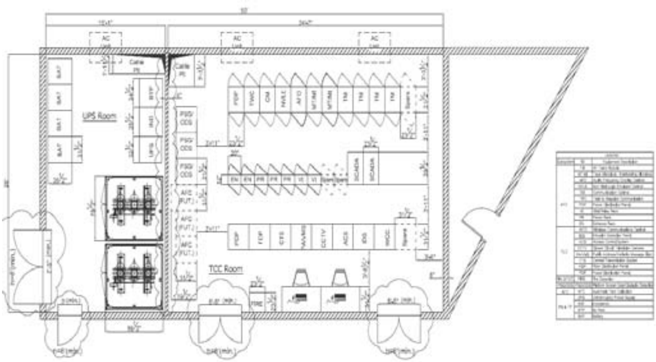


Figure 2-4 - Typical TCCR in Elevated Stations
Courtesy of HART

Per the system site map listed below (see Figure 2-5) there will be 13 system site locations and 21 stations all having differences depending on the location, surrounding infrastructure and land restrictions.

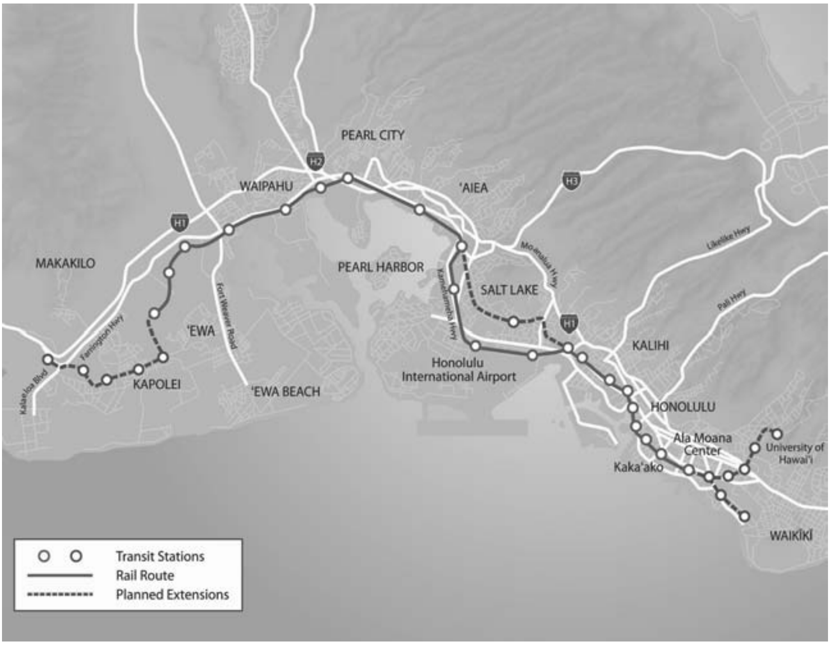


Figure 2-5 - System MAP
Courtesy of HART

Developing interfaces

The HART approach to developing interfaces between contractors was quite unique. For example a matrix approach was developed to have certain items provided by each contractor and others contracts buy material for others in order to take advantage of mill runs and economy of scale for other such items. For example, see Figure 3-1 - Interface Responsibility.

IC Item Number	**Interface** S=Specify requirements, D=Design, F=Furnish, I=Install, C=Construct, R=Requires coordination	Core Systems Contract #	W. O'ahu/ Farr. and Kamehameha Guideway DB	MSF (DB-200)	CM/GC	Guideway Design Contract	Guideway Construction Contract	Station Design Contract	Station Construction Contract	Escalator/ Elevator	Reference Drawing Number
	GUIDEWAY										
	Trackwork										
1	Running rail and special track work	R	I	F			I				
2	Track structure	R	D,I			D	I				
3	Insulated joint		F,I				F,I				
4	Limits of all track sections		R	R	R	R	R				
5	Structure borne noise and vibration	R	R			R	R				
	Electrification										
6	Contact rail assemblies	R	I	F			I				
7	Contact rail system	R	D,I	F		D	I				
8	Cable connections to contact rail	F,I	R	R		R	R				
9	Deck penetration sleeves for feeder cables	S	D,F,I			D	F,I				
10	Walkway sleeves for crossbonds	D	F, I				F,I				
11	Exposed raceway support elements	S	D,F,I			D	F,I				
12	Underground raceways	S	D,F,I	D,F,I							

Figure 3-1 - Interface Responsibility *Courtesy of HART*

Listed below (see Figure 3-2 – Interface to Outside Agencies) are the agencies that interfaces needed to be coordinated and developed. There were many working sessions and coordination meeting to iron out all the concerns and needs related to the rail system infrastructure.

1. **Electrical power feeds** (FFC / Hawaiian Electric Company)
2. **Telephone connections** (CSC , FFC / Hawaiian Telcom)
3. **Public Telephones** (CSC, FFC / Hawaiian Telcom)
4. **Direct line telephones** (CSC, FFC / Hawaiian Telcom, Various Emergency Agencies)
5. **Master Fire Alarms** (CSC, FFC /Hawaiian Telcom, Fire Dept.)
6. **Facility water and sewage** (CSC, FFC / Board of Water Supply)
7. **Storm drains** (CSC, FFC / Local Municipalities, Honolulu Department of Environmental Services)
8. **Street Lighting** (FFC / Hawaiian Electric Company)
9. **Maintenance of Traffic** (FFC / HDOT-State of Hawaii and DTS-City & County of Honolulu)
10. **Public Rerouting (**FFC / TBD)
11. CCTV (CSC / Honolulu Police Department)

Figure 3-2 - Interface to Outside Agencies

Contract Packaging

A mix of Design-Build (DB) and traditional Design-Bid-Build (DBB) delivery methods are being used on the Project to provide HART with greater economic and schedule advantages. A major portion of the work is requiring the procurement of individual design organizations under Final Design (FD) contracts who are preparing design documents for individual construction packages which are being procured using the Design-Bid-Build (DBB) approach. Procurement of the Core Systems (including Passenger Vehicles) is being accomplished through a Design-Build-Operate-Maintain (DBOM) contract that will improve integration and coordination of system elements with the fixed facilities, as well as, the transition to system-wide operations. Manufacture-Install-Maintain (MIM) contract(s) are being used for project-wide Elevators and Escalators. Trackwork and Contract Rail for the entire Project is being provided through the Maintenance & Storage Facility (MSF) Design-Build Contract. Each individual line segment contractor will obtain these materials at the MSF Site for installation in their respective line sections. Construction Engineering and Inspection Services (CE&I) contracts will be procured to provide contract quality control (inspection) of the construction contracts procured through the traditional design-bid-build approach. All of the various methods of contracting are being overseen by the GEC. There are currently forty-six (46) separate contracts identified.

As described above a variety of contracting approaches have been selected for implementation of the Project. These forms include:

- Fixed Price Proposals (D-B best value selection) for guideway first segments and the MSF
- Fixed Price Bidding for construction of guideway last segments and stations
- Design-Build-Operate-Maintain Proposals (best value selection) for Core Systems
- Competitive Proposals for professional services, except design
- Qualifications Selections for engineering and design services

Selection of contract packages and contract forms began during the Alternatives Analysis phase of the project and continues to the present day. In analyzing contracting approaches, HART used the services of its own staff, the Program Management Support Consultant (PMSC) and the GEC. Schedule needs, contracting risk, ease of administration, availability of qualified contractors and other aspects of contracting were considered. The procurement team also undertook consultations with a variety of industry sources.

- HART convened a Technology Selection Panel consisting of experts in the implementation of fixed guideway transit projects. While selection of the system technology was the primary function of this panel, they also provided input on the various approaches to project implementation.

- A Structures Forum was held to consider various structures types. This forum included the participation of structural designers not directly connected with the project to evaluate potential types of guideway structures. Availability of contractors was one factor in this evaluation.
- A Contractors Forum was held to discuss guideway construction with a selected group of major contractors familiar with segmental guideway construction. These contractors were queried for their opinions about the best approach for contracting this work. Seven (7) general contractors participated in this forum.
- An open Construction Workshop was held to discuss contract packaging with any contractor who wished to attend. Over 100 contractors attended this meeting to learn about the Project, provide input regarding contracting approaches and to network with other contractors interested in bidding or providing services.
- In August 2008, a Systems Forum was held. The Forum was open to suppliers of vehicles, and suppliers and installers of train control, traction power and communications systems for transit systems. These contractors and suppliers were queried as to their preferred approach to providing and installing equipment for the project. Meeting requirements for integration of various systems was a major topic of discussion.
- HART Staff participated in two FTA sponsored Construction Round Table meetings and utilized these meetings to obtain the input of other agencies involved in the implementation of major fixed guideway transit projects.

Issues which led to the selection of the various contract delivery approaches included the following factors:

- It was determined that the selection of a single overall entity to be responsible for the entire construction, manufacture and installation of the project would have a high risk of success because of the very large size of the project. This would have meant an overall contract in excess of $3 billion which would have limited competition and been difficult to bond. At least two contractors willing to approach the project in this fashion were identified, but the City determined that a reasonable cost might not be obtained given the incomplete level of design and the small number of candidate contractors.
- The City had a desire to begin construction as soon as possible so that the citizens of Honolulu could experience tangible progress for the tax dollars being collected. The design-build procurement approach was selected as meeting this need. The DB delivery method gives the opportunity to have a look-ahead, early in the project value for any single construction package.
- After the start of the recession in December, 2007 it became apparent that the bidding climate for construction projects was very favorable and would continue for some period of time, but not indefinitely. During this period, the City wished to take advantage of this favorable condition and to provide some stimulus to construction employers during the slow economic times.
- Firm fixed price bidding following complete design under the control of the City was determined to be desirable for contracts where the City needed to exercise control over the designs produced. Control over the design details of

transit stations was felt to be more important than control over such details for the guideway.

- Firm fixed price bidding was the selected method for contractor selection for those guideway segments to be built later in the program. This approach gave the City the most control over the designs in the central area of the City and since these segments are to be constructed later in the program, the time was available for complete final designs to be prepared in a manner consistent with the overall desired schedule.
- FTA published DB guidance which permitted the early solicitation of design-build procurements which could be used to develop design details necessary to the proper consideration of environmental issues while advancing the program consistent with other goals.
- The geography of the project was evaluated and five principal geographic areas with similar characteristics were identified.

The first two of these five areas were combined into a single guideway design-build contract. The remaining three geographic areas comprise the other guideway contracts.

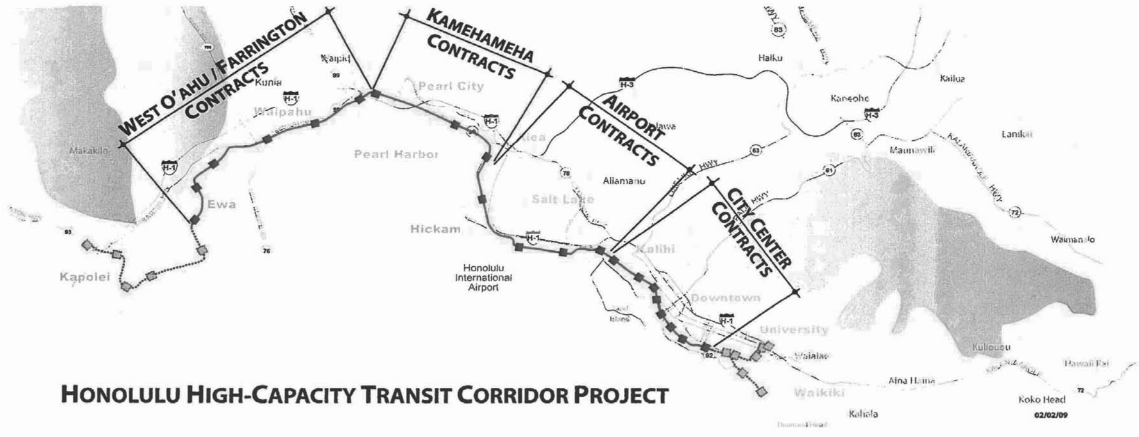
- The City decided to separate station construction from guideway construction for a number of reasons.
  - Stations are primarily building structures which involve contractors experienced in such features as elevators, escalators, flooring, roofing, electrical equipment and building finishes. Guideway heavy civil-type contractors are not necessarily suited for this work.
  - Stations are discrete units of construction which can be constructed independent of guideway construction and grouped together to form a variety of contract sizes as may deemed appropriate.
  - Stations can be constructed after guideway construction during the period of track and systems installation along the guideway. Station equipment rooms are necessary for the completion of systems installations.
  - Stations design typically involves a level of public participation above and beyond the guideway.

For this Project, stations generally have been grouped into packages of three each, which should result in contract sizes of approximately \$50 to \$60 million, a size adequate to attract large contractors without shutting out the local contracting community.

- Interface among construction contracts is the responsibility of the GEC. When there are a large number of separate contracts involved in a project, there are proportionately more interfaces to be controlled. The number of contracts selected in this contract packaging plan is felt to give the City a reasonable manageable number of interface points to be controlled. Interface control procedures have been established to address this issue.
- At the Core Systems Workshop, an extensive discussion took place among the participants regarding the packaging of the various project systems elements. Most major suppliers indicated a preference for the DBOM approach whereby

they would provide all operating systems for the project, take on the responsibility for functional integration of those systems and the responsibility for operations to a stipulated level of availability. While the City, through its consultants, felt that it was possible for the City to take on the systems integration function, the contractors successfully argued that they already had established relationships and generally integrated systems. If the City chose to procure the major functional systems separately, it would lose the advantage of the level of "prepackaged" integration that the suppliers could bring to the table.

- The early design-build procurements allowed the City to confirm its design and costing assumptions early in the process, thereby reducing the risk of unforeseen budget problems which might otherwise only surface following completion of final design. The additional risk pricing added by D-B contractors proposing on incomplete designs was accepted since it was balanced by the earlier certainty of construction costs afforded by the D-B procurement process.
- As noted previously, this Contract Packaging Plan for the Project will continue to evolve as the work progresses. HART and contracting community will both gain experience with the developing work and HART may determine that it is in its best interest to combine, separate or change the contracting form for the packages described herein.



CONTRACT PACKAGING SITE MAP

West O'ahu / Farrington Contracts	Kamehameha Contracts	Airport Contracts	City Center Contracts	Project Wide Contracts
FD140 W. Oahu Stations (3) Design FD240 Farrington Stations (3) Design FD245 Pearl Highlands Station, Parking Structure and Ramps Design DB120 W. Oahu / Farrington Guideway DB DB200 Maintenance & Storage Facility DB DBB170 W. Oahu Stations (3) Construct DBB270 Farrington Stations (3) Construct DBB275 Pearl H'lands Sta, Garage & H-2 Ramps Construct MM180 W. Oahu/Farrington Station CE&I	FD340 Kamehameha Hwy Stations (2) Design DB320 Kamehameha Hwy Guideway DB DBB370 Kamehameha Stations (2) Construct MM380 Pearl H'lands & Kamehameha Stations CE&I	FD430 Airport Utility & Guideway Design FD440 Airport Stations (3) Design DBB450 Airport Utility Relocation DBB460 Airport Guideway Construct DBB470 Airport Stations (3) Construct MM480 Airport Utility & Guideway CE&I MM485 Airport & Dillingham Stations CE&I	FD530 City Center Utility,Guideway and Ala Moana Station Design FD540 Dillingham Stations (3) Design FD542 City Center Stations (3) Design FD545 Kaka'ako Stations (2) Design DBB550 City Center Utility Relocation DBB560 City Center Guideway Construct DBB570 Dillingham Stations (3) Construct DBB572 City Center Stations (3) Construct DBB575 Kaka'ako Stations (2) Construct MM580 City Center Utility & Guideway CE&I MM585 City Center & Kaka'ako Stations CE&I	MM900 Program Management Support Consultant MM905 General Engineering Consultant (EIS/PE) MM910 General Engineering Consultant (Final Design & Construction) MM920 HDOT Coordination Consultant DBOM920 Core Systems DBOM MI930 Project Wide Elevators & Escalators OF950 Owner Furnished Plants & Shrubs

Contract Coding :
FD Final Design Contracts
DB Design-Build Contracts
DBB Design-Bid-Build Construction Contracts
DBOM Design-Build-Operate and Maintain Contract
MM Management Contracts
MI Manufacture + Install Contracts
OF Owner Furnished Contracts

Contract numbers typically 3 digits
First digit indicates location:
1xx West Oahu
2xx Farrington
3xx Kamehameha
4xx Airport
5xx City Center
9xx Project Wide

Second digit indicates category:
x2x Design Build
x3x Design Utility & Guideway
x4x Station Design
x5x Utility Relocation
x6x Guideway Construction
x7x Station Construction
x8x Construction, Engineerig & Inspection
Second digit rule does not apply to 9xx series.

Revision: December 14, 2009

Figure 4-1 – Contract Packaging Map
Courtesy of HART

Specification Development

Parts of the Specification

Listed below are the major parts of the specification to procure the ALM for Honolulu.

a. Part 1 - The Agreement;
b. Part2 - The Special Provisions, Management Provisions, Technical Provisions;
c. Part 3 - The General Conditions of the Design-Build Contract;
d. Part 4 - The Design Criteria;
e. Part 5 - The Engineering Data;
f. Part 6 - The PE Drawings;
g. Part 7-The Standard Specifications;
h. Part 8 - The Standard and Directive Drawings;
i. Part 9 -The Contractor's Proposals

Part 1-The Agreement

This is the top level document that gets signed and witnessed by the legal and commercial representative. The agreement also specified the value of the contract and in what currency.

Part 2- Special, Management and Technical Provisions

The Special Provisions are intended to modify, amend, and provide specific Project requirements to the General Conditions of Design-Build Contracts (see Part 3). This includes the commercial terms which are unique to this particular contract.

The Management Provisions provide additional performance requirements specific to the Project related to the management responsibilities. This includes the management terms which are unique to this particular contract.

The Technical Provisions provide performance requirements specific to the Project related to the technical aspects. This includes the Technical terms which are unique to this particular contract. The technical terms that pertain to the overall Project and also what all contractors should know are contained in the design criteria (see Part 4)

Part 3- The General Conditions of the Design-Build Contract

The General Conditions of Design Build (GCDB) contracts incorporated the City's standard policy and requirements relating to design-build projects as authorized by

Hawaii Law. As stated above, the special provisions are issued in RFP Addendums to modify any terms called out by the GCDB which are special for this particular Design-Build contract.

Part 4 - The Design Criteria

This compendium of design criteria (DC) establishes the criteria to guide the preliminary engineering and final design of the Honolulu Project. These document requirements are adhered to by all contractor (if applicable) regardless of their work scope. These documents are revised during the project and are baseline documents to all contract work. The DC also would be used as a HART standard for any work being done to the HART system including expansion of the system.

Part 5 - The Engineering Data;

This section includes draft documents which will be required as final submittals by the contractor.

Typical documents are as follows:

1. Geometry Data and Calculations
2. Primary Control Report (Control Point Surveying)
3. Draft Construction Safety and Security Program Manual
4. Draft Fire Life Safety Report
5. HART Quality Plan
6. Draft Safety and Security Certification Plan
7. Draft Safety and Security Management Plan
8. Draft Work Breakdown Structure (WBS Dictionary)

Part 6 - The PE Drawings

This section is given to the CSC to use for costing and are taken and revised by the contractor during the project development and interface management. These drawings are used to go through DD, ID and FD.

Part 7-The Standard Specifications

This section contains Construction Standard Institute (CSI) specifications adopted by HART to keep a level of consistency between contracts. Many industry standards are recognized and adhered to by each contract.

Part 8 - The Standard and Directive Drawings

This section contains standard and directive drawings. Directive drawings are a suggestion and if keeping to these drawings will guaranty compliance and acceptance during design and construction but can be changed by the contractor during the phases of design reviews. The standard drawings are to be strictly adhered to and are considered the standard of the authority (HART).

Part 9 -The Contractor's Proposals

This section contains the winning Offeror's proposal with certain consideration concerning cost information. The proprietary nature of the Offeror's costs is not included in the public sector. Also proprietary information on intellectual properties is also not displayed publicly.

Development

The technical specification development involves an entity to study existing successful operating systems and specify parameters that are achievable in the industry. This entity must also be a visionary in the area of new developments which may be implemented in the time period of design and commissioning of the project. This usually involves an experienced transit consultant with a long history of success in the industry. Until this industry is more developed in the US and abroad, technical specification will need to be developed for each system. Standardization is a must if the design costs are to be lowered for future projects. This author has been involved in contracts where visionaries has asked to let the market control the requirements but too often these projects lead to issues in service or expensive retrofits.

Once the exercise of system performance is completed, one must start the industry review process. The process first starts with technical experts bring forward recommendation in the form of White Paper reports. These reports may include such things as:

1 Corrosion Survey & Report
2 Draft Operations and Maintenance Plan
3 Evaluation of System Automation of Train Control
4 Fixed Guideway Fleet Sizing Report
5 Project Approach for Train Control
6 RF Radio Coverage Maps
7 System-wide Sustainability Report
8 Traction Electrification Power Estimates Summary Report
9 Vehicle Stored Energy Technology Report
10 Approach to Integrating Joint Existing Services such as Fire and Police

These recommendations must be evaluated by committee in order to develop the correct mix of proposers who bring local content such as fixed facility contractors for station, guideway and maintenance facility, as well as, train suppliers who can make the equipment envisioned by the committee. It is a very delicate set of recommendations that all need to be put into a package called the Contract. HART thinks it has done just that and still needs to prove to the world that the project is a leading success story.

Automated Systems for Last Mile Connections at High Speed Rail Stations

J. Sam Lott, P.E.

Kimley-Horn and Associates, Inc., 12012 Wickchester Lane, Suite 500, Houston, Texas 77079; PH 281-597-9300; FAX 281-597-8032; sam.lott@kimley-horn.com

Abstract

The paper examines the prospect of applying automated transit circulator systems for the "last mile" conveyance of passengers between a high speed rail station and their destination in the surrounding urban district. The characteristics of high speed rail stations are discussed with respect to their scale, urban context and ridership demand patterns, and the capacity requirements for automated systems to serve in the "last mile" function. Current project work on the Texas DOT Intercity Passenger Rail Ridership Study is referenced, and a discussion of the simulation and analysis methodologies being used in the study are compared to similar methodologies previously applied to study automated guideway transit connector systems in airports. The paper concludes with an assessment of the suitability of conceptual aerial guideway automated transit systems in conjunction with at high speed rail stations for each of the main classifications of automated transit technologies.

Introduction

There is a growing initiative to plan and build high speed intercity rail systems within the United States which would provide convenient service connecting our densest, most populated urban areas. The justification of building such sophisticated rail systems is based on their ability to compete with air travel by improving the total travel times of intercity travelers, typically for travel distances of 150 to 350 miles (250 to 550 kilometers). When total travel time advantages are combined with the prospect of rail connections penetrating into the heart of the largest cities, ridership potential can begin to favor the rail option. The successes of high speed rail (HSR) service connecting the largest cities within Europe and Asia have fostered the new U.S. federal and state government initiatives to advance HSR projects in the U.S.

These initiatives are bringing into focus the important "next question" of how large numbers of passengers will be moved from the HSR station to the surrounding urban districts located in proximity to the station. And for the wholly new rail stations that will be created to serve high speed rail in particular, this question is critically important to answer.

Along the northeastern coast of the United States where population densities have been at levels comparable to Europe since the 1900s, the introduction of higher speed rail service has been underway for over a decade. In this particular part of the country, there already exists effective mass transit infrastructure to connect the high speed rail stations with the surrounding urban districts so the issues addressed in this paper are less relevant.

However, most of the new high speed rail projects currently being initiated in the U.S. would connect cities throughout the parts of the nation where the existence of mature, high capacity transit is far less common. As a result, there is an important need to also address new transit connector systems that are sufficient for the "last mile" access and circulation movements within the urban districts near the high speed rail station. And with respect to the largest metropolitan areas, it is particularly problematic in that the roadways and surface transportation systems are often extremely congested and incapable of supporting at-grade transit solutions that have adequate capacity for this last mile connectivity, especially when future growth and development that will likely be induced by the new station are considered. Furthermore, regional-scale transit connections such as conventional commuter rail service are often naturally incorporated into the HSR station location.

The challenge therefore involves planning for adequate local district connections and circulation/distribution functions, creating an even greater need for a suitable connector/circulator system. The use of automated systems for this very purpose has been proposed in prior technical presentations at major transportation conferences (ref. 1 and 2). Past studies by Bay Area Rapid Transit (BART) have evaluated automated guideway transit systems that would serve as circulator systems to connect major rail stations with the nearby urban district (ref. 3). These studies clearly indicated that the application of advanced technology is viable, but that the selection of the class of automated guideway transit system is important to carefully analyze in the early stage of planning. Other specific studies are described below that provide further insight into these issues.

Note that in the discussion that follows, reference will be made to high speed rail service with the designation of "Core Express" which FTA identifies as service having an average commercial speeds of 150 mph or greater

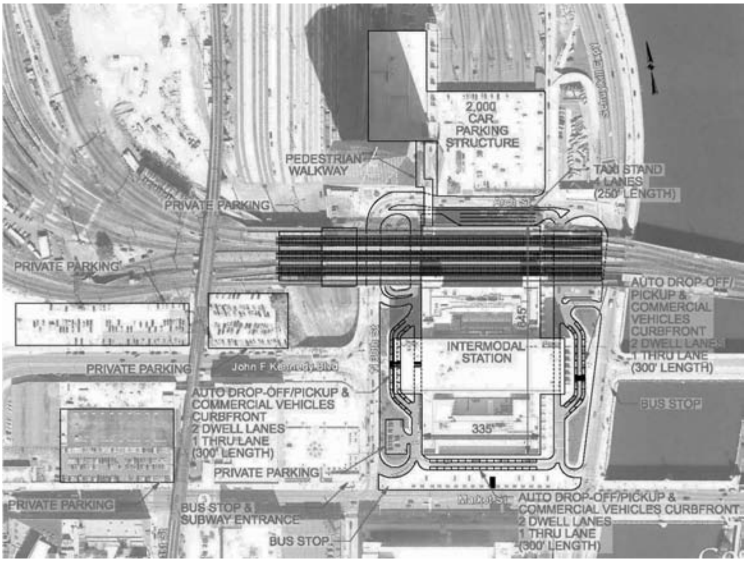
Unique Requirements of High Speed Rail Stations

Multimodal transit solutions are currently being investigated as part of the Texas high speed rail (HSR) studies. These studies are providing analytical information and practical insight into the intermodal functions required at the stations, which can then be considered in assessing the benefits of using automated transit technology applications to provide the last-mile connections into the dense urban districts.

Six sites in Texas are currently undergoing specific study for HSR stations – three in the Dallas/Fort Worth region, and one each in Houston, Austin and San Antonio. The studies show that the scale of operations at these locations begins to replicate the intermodal environment of an airport, since the Core Express class of HSR service is expected to have trains arriving and departing at least every 30 minutes between specific city pairs during peak periods of the day. Due to the rail traveler having characteristics and expectations very similar to air passengers, the transportation facilities are being planned in a manner similar to the landside/terminal intermodal infrastructure of a medium sized airport. In addition, the HSR stations also typically serve other transit modes such as light rail, commuter rail, bus and pedestrian access.

In most of the cities around the world where HSR stations are located in urban settings, these is existing mature transit infrastructure with adequate capacity to move large quantities of arriving and departing HSR passengers between the station and the nearby urban districts. In Texas, however, mature high capacity transit systems and infrastructure are typically not in existence at the most desirable station locations.

As a model for the functional aspects of an effective station design, the high speed intercity passenger rail ridership study currently being performed under the auspices of the Texas Department of Transportation (TxDOT) is using the Philadelphia 30th Street Station to establish a general benchmark – a generic definition of a complete HSR intermodal station. **Figure 1** illustrates the set of reference metrics have been established for each functional element of 30th Street Station, include automotive curbfronts, commercial vehicle staging and loading areas, taxi queuing provisions, as well as structures to house rental car and parking. Transit provisions include additional station berths and platforms to serve light rail, commuter rail, regional bus and intercity bus, as well provisions for local bus service.



SOURCE: Kimley-Horn and Associates, Inc.

Figure 1 Philadelphia 30th Street Station Provides a Benchmark for High Speed Rail Station Functional Elements

Intermodal facilities for new HSR station sites must be considered for all of these transportation modes. With respect to creating a transit circulator/connector system to serve the station site, almost all conventional transit technologies such as buses or light rail systems which access and egress the station site would have limited capacity. The basis for this limited capacity assessment is that the transit operations would typically occur at grade-level in the midst of traffic moving along congested roadways.

As a proposed alternative, the utilization of a grade-separated automated guideway transit system that would provide the primary means to convey transit patrons to and from the HSR intermodal station district and beyond to the surrounding subregional area has significant capacity advantages. Automated, aerial guideway transit provides an answer to the dilemma of providing reliable, high capacity last mile connectivity for access and egress from the HSR station.

Effectiveness of Automated Aerial-Guideway Circulator Systems

The initial studies of HSR system for Texas are being performed on the premise that the station activity will be high, having traffic and pedestrian movements similar to that of the landside and terminal complex of a medium sized airport. The passengers passing through the station will be using not only the HSR system, but also the other mass transit systems that are expected to interconnect at most of the station locations.

A common misconception among urban planners is that to provide a district-wide transit circulator system, all that should be required is a local bus route or streetcar/light rail line operating along the city streets between the HSR intermodal station and the surrounding urban district. However, the increase of traffic and densification of the major Texas cities within the dense urban environment around the station sites will often render at-grade transit solutions ineffective and incapable of providing carrying capacity such as suggested above. **Figure 2** shows the type of intense multimodal environment that is expected around a major HSR station – operating conditions which substantially constrain the capacity of at-grade transit systems.

SOURCE: Kimley-Horn and Associates, Inc.

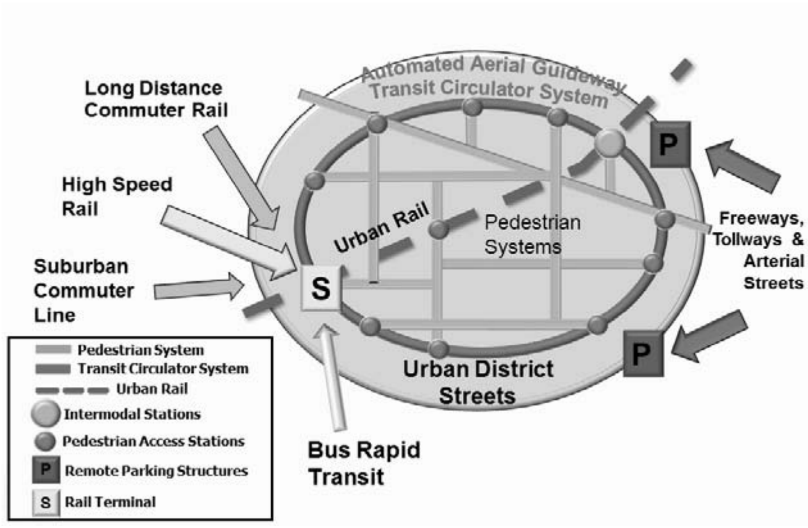
Figure 2 Intense Intermodal Operations Constrain the Capacity of At-Grade Transit

In contrast, grade-separated transit systems can provide substantially greater capacity to meet the high demand conditions necessary for the district circulator system serving the HSR intermodal station, since the guideways are isolated from the at-grade traffic and pedestrian activity within the urban district. A grade-separated circulator system alignment will provide the necessary reliability of service and passenger carrying capacity irrespective of how traffic congestion builds; and with full grade-separation comes the opportunity to install automated guideway transit technology. These advanced transit technologies include those of automated people mover systems (APM, ref. 4), automated urban guided transport systems (AUGT, ref. 5) or automated transit network systems (increasingly referred to as “pod” systems).

Nearly a half-century of experience has now been gained by the worldwide automated transit industry since the first prototypes were tested, and automated systems are well proven as flexible and effective transit technologies for deployment as a high capacity circulator system within the environment of a dense urban district or major activity center.

When an automated guideway circulator system is considered as a last-mile solution for a HSR intermodal station, then additional benefits can also be realized for the surrounding urban district served by the circulator/connector system as illustrated in **Figure 3**. In particular, intermodal connections can be accomplished even when the transportation infrastructure is located away from the HSR station site, as described below.

- Pedestrian Access – An aerial transit circulator system can connect numerous pedestrian access points to the station with pedestrian nodes in other parts of the district, even when these pedestrian nodes are located some distance from the intermodal station or when they are isolated by a major freeway or highway system.
- Transit Connections – Correspondingly, an automated circulator system can provide convenient connections to passengers transferring to of from existing transit lines also serving the district, but which have stations/stops along an alignment some distance away from the HSR station site.
- Perimeter Parking – Finally, aerial guideway transit circulator systems can conveniently connect the district and the HSR station with multiple parking facilities that are often remote from the station, such as parking located around the perimeter of the district where convenient access and egress can be provided to the surrounding local street, arterial and freeway network.



SOURCE: Kimley-Horn and Associates, Inc.

Figure 3 HSR Intermodal Station With Multimodal Connections and Last Mile Circulator/Distributor Automated Guideway Transit System

This application of automated, advanced transit technology on aerial guideways can be described as a "Mini-Metro" system, since transit systems of this type are relatively small and flexible compared to other fixed guideway options, yet provide suitably-high capacity to serve as a full metro system when the application is properly designed. It is the attributes of high passenger carrying capacity, alignment flexibility and reasonable capital and operating costs that make automated aerial-guideway systems ideal for the last-mile circulator/distributor function.

Passenger Carrying Capability – As a general objective, the highest activity levels at some major intermodal stations serving HSR are anticipated to occur in brief periods of time (e.g., 15 minute periods) and to ultimately require a local circulator/distributor transit system with a carrying-capacity suitable for passenger flow rates of 5,000 to 10,000 or more passengers per hour per direction (pphpd) during the surge flow periods. This functional requirement of carrying passengers away from the station site with a high level of service should not be underestimated. An intercity rail passenger who has traveled long distances with extended travel times should not be met with delays of 10 or 15 minutes while they are waiting to board the district circulator system, no matter whether the delay is due to extended operating headways or to inadequate capacity of the circulator system itself.

A fully automated, driverless transit system designed for application as an urban district circulator are that it can provide a moderately-high capacity of up to 10,000 to 15,000 passengers per hour per direction (pphpd) with 4-car trains operating 90 to 120 second headways – assuming that the vehicles are 40 to 50 feet (12.2 to 15.2 meters) long and that most passengers are standing as they make the brief local trip within a district or subregional area. The directional capacity equates to a throughput roughly equivalent to a freeway with 5 lanes in each direction, or a bus system operating with 200 buses an hour in each direction.

Alignment Flexibility – A second key characteristic of automated guideway transit is that the guideway alignment flexibility facilitates the circulator system's insertion into a dense urban environment, in part due to its capability to run short trains on very close headways. The resulting benefits are smaller station platforms and footprints, and when combined with the other common attributes of smaller curve radii and steeper grades along the alignment the aerial guideway systems can be realistically retrofitted into even a fully built environment.

Figure 4 shows the very compact stations in Downtown Miami along the Metromover urban circulator system, demonstrating how automated aerial guideway systems can be integrated into the urban context.

Reasonable Capital Cost – Although in some locations below-grade alignments could be the preferred choice for grade separation of a district circulator/connecter system, the most cost-effective grade-separated alignment for a high capacity transit system is typically achieved with aerial guideways – a configuration which is around half the capital cost of below-grade alignments. A further cost benefit of a fully automated system if that the size and number of trains has no significant impact on the operating cost of the transit line, since there are no drivers or operations personnel required to be continuously present on any train. And finally the capability to operate short trains on very close headways allows the stations to be much smaller in size than more traditional transit systems, which in turn substantially reduces the capital costs. In fact, the total capital costs may be close to the same order of magnitude of capital costs as recent projects that have installed at-grade light rail transit within dense urban district environments.

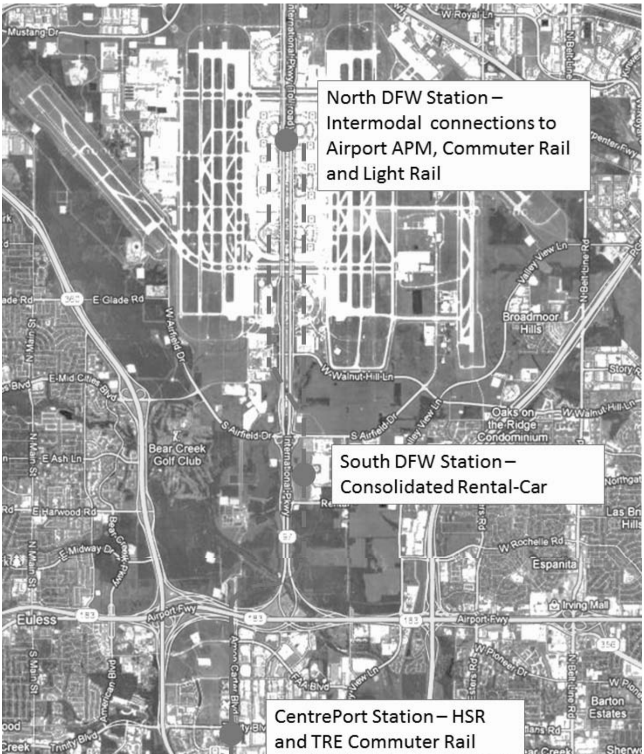
SOURCE: Kimley-Horn and Associates, Inc.

Figure 4 Photos of Miami Metromover Showing a Typical Downtown Station Integrated Into Urban Environment and Flexibility of Guideway Alignment

High Speed Rail Station Area Studies

The application of fully automated transit systems to connect a HSR station with a nearby district /major activity center has precedent here in the United States. For over a decade a fully automated, aerial-guideway transit system has been operated by the Port Authority of New York and New Jersey to connect the Northeast Corridor Station (NEC) with the airport terminals, remote parking, ground transportation center and rental car facilities at the Newark Liberty International Airport. The NEC is a major rail station where air passengers connect to high speed trains operated by Amtrak and to conventional intercity and regional commuter trains operated by New Jersey Transit. Recent studies have further evaluated the technology and alignment alternatives for a replacement or upgrade to the existing small monorail transit connector system that would provide sufficient capacity to serve a planned new Terminal A (ref. 6).

Figure 5 shows an example that is defined as a conceptual connector system to a station near the Dallas/Fort Worth International Airport. This connector system is being assumed to exist as part of the TxDOT study of high speed intercity passenger rail ridership in order to represent local area connectivity of the HSR intermodal station with DFW Airport. For reference purposes in the TxDOT study, a baseline automated aerial guideway system defining this conceptual connector transit system has been established as that used in the AirTrain system between New York's JFK Airport and Jamaica Station.



Aerial Photo Source: Google Maps
Graphical Concept Source: Kimley-Horn and Associates, Inc.

Figure 5 Conceptual Transit Connector System Between a High Speed Rail Intermodal Station and Dallas/Fort Worth International Airport

This particular example of an aerial guideway circulator system is called the JFK AirTrain, a project also conceived and implemented by the Port Authority of New York and New Jersey. The fully automated system provides a direct connection between the Long Island Railroad at Jamaica Station, the New York City Transit at Jamaica Station and Howard Beach Station, and the airport district comprising all airport terminals and the airport landside facilities that provide parking and rental car services. The technology is a rail car with linear induction motor (LIM) propulsion.

The system operates along an aerial guideway that was built within a freeway median over a portion of its length. **Figure 6** shows photographs of the JFK AirTrain system and its aerial alignment.

The figure shows that many passengers choose to stand throughout their ride on the AirTrain system, since the duration of the trip is short and the ride is quite comfortable. Seating is available for the any who desire it and the station/platform interface is fully ADA compliant, allowing wheelchairs to easily roll onboard.

SOURCE: Kimley-Horn and Associates, Inc.

Figure 6 JFK AirTrain connects the JFK Airport District with Jamaica Station

Planning Techniques Applying Simulation-Based Analyses

The similarities of airport intermodal functions and HSR station intermodal functions have been noted above, and in light of those similarities there is considerable benefit in utilizing planning techniques and analysis tools that are commonly used to study airport landside, ground transportation and terminal facilities. The TxDOT study of intercity rail ridership and associated HSR intermodal stations is applying the Advanced Land-Transportation Performance Simulation™ (ALPS™) software in the studies of the station operations and the passenger's access to the station site. This software has been applied to studies of ground transportation and terminal facilities at a number of major airports and rail stations, providing a deeper understanding of the multimodal operational dynamics that result from large quantities of passengers arriving and departing based on a fixed schedule of transport (ref. 7).

Important aspects of the ALPS methodology which are of great benefit in the study of automated guideway transit systems serving as circulator/connector systems for both airports and HSR intermodal stations include:

- Detailed transit circulator/connector system performance, fleet operations and train-by-train ridership analyses.
- Holistic analysis of all modes and all transit systems/lines operating together in one integrated simulation.
- Functional, performance and operational analysis of the multimodal transportation system throughout the entire 24-hour day.

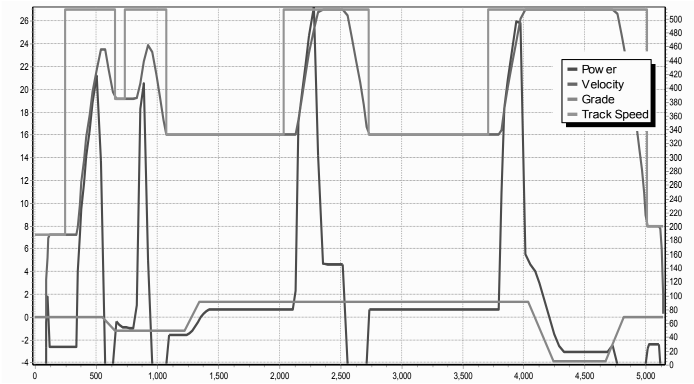
The ALPS models have been used extensively to study automated guideway transit and APM systems of all types in a variety of applications. For example, during the design phase of Jamaica Station, simulation-based studies were conducted to analyze the comprehensive pedestrian operations. This is the major intermodal rail station that was expanded to incorporate the JFK AirTrain system connecting Kennedy International Airport with the station.

The same ALPS simulation models have also been used to study the alternative technologies and alignments for the transit circulator system that connects the NEC Station and Newark Airport. The study analyzed multiple alternatives for upgrade or replacement of the existing technology (ref. 6), as described previously.

Figure 7 shows a train performance graph of one case study from the ALPS models of Newark Airport transit connector system. The comparative assessment of train performance and fleet operations for the alternative train control systems and vehicle/guideway technologies was one aspect of the study. As an integral part of the multimodal simulation process, ALPS was also used to modeled the flow of passengers as they traveled from NEC corridor trains through the station to board the circulator/ connector transit system and then complete their trip a specific terminal destination. The person-trips for all of the pedestrian movements and transit ridership were generated from an airport flight schedule representing 10 years in the future.

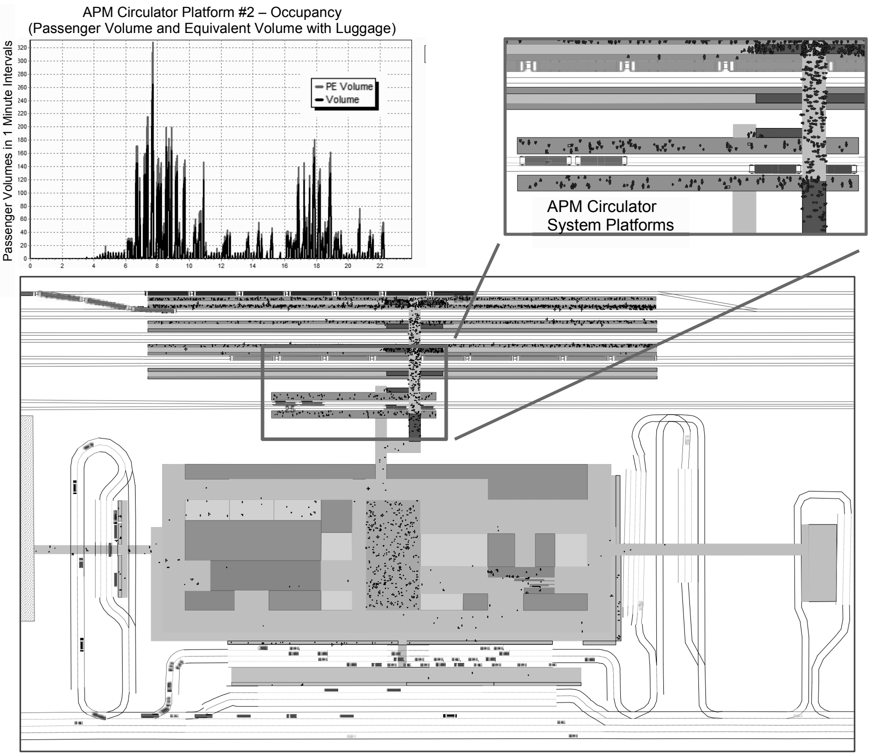
The use of simulation models also provides the same capabilities to study the complete operational environment of a HSR intermodal station, with pedestrian, automobile, commercial vehicles, buses, light rail and commuter rail, and intercity trains all dynamically interacting within the station site (ref. 8). The ALPS analysis tools are being used in this way to analyze the complex intermodal station operation in the initial phase of study of early concepts for the HSR system in Texas. The analysis has practical benefits – even when the stations are only defined conceptually – when the vehicular and pedestrian activity is driven by a hypothetical schedule of trains and ridership, since the intensity of activity that is possible in each station site is visually portrayed.

Figure 8 shows an image from the ALPS model of a generic high speed rail intermodal station that is being used in the early stages of the TxDOT study. The model is providing preliminary insight into the station operations for each prospective station location in each strategic, high density urban areas being considered. The



SOURCE: Kimley-Horn and Associates, Inc.

Figure 7 ALPS Performance and Operations Model of Automated Guideway Transit Circulator System Connecting the NEC Station with Newark Airport



SOURCE: Kimley-Horn and Associates, Inc.

Figure 8 ALPS Model of a Generic High Speed Rail Intermodal Station

analysis of the hypothetical station fosters an effective dialogue with local working groups in each of the major regions that would be affected by the planned high speed intercity rail system. And with respect to the interests of this paper, the figure also illustrates the benefits of analyzing the ridership demands placed on an automated transit connector system under the hypothetical scenarios for station operations.

The boarding and alighting of the automated transit connector system ridership can be analyzed train-by-train, as well as for the intermodal station as a whole. Using the simulation as a conceptual planning tool, platform densities, vertical circulation flows and access corridor level-of-service can also be quantified to assess the impacts of surge flows resulting from the overall schedule of trains.

Conclusions on Role of APMs as HSR Station Connectors

High speed rail systems in the United States are expected to require major intermodal stations in some urban locations where high capacity transit infrastructure does not currently exist. This insertion of major HSR station facilities may require new transit infrastructure to be built that connects these intermodal stations with the surrounding district, especially when at-grade transit is seriously hindered by traffic congestion. Under such circumstances, it is concluded that the installation of grade-separated aerial guideway systems operating with fully automated trains can be an important element of the station area infrastructure when a high capacity connector system is required to serve the HSR intermodal stations.

All classes of automated system are candidate technologies to serve as connector systems, depending on the specific needs and demand requirements of each unique station site. Conventional automated guideway transit technologies with self-propelled vehicles are the anticipated norm for transit circulators that connect HSR intermodal station to the surrounding urban districts, whereas some shuttle APM technologies (e.g., cable drawn systems) could also play an important role under some circumstances. For other applications where the demands are within a range suitable for automated transit network/PRT systems (i.e., pod systems), the demand-responsive nature of these new technology systems will also be an important part of the last-mile solutions to serve HSR stations in the years to come.

Due to the complexities of the intense intermodal activity and the dense urban settings within major downtown districts, the use of simulation models like those utilized to study airport landside and terminal environments is proving very beneficial in the Texas Department of Transportation study of HSR stations. The models are particularly useful to analyze the surge flow conditions as passengers move to and from the various transportation modes. In addition, the operations of the automated connector system can be beneficially studied using simulation based analysis tools, and in particular these analysis techniques can test the size and service frequency required for the connector system trains. Further, the suitability of alternative APM shuttle systems or automated network transit/PRT can be tested through simulation tools to determine the best application at each specific station/urban district location.

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Cable propelled transit systems – Emirates Air Line London

Johannes Winter [1]

[1] *Senior Operations Manager, DCC Doppelmayr Cable Car GmbH & Co KG, Holzriedstrasse 29, 6961 Wolfurt, Austria; Phone (+43)55746041290, email: Johannes.Winter@doppelmayr.com*

ABSTRACT: The Emirates Air Line provides an innovative and welcome new river crossing and an exciting new landmark for London. It is the newest member of the Transport for London family and rising to a height of 90 meters above the river Thames, provides a unique London experience and offers some of the most spectacular views the UK capital has to offer.

The 1100m Emirates Air Line is an innovative, urban and new transport link for London. It is the first urban cable car system of its kind in the UK, providing a unique river crossing linking two key destinations.

The Cable Car is connecting with its 34 gondolas local communities improve access to visitor destinations and speed up river crossings. It will also encourage further regeneration at The Royal Docks and Greenwich Peninsula.

Owned and operated is the Cable Car by Dockland Light Railway Limited (DLR) a part of the TfL network, Emirates is the Scheme Sponsor in a 10 years sponsorship deal. The Operations is a unique partnership of world class companies. Each has committed to strive for the highest standards in its industry sector. The combined expertise of TfL, MaceMacro, Doppelmayr Cable Car, Continuum, CUK and Easy Clean is focused on making the Emirates Air Line a unique experience for London and not just a service.

In October 2011 The Mayor of London, Boris Johnson, announced that global airline Emirates will sponsor London´s new cable car river crossing, build by Doppelmayr, to be known as the Emirates Air Line, in a ten year deal worth £36m. The Emirates Air Line is a key element of the Mayor´s vision to transform east London into a bustling metropolitan quarter teaming with new businesses, entertainment and leisure facilities supported by world-class transportation.

Creating a direct link between the O2, Europe´s biggest entertainment venue, and ExCel, the UK´s largest exhibition centre, the Emirates Air Line is also providing an additional interchange between the DLR and Jubilee line. Both areas surrounding the Emirates Air Line have been earmarked for a number of regeneration projects with the Royal Victoria Docks selected as one of the new Local Enterprise Zones. The Emirates Air Line is playing a key role in supporting these regeneration projects by providing a faster and more direct link, taking just five minutes to cross the river. It is also providing the local communities accessing to a range of entertainment, job and leisure opportunities that are set to become available as part of the regeneration.

The £36m sponsorship deal forms part of the funding strategy to recoup the construction costs provided for the link and provides 80 per cent for the cable car including an application to a grant to the European Regional Development Fond (ERDF), additional sponsor agreements, retail space rental and fare revenue.

For construction and operation Mace has been selected as principal contractor to build the cable car and operate if for three years. Mace was leading a consortium of experts, including Doppelmayr as the cable car specialist for the construction and Doppelmayr Cable Car as the company to operate it. Parts of the consortium as well were Watson Steel, URS Scott Wilson, Buro Happold and Aedas. The cable car has been designed to the highest standards by Wilkinson Eye.

Planning permission was granted for the Cable Car by the London Boroughs of Newham and Greenwich and the London Thames Gateway Development Corporation on March 2011. All of the necessary land interests and rights were acquired by private negotiations. The contract for the construction and operation of the Cable Car was let to Mace Limited on April 2011. The Cable Car is no operated on behalf of Dockland Light Railway Limited (DLRL).

The construction of the mechanical and electrical Cable Car components of a cable driven urban transit system carrying 2,500 passengers per hour in each direction – the equivalent of 50 London buses) and accessible with an Oyster Card was led to Doppelmayr Seilbahnen GmbH.

Doppelmayr Seilbahnen GmbH located in Austria is the world leader in ropeway engineering. Doppelmayr has production facilities, sales and service locations in over 33 countries and to date has built more than 14,300 installations in over 87 countries.

Cable transit is a transportation technology that moves people in non-motorized vehicles (cabins) propelled by a cable. While the technology can be subdivided into two categories – bottom supported people mover systems and top supported aerial systems – this paper will focus on the aerial system. In the last seven years, several cities around the world have discovered the benefits of cable transit. Dozens of systems have already been built and many cities are contemplating, proposing, and studying the benefits of using ropeways as a part of their public transit. There are numerous examples of urban aerial cable systems in the world today. Depending on the location and function, each varies in terms of network integration and target ridership. Systems designed for commuter use, as part of a transit network, both physically and fare integrated. The more tourist-oriented systems tend to cost more to ride and are not always integrated directly with other modes of transit. Varying are utilized, which demonstrates the wide variety of uses for cable in the urban environment as well as the costs of each system varies depending on everything from customization, location, and technology.

The ropeway system is a continuous monocable system with 34 gondolas. The system is designed to transport passengers at a constant speed of maximum 6m/s. Besides the electric main drive unit (AC motor), two independent hydrostatic emergency drive units are installed. The detachable system features friction sheaves at the incoming and outgoing sides of the stations. With these sheaves the system is transmitting the speed of the rope via v-belts to the conveyors which transport the carriers through the stations. This configuration ensures positive control and synchronization of rope speed in each station in both forward and reverse directions. Key functions of the cable car, such as rope speed and grip opening and closing operations, are monitored and controlled by electronic safety circuits in order to ensure smooth operation and maximum safety. Fixed rope tensioning is achieved by two hydraulic cylinders in the South Station. The parking of cabins is carried out automatically and location is sufficient for all cabins.

Table 1. Technical Data

Horizontal Lengths	1,086.90	m
Hourly Capacity	2,500	pphpd
Drive Speed	0 – 6.00	m/s
Station Speed	0.20 – 0.30	m/s
Trip Time	4.14	min
Carrier Distance	86.40	m
Carrier Interval	14.40	sec
Passenger per Carrier	10	
Number of Carriers	34	
Haul Rope Diameter	50	mm

The Cable Car is supported on three steel towers between the two stations. The tallest of the three is the North main tower, rising to 93,00m above datum. The South main tower is slightly lower, at 88,84m above datum and the North intermediate tower structure terminates at 66,00m. The South main tower is founded within the river Thames whilst the north main and intermediate towers are founded on land. For example the South Tower is made up of approximately 6,500 steel pieces measuring between 30-50mm thick and weighing around 570 tones. The first piled foundation was driven down to a depth of 48m and includes over 130m3 of concrete to ensure the support of this impressive structure. The stringing of the cable across the Thames has been a highly complex and intricate part of the construction of this landmark project. The construction team used boats to make the initial rope connection during the short night-time window when the tide was at its lowest, working with the Port of London Authority to keep the river way clear, and this was eventually replaced with the cable itself.

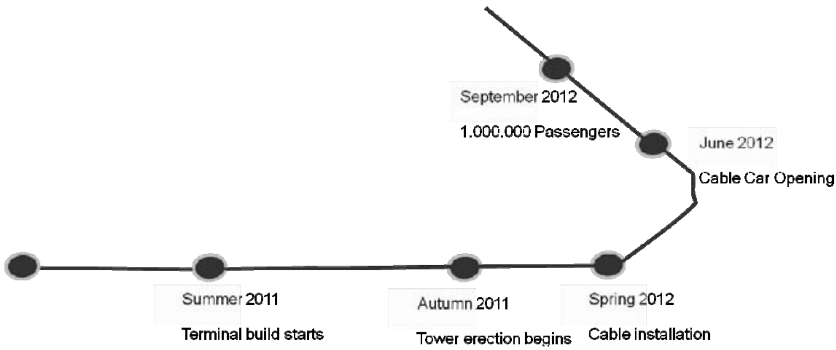

Figure 1. Milestones – Johannes Winter

The Emirates Air Line is an exciting new river crossing and part of the Transport for London network – but it is much more than this. Much more, even, than an iconic new landmark on the London Skyline – an Experience. In addition to carry up to 2,500 people per hour and direction it will provide as well:

Table 2. Experiences

1.	Direct crossings between Greenwich Peninsula and the Royal Docks in five minutes
2.	Cabins every 15 seconds
3.	Direct link between The O2 and the ExCel Centre
4.	An accessible and bike-friendly service
5.	A new visitor attraction for East London
6.	A low-emission form of transport
7.	Another travel option for Oyster cardholders

It will also encourage further regeneration at the Royal Docks and Greenwich Peninsula, each a dedicated enterprise zone, with plans for the SS Robin (the world´s oldest complete steamship) and Siemens “The Crystal Urban Regeneration Centre” opened in September 2012, on the north side of the river.

There is a ‘frequent flyer’ boarding pass for regular users, which will allow them to make ten single journeys for £16, equating to £1.60 per single journey. The frequent flyer boarding pass will appeal to people living or working in the local area who wish to use the Emirates Air Line on a regular basis. A single fare boarding pass using Oyster pay as you go will cost £3.20 (child fare £1.60). Passengers with a Travel card or other Oyster cards will be able to fly for the same fare but will need to buy a boarding pass from ticket offices or vending machines. There is also the option to take a non-stop return journey which will cost £6.40 with Oyster.

Journey times during commute hours (07:00 to 10:00 and 15:00 to 21:00 during the summer) are approximately five minutes. TfL recognizes that some visitors will want to experience the journey for as long as possible so the scheme will operate at slower speeds during non-commuter periods meaning a single journey could last up to 10 minutes between 10:00 and 15:00.

Within the first three months of operation under Doppelmayr Cable Car the gondola reached 99.80% of Availability and transported more than 1.000.000 passengers over the river Thames. Many tourists have come to east London this summer to use the gondola as a travel link during the London Olympics 2012 Games, but Londoners are also starting to change the way the normally get between Greenwich and the Royal Victoria Docks by choosing the Emirates Air Line as a way to commute.

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EVOLVING CLARK COUNTY AMUSEMENT AND TRANSPORTATION SYSTEM (ATS) CODE REQUIREMENTS

J. David Mori, P.E., President[1] and Antonio Garcia[2]

[1]Jakes Associates, Inc., 1940 The Alameda, Suite 200, San Jose, California, 95126, USA. PH: (408) 249-7200; FAX: (408) 249-7296, E-mail: jakes@jakesassociates.com, Website: www.jakesassociates.com

[2]Clark County Department of Development Services, Building Division, 4701 W. Russell Rd., Las Vegas, NV 89118 PH: (702) 455-8091; FAX: (702) 221-0630, E-mail: acg@clarkcountynv.gov

Abstract

APM code requirements within the Clark County (Las Vegas, NV) environment are continuing to evolve. New sections of the ASCE and NFPA APM codes have been adopted as have specific safety, liability and responsibility requirements. Having the primary objective of further improving patron safety, their integration (when combined with other standard and code requirements such as those of ASME, NFPA, ASTM, NEC, etc.) have directly helped to form future APM system development within the United States. Additionally, Clark County has recently introduced an approval program for amusement and transportation system fabricator/manufacturers to oversee Quality Assurance/Quality Control manufacturing and fabrication of amusement and transportation to be installed within Clark County's jurisdiction. Several complex systems have recently been commissioned under this program. This paper further explores evolving code requirements within the Clark County jurisdiction.

Introduction

Over the last decade, the American Society of Civil Engineers (ASCE) along with the American National Standards Institute (ANSI) and the Transportation and Development Institute (T&DI), has updated and refined a set of Automated People Mover standards that serves as a benchmark for the entire industry. The latest standards include:

Part 1 (ANSI/ASCE/T&DI 21-05), revised in 2005 with the following scope:

- Operating Environment;
- Safety Requirements;

- System Dependability;
- Automatic Train Control (ATC);
- Audio and Visual Communications;
- System and Safety Program Requirements.

Part 2 (ANSI/ASCE/T&DI 21.2-08), revised in 2008 covering the following:

- Vehicles;
- Propulsion and Braking.

Part 3 (ANSI/ASCE/T&DI 21.3-08), revised in 2008 covering the following:

- Electrical;
- Stations;
- Guideways.

Part 4 (ANSI/ASCE/T&DI 21.4-08), new for 2008 and including the following:

- Security;
- Emergency Preparedness;
- System Verification and Demonstration;
- Operations, Maintenance, and Training;
- Operational Monitoring.

For most North American APM system applications, both public and private, these standards are often used as a representative guideline for APM design and development, but their enforcement is not legally mandated. According to the ASCE standard, "the overall goal is to assist the industry and the public by establishing standards for APM systems". The ASCE standard goes on to clarify that it " may acquire legal standing" by any of the following or a combination thereof:

1. Adoption by an authority having jurisdiction;
2. Reference to compliance with the standard as a contract requirement;
3. Claim by a manufacturer or manufacturer's agent of compliance with the standard.

Such is typically the case that all or part of the standards are adopted by a customer seeking proposals for a new APM project, while adding further requirements as necessary to cover specific needs of the project in question.

Las Vegas, Nevada (Clark County jurisdiction) has experienced perhaps the most active APM private sector development activity in the world. In these cases, system regulation falls not on Federal oversight committees, such as for the Regional Transportation Commission or the State of Nevada, but by the Clark County Building Department. Oversight applications include resort installations such as the CityCenter

APM, Mandalay Bay Express APM, Mirage/Treasure Island APM, Primm Valley APM and monorail, and the Las Vegas Monorail. In addition, there are a series of APMs already operational and in process at McCarran International Airport in Las Vegas. Clark County has opted to adopt the ASCE APM standards (Parts 1 thru 4) directly as part of its Amusement/Transportation System Code for commissioning and oversight testing.

Case Study Examples

The two cases below represent examples of APM systems where slightly different levels of oversight and requirements (both Clark County ATS and ASCE 21) were applied based upon unique system characteristics.

Mandalay Bay Express

The Mandalay Bay Express People Mover tram system in Las Vegas, operates between a the Las Vegas Boulevard/Tropicana Avenue intersection station and the Mandalay Bay Resort station with intermediate stops at the Luxor and Excalibur Hotels and Casinos. It is a fully automated cable-propelled transit system designed to provide transportation along a dual-lane, elevated steel guideway structure utilizing two (2), 5-car trains. The system was originally manufactured by Doppelmayr Cable Car (DCC) and represents an innovative, state-of-the-art People Mover and guideway design.

Figure 1: "Mandalay Bay Guideway" illustrates the system dual-lane elevated guideway design. The system was designed without an emergency egress walkway between stations, as it was a.) not considered functionally necessary, and b.) not part of Clark County adopted ASCE code requirements at the time of system installation. In the event of a vehicle emergency and/or failure on the elevated guideway, where a vehicle is unable to return to a station for passenger unloading, first a vehicle-to-vehicle supervised evacuation via the use of a specially designed portable bridge is used. If this method is not feasible, local fire department and system personnel would be dispatched to the train site. They would access the vehicles from hook-and-ladder trucks positioned below the guideway. A manual exterior door opening mechanism installed as part of the emergency exit doors for each vehicle would be utilized to reach the passengers and escort them to safety via the truck ladders.

Per ANSI/ASCE/T&DI 21.3-08, Part 3, Section 11.3, "The APM guideway emergency evacuation and access shall be designed in accordance with the requirements of *Fixed Guideway Transit and Passenger Rail Systems*, NFPA 130, 2007 edition". These requirements imply a need for an emergency walkway along the entire guideway length outside of station areas. However, a walkway adds significant structural cost to an APM system, not to mention the additional cost to allow passengers manual access to the walkway from the vehicle interior. Further, a control system must be implemented to prevent door egress except in emergency situations. For the Mandalay Bay Express APM system, the additional capital costs of an emergency walkway and door control system was estimated at approximately $5 million.

Therefore, for similar installations that can be accessed from the streets or parking areas below or feature reliable train to train evacuation, the cost of an emergency walkway is not justified. Project development risk evaluation has concluded that where at least two (2) reliable means of emergency evacuation already exist in the event of fire or loss of system power, that the cost benefit of adding a dedicated walkway would not be justified.

Figure 1. Mandalay Bay Guideway.

This does not mean that all APM installations (for Clark County or elsewhere) should not require an emergency walkway. For systems with all or part of an elevated guideway constructed at heights taller than fire department ladders can easily reach, or a system that has sections not easily accessible from below, a walkway for passengers (along with appropriate means of access from the train interior) may be the only viable emergency evacuation option, and also a necessary and vital safety component. Clark County strictly adheres to the International Building Codes with regards to guardrails and handrails for elevated walking surfaces.

Due to this, the County does not recognize walkways as such, but instead as emergency and/or maintenance platforms that may be utilized for evacuation if the procedures are performed in correlation with the Clark County/Las Vegas Fire Departments. Each new system is afforded the opportunity to present procedural methods, provisions, and/or designs to address not only evacuation, but also other life safety concerns. Oversight processes need to be in place that allow functional interpretation of the ASCE APM standards for just such gray areas within the Code requirements.

In addition, past fabrication and QAA assurance concerns have prompted Clark County to implement an Amusement/Transportation System Fabricator/Manufacturer Approval Program (AFMAP) to review the manufacturing/fabrication facilities and insure that an acceptable QAA process is in place. The process also requires that design Verification & Validation activities required to be performed at the facilities are performed and documented to further insure that potential fabrication/manufacturing induced hazards identified in the FMEA/FMECA are effectively mitigated.

McCarran Airport T3

Newer APM installations are designed or configured such that a greater degree of oversight has been applied based upon system constraints and opportunities. As an example, the recently completed Las Vegas McCarran Airport Terminal 3 integration project includes an APM system to link Terminal 3 with Satellite Concourse D as part of an expansion effort. The APM system design consists of two 245 meter (803 ft) tunnels connected by ventilation shafts at each end. Adjacent to each of the stations is an emergency ventilation shaft, where the emergency fans are installed. These shafts vent to the atmosphere and are grated at the interface between the ventilation shafts and atmosphere. Figure 2: "Terminal 3 Station Ventilation Flow Concept" provides a rendering of the ventilation flow path for a fire event in a tunnel.

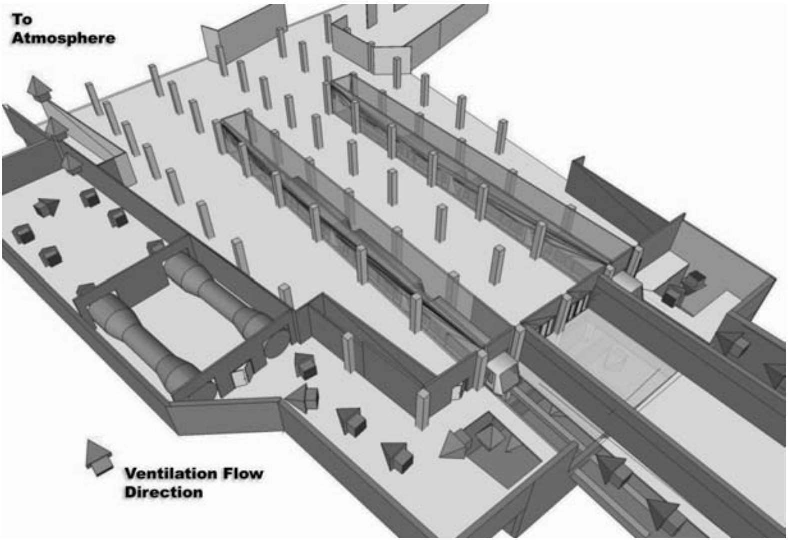


Figure 2. Terminal 3 Station Ventilation Flow Concept.

The control of smoke and fire suppression is necessary for an underground/ subterranean guideway to facilitate the evacuation of APM passengers to a point of safety. This is achieved in the APM System tunnels by providing tunnel emergency ventilation systems. Being a fixed guideway tunnel APM System, local Clark County NFPA 130 codes require that an emergency ventilation system be designed for the Terminal 3 APM System. Half of the APM System tunnels, stations and emergency ventilation shafts were already constructed. Some conceptual analysis of the emergency ventilation system design was performed by others prior to the construction of the existing facilities, however a detailed design analysis of the required airflows, ventilation equipment and ventilation control strategies had not been developed for the existing APM fixed facilities design.

Therefore, the ventilation system was modeled and designed in accordance with industry standard subway design principals within the constraints of the existing tunnel and ventilation shaft designs at Concourse D. In addition, an engineering analysis and simulation of the proposed APM ventilation system design was performed to identify design parameters and ventilation control strategies necessary to maintain a tenable environment for APM System passengers, maintenance staff and other people that may access the APM System tunnels in emergency and non-emergency situations.

Research of other similar transit system applications suggests that smoke control and fire suppression during emergency tunnel conditions, as well as the elimination of heat gain due to normal APM System operations, are best accomplished within the constraints of the existing facilities with reversible, axial-flow fans mounted in equipment rooms at each end of the tunnel system. Axial-flow fans are capable of providing the volume of airflow required to direct smoke flows away from evacuating passengers during tunnel fire events. Axial-flow fans can also be designed with a low-speed function for ventilating the tunnels during normal train operation. The T3 APM tunnel system was equipped with fans in each tunnel emergency fan room located in each tunnel ventilation shaft. Such positioning allowed the ventilation system to utilize the ventilation shafts as a means of drawing fresh air into the tunnel and exhausting smoke out of the tunnel.

This fan arrangement allowed a “push/pull” concept to be used during a tunnel fire event. Depending upon the location of a tunnel fire, it was considered desirable to force smoke out of the tunnel through Concourse D ventilation shafts by operating the Concourse D emergency fans in exhaust mode (pull), simultaneously operating the emergency fans in Terminal 3 in supply mode (push). In this fan operating scenario, passengers would evacuate the tunnel system in the direction of ventilation air flow toward Terminal 3 station. In other tunnel fire scenarios it was considered desirable to supply fresh air in through the Concourse D ventilation shaft and exhaust air from Terminal 3 ventilation shafts with passenger evacuation toward Concourse D station.

Although for this case study a comprehensive emergency evacuation and ventilation system has been developed, it can be considered prudent to expand ASCE/NFPA requirements and/or Clark County code requirements for similar tunnel systems given the extreme sensitivity of such a system to an emergency scenario and high potential for liability. Additional specific requirements to be addressed could include:

- Required airflows based on system size;
- Ventilation control strategies based on number of passengers evacuating the train(s) and emergency personnel entering the area;
- Fan size and/or quantity and blade speed based on emergency smoke removal rates, ventilation requirements and/or elimination of heat gain during normal operations;
- Fan operational requirements for “push/pull” arrangements based on location of incident and direction of nearest evacuation point.

ASCE APM Standard, Part 4

As referenced at the beginning of this paper, ASCE recently released Part 4 of the APM Standards (ANSIASCE/T&DI 21.4-08) with requirements for security, emergency preparedness, system verification and demonstration, operations, maintenance, and training, and operational monitoring. From a safety and security perspective, these additional standards certainly encompass a much more detailed and thorough action plan for verification of system security, emergency preparedness, coordination, training, recordkeeping, and operational monitoring programs than what was discussed previously in the other three parts of the APM Standards.

However, the majority of these requirements typically surface for larger public entity projects such as airport APMs. When an oversight agency such as the Clark County Building Department utilizes these standards as part of its code requirements, they may be taking on a level of regulation that is not necessary for the smaller-scale privately funded projects that are typical of Las Vegas and Clark County. Instead, consideration should be given to simply establishing an alternative framework for safety and security, operations and maintenance, training and auditing standards without requiring documentation such as:

- System Security Program Plan
- Emergency Preparedness Program Plan
- System Verification Plan
- System Operations Plan
- Service Restoration Analysis
- Maintenance Plan
- Training Plan
- System Operational Monitoring Plan
- Independent Audit Assessment
- Other.

Conclusion

New sections of the ASCE Automated People Mover standards have recently been adopted which have shined a spotlight on APM security and safety. These recommendations are being or have been adopted by some jurisdictions (including Clark County) as Code. This could create situations where a broad enforcement of the Code affects the marketability of APMs for which viable and cost-effective alternatives exist to what is called out in the standards. In other instances, the standards may not be enough to adequately ensure public safety. The standards effectively serve as development and operating guidelines while specific implementation can be case dependent.

An oversight process must be implemented that allows functional interpretation of the ASCE APM standards. Further, when adopting the standards for use in Clark County, special consideration should be given to the needs and requirements of smaller-scale, privately funded projects that are typical of Las Vegas. To date, Clark County officials have proven their ability to both understand and apply this distinction in a safe and economic manner.

A Modern Mobility Solution for Urban Transit with the Latest Generation of the *INNOVIA* System

Yihong Xie, P. ENG, Manager, *INNOVIA* Metro

Bombardier Transportation Systems, P.O. Box 220, Station A, Kingston, Ontario, K7M 6R2, Canada; PH 613-384-3100; FAX 613-384-5726; email: yihong.xie@us.transport.bombardier.com

Abstract

High quality transportation systems developed by Bombardier Transportation have literally shaped the physical, social and economic landscapes of many cities. From large scale urban transit networks to fully automated systems at major airports, Bombardier has delivered over 60 transportation systems around the world with an impressive annual ridership of 1.7 billion passenger journeys. Our turnkey solutions integrate Bombardier's full range of expertise, including rolling stock, signaling, operations and maintenance, project management and system integration, underpinned by 40 years of experience in providing and supporting transportation systems.

With 62 production and engineering sites in 25 countries and more than 40 service centers at customer premises across the world and with over 100,000 vehicles in operation, Bombardier Transportation is the global leader in the rail industry. Bombardier is also the global leader in providing the most number of fully automatic, driverless, unattended rail transportation systems in the rail industry. Bombardier provides three types of fully automatic, unattended systems: Advanced Rapid Transit system, Monorail system and Automatic People Mover system.

Advanced Rapid Transit Systems

A top performer in driverless automation, Bombardier's advanced rapid transit systems fill the gap between street-running trams and heavy metros. Excelling as a medium capacity transit system, the latest *BOMBARDIER* INNOVIA** Metro 300 system operates on a dedicated guideways, whether at-grade, elevated or underground – moving more than 40,000 passengers per hour per direction.

Monorail Systems

For dependable mass transit, the beautifully designed, lightweight *BOMBARDIER* INNOVIA** Monorail 300 system provides a smooth and quiet ride experience for passengers. Fully automated driverless operation allows frequent, safe and reliable service, attracting passengers and generating revenue. Bombardier's latest monorail technology permits small, unobtrusive and easy-to-construct aerial guideway structures, which both guide the vehicle and provide its structural support. In dense urban areas, the *INNOVIA* Monorail system offers fast installation and requires minimal land expropriation, enabling transport authorities to deliver a convenient alternative to road vehicles in a short time.

Airport and Urban Circulator Systems

Bombardier is the recognized world leader in driverless automated people mover (APM) systems. Our rubber-tired BOMBARDIER* *INNOVIA** APM systems operate on a dedicated guideway – at grade, in tunnels, completely elevated or in any combination – to offer airport and urban authorities exceptional route flexibility. First introduced in 1971 in Tampa, Florida, the Bombardier APM systems have established an unprecedented track record for reliability and dependability. Our latest *INNOVIA* APM 300 solution offers a long list of pre-designed and integrated options, allowing for numerous configurations. Bombardier customers benefit from lower overall capital and reduced life-cycle costs, as well as greater availability and reliability. Customers also profit from our passenger-oriented operations assistance and turnkey systems expertise.

Introduction

Mobility issues are becoming increasingly important (and in some cases critical) in urban environments where ever-growing numbers of private automobiles now occupy the limited numbers of roadways that have also reached their travel capacity. Fortunately, more local governments and authorities are recognizing this fact and are addressing the issue by the construction of grade-separated automated urban transit systems.

The ability of such transit systems to move more people, more economically, between their residences, places of work and leisure activities brings social, economic and environmental benefits that enhance the quality of life of city dwellers. These are undeniable benefits to urban residents, employers, and to the population in general, however, once a decision is made to implement a public transportation system, the selection of train technologies (Metro, LRT or Monorail), as well as the mode of operation (fully automatic without a driver, automatic with onboard drivers, or manual operation) will have the most impact on the public. In general, the funding for public transportation is provided by a government agency and is indirectly funded by the tax payers, thus the selection of technology must fit with the existing urban environment. Including, the public safety, visual impact, noise and vibration, EMI, energy consumption, and road obstruction caused during system construction will all concern the general public especially the residents living near the transportation corridor.

In order to meet the rapidly increasing demands for public transportation expansion, as well as to minimize the negative impact of the public transportation system, all public transportation system suppliers strive to develop new products equipped with state of the art technology to facilitate transportation system implementation and operations.

Bombardier is the supplier of the world's first fully automatic, driverless, LIM powered vehicle and turnkey ART system. Bombardier has been continuously adapting new technologies to improve the functionality and performance of the ART vehicles. Bombardier also invests in R&D to explore and validate innovative design concepts for the new generations of ART vehicles.

This paper describes the evolution of one of Bombardier Transportation's fully automatic, unattended train systems' family member – *INNOVIA* Metro (formerly *INNOVIA* ART); also discusses the benefit and advantage of the ART vehicle technology.

INNOVIA ART Evolution

- **ART MK I (Recently renamed *INNOVIA* ART 100)**

The first driverless steel-wheeled transit vehicle in the world began its service in Vancouver SkyTrain, Canada, in 1986. It is known as Bombardier's ART MK I. Other ART MK I systems include Detroit Downtown People Mover and Scarborough Rapid Transit, Toronto, Canada. The total number of MKI vehicles delivered to revenue service is 190 cars. Figure 1 shows the pictures of MKI vehicles Bombardier delivered.

Toronto, Canada (1985) **Vancouver, Canada (1986)**

Detroit, USA (1987)

Figure 1. Photos of MKI Vehicles

The MKI vehicles are smaller in its size compare to its next generations with the vehicle length at 12.7m and width at 2.5m. MKI basic unit is two vehicles semi-permanently coupled with no gangway, and each basic unit is equipped with fully automatic electrical couplers to connect the basic units to form a four to six-car consist.

The MKI vehicle has an open driver's area but the controls are contained in the adjacent lockers with keyed access doors. The vehicle has straight side walls and boxy appearance. It has one service door at each end of vehicle and four, 1.2 meter wide bi-parting passenger doors per car. The vehicles have longitudinally arranged bench seats and a passenger carrying capacity of 82 per car at the density of four passengers per square meter. The design life of the MKI vehicle is 20 to 25 years and the in service MKI vehicles are near the end of their design life. Currently Detroit MKI vehicles are under overhaul. Refer to figure 2 for the general layout of MKI vehicle.

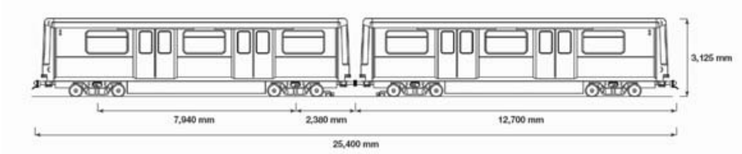


Figure 2. ART MKI Vehicle General Layout

- **ART MK II (Recently renamed *INNOVIA* ART 200)**

In mid 1990's, Bombardier developed the second generation of a fully automatic ART vehicle named ART MKII. In addition to maintain the key features of full automation, linear induction motor (LIM) propulsion and steerable bogies from MKI vehicles, multiple improvements were implemented into MKII vehicles to enhance its capacity and performance. The MKII vehicles are fully compatible with the MKI system guideway with an equivalent width at the vehicle floor elevation and door thresholds but with a wider waist of 2.65 m. MKII is capable of mixed fleet operation in the existing alignments.

The MKII vehicles are longer and wider than its first generation vehicles with the vehicle length at 16.85 m to 17.35 m, and two different width options: a narrow carbody option at 2.65 m, or a wide carbody option at 3.2 m.

The initial narrow body MKII vehicle is a two-car semi-permanently coupled basic unit with a walk through gangway between the two cars. The MKII has the option to utilize a fully automatic electrical coupler in each end of the two-car train to form a four-car consist. A four-car basic unit arrow body MKII was later developed to meet a customer's requirements for increased passenger carrying capacity. Refer to figure 3 for the general layout of a typical two-car consist MKII vehicle, and figure 4 for a typical four-car consist, narrow carbody MKII vehicle.

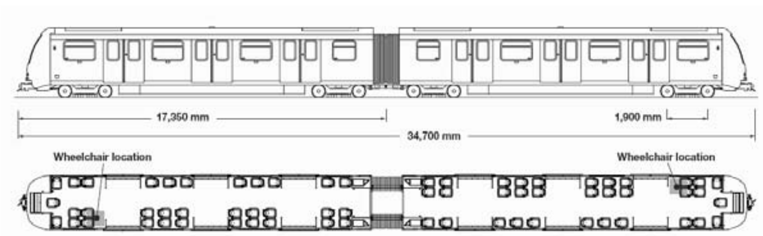


Figure 3. Two-car Consist ART MKII Vehicle General Layout

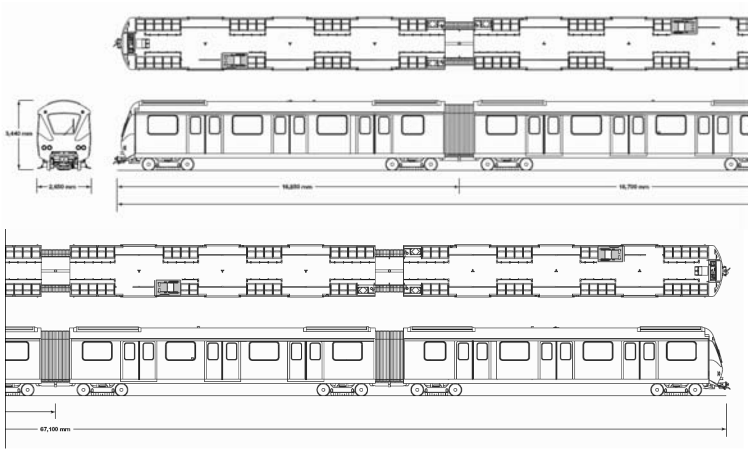


Figure 4. Four-car Consist Narrow Body MKII Vehicle General Layout

The initial wide body ART MKII is a single car basic unit and a fully automatic electrical coupler can be utilized to form a two-car, three-car or four-car consist. Later, a four-car basic unit wide body MKII was developed to meet higher passenger carrying capacity requirements. Refer to figure 5 for the general layout of a typical wide carbody MKII vehicle.

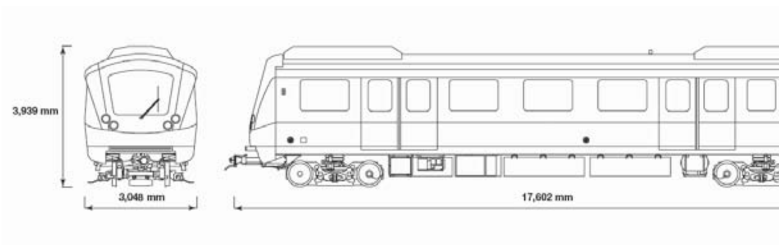


Figure 5. Wide Carbody MKII Vehicle General Layout

The MKII vehicles also adapted two types of power collector systems: a 4th rail system or a 3rd rail system, while MKI vehicle has only the 4th rail power collector system option.

Besides the vehicle size increase, the MKII vehicles have adapted many other design improvements. It has a more ergonomic driver's area. The driver's control panels are locked under a hinged cover during UTO operation and the cover is unlocked and open when in manual operation. The vehicle has kinked side walls for more shoulder room for the seated passengers, and a larger, single front windshield to allow for better viewing for the driver and onboard passengers. On the narrow body vehicle, six 1.6 meter wide bi-parting passenger doors per car are provided. The wide body vehicle has four, 1.8 meter wide bi-parting passenger doors per car. The MKII vehicles have the combination of longitudinally and transversely arranged seats, and an increased passenger carrying capacity of 132 per car (narrow body), and 164 per car (wide body) at the density of four passengers per square meter. The design life of the MKII vehicle was increased to 30 years.

Also, the MKII vehicles have many other new, improved safety and passenger comfort features such as the installation of HVAC system, larger, openable windows and CANBus train health monitoring system.

The first delivery MKII vehicles are approaching 15 years in service. To date, the total number of MKII vehicles in revenue service is 420 cars. Refer to figure 6 for photos of the MKII vehicles Bombardier delivered.

The city of Kuala Lumpur in Malaysia was the first customer to receive the ART MKII vehicles. The 70 MKII vehicles, in two-car consist, entered into revenue service in September 1998 to service the 29 km, mostly elevated alignment with 24 stations. The system maximum grade is 6% and the minimum horizontal yard curve radii is 50 m.

In 1998, to meet the increased passenger capacity requirements as a result of its new 20 km Millennium line expansion, Vancouver SkyTrain ordered 60 MKII vehicles to expand its existing fleet to 210 vehicles (150 MKI and 60 MKII). The new MKII vehicles entered into revenue service in January 2002. The larger MKII vehicles have the capability to operate within the existing depot, and on both the original Expo line and Millennium line which include a maximum grade of 6.5% and the minimum horizontal curve radii of 35 m in the depot yard and 70 m in the mainline.

In May 1998, The Port Authority of New York and New Jersey placed an order for 32 wide body ART MKII cars for the newly built JFK International Airport AirTrain system, which is a combination airport connector and circulator, connecting all terminals in JFK's Central Terminal Area with New York's regional transit system: New York Subway and Long Island Railroad stations. The length of the alignment is 13 km and mixed with elevated, in tunnel and in grade guideways.


Kuala Lumpur, Malaysia (1998) **Vancouver, Canada (2002)**


New York, USA (2003) **Beijing, China (2008)**


YongIn, South Korea, (2010) **Vancouver, Canada (2009)**

Kuala Lumpur, Malaysia (2009)

Figure 6. Photos of MKII Vehicles

The single car basic unit AirTrain cars are equipped with fully automatic electrical couplers and can operate as a single car, two-car, three-car or four-car consist in revenue service. The AirTrain system operates 24 hours, 365 day per year revenue service. Currently Bombardier is operating and maintaining the JFK AirTrain system.

In March 2006, Beijing Airport Link ordered 40 wide body ART MKII vehicles from CRC/Bombardier. The vehicles entered into revenue service in July 2008, in time for the 2008 Summer Olympic Games. This is the first fully automatic, driverless transit system in China, and it's the first time ART vehicles are successfully manufactured in a foreign country under a partnership agreement.

The Beijing ART MKII vehicles are in a four-car basic train unit servicing a 28 KM system. The trains are operating at maximum speed of 105 km/hr and the trains are running 1000 km per day on average. The vehicle first overhaul was begun last year.

In 2006 and 2007, KL placed two additional orders for the total of 140 MKII vehicles to meet its increased passenger capacity requirements in the existing line and to serve the new Kelana Jaya line extension. The new four-car MKII vehicles entered into revenue service in December 2009.

In December 2009, Vancouver SkyTrain's order of additional 48 MKII vehicles went into revenue service in time to meet the increased ridership demand in the upcoming 2010 Winter Olympic Games. That brings the total number of MKI and MKII vehicles fleet in operation at SkyTrain to 258 cars.

Bombardier also delivered 30 wide body MKII vehicles to YongIn Everline in South Korea. The YongIn Everline system is an 18.3 km elevated system where the vehicle is configured to operate in single car trains. In October 2010, the 30 MKII vehicles were fully tested and qualified for revenue service.

- ***INNOVIA* Metro 300 (formerly known as *INNOVIA* ART 300)**

INNOVIA Metro 300 (refer to Metro 300 hereafter) is the next generation of ART MKII.

In early 2009, through market research and analysis, as well as lessening to the voice of existing MKII customers, Bombardier recognized the needs of developing a new generation of more competitive and attractive ART vehicle.

The objective of this new development is to gather and analyze the available new technology and methodology in the rail transportation as well as other industries, and to utilize those applicable technologies to the new Metro 300 vehicles.

Through three years development, Bombardier has designed and manufactured two prototype Metro 300 vehicles at the Center of Competence for Mass Transit Vehicles (short for CoC), in Kingston, Ontario, Canada.

In November 2012, Bombardier received an order of 28 cars of the new Metro 300 vehicles from Vancouver SkyTrain. The 28 Metro 300 cars, in a four-car consist, will further expand SkyTrain's passenger carrying capacity. Figure 7 shows the new look of Vancouver SkyTrain's newest generation vehicle.

Figure 7. Vancouver *INNOVIA* Metro 300 Vehicle

In addition to maintain the key features of full automation, linear induction motor (LIM) propulsion and steerable bogies from MKI and MKII vehicles, Metro 300 adapted new design and improvements such as lighter weight vehicles design to save energy, “mobile factory” concept to accommodate localized manufacturing requirements, and modular design to improve the quality and reliability of subassembly as well as to reduce the final assembly time. The other functional and performance improvements to the MKII vehicles include replacing the outside sliding doors with the micro-plug doors for improved sealing and acoustic properties, improving LIM maintenance access, enhancing LIM Motor/LIM Fan reliability, and replacing Ni-Cad battery with environmentally friendly Sodium-Nickel battery. The Metro 300 vehicles are also compatible with the MKI and MKII vehicles in service and are capable of mixed fleet operation in any existing alignments with the existing automatic train control system.

The Metro 300 vehicle design also put great emphasis on the esthetics of the vehicle. It has a large front windshield and very low profile driver’s console to allow the best viewing angle of the surroundings for onboard passengers and operators. The carbody has a constant curved shape, and the windows are extra large and constant curved to match the shape of carbody. A redesigned front end cap is fitted with modular, modern looking headlights and LED marker lights.

The vehicle interior arrangement is also improved. Cantilevered longitudinal and transversal seating arrangements allow for easier floor cleaning access; energy efficient, longer life LED lightings are used to replace the old florescent lightings to reduce operation and maintenance cost. Also, the HVAC air duct was redesigned to improve the airflow and reduce interior noise level.

Fully automatic *INNOVIA* ART vehicle advantages and benefits

- **Provided reliable and consistent service under all weather conditions**

If it is required to provide reliable and consistent service in all weather conditions, conventional rail technology is usually limited to grades of approximately 3.5%. In Japan, this limitation is spelled out in the regulations. It is related to spin/slide issues and wheel-rail adhesion. Rail technologies that use linear induction motor (LIM) propulsion, and which therefore do not rely on wheel-rail adhesion for propulsion or service braking, are capable of operating on steeper grades. The same Japanese regulation allows LIM systems to operate on grades of 6%.

Almost all modern transit technologies include the capability of regenerating energy through their propulsion system when in braking mode, thus recovering energy that would otherwise be dissipated in friction brakes. Conventional rotary propulsion systems rely on wheel-rail adhesion to accomplish this, while systems with LIM propulsion provide regenerative braking without any requirement for wheel-rail adhesion. Instead, regenerative braking forces are produced directly in the magnetic field between the LIM primary (mounted on the vehicle in ART technology) and the LIM secondary (reaction rail, which is fixed to the guideway surface). This provides assured levels of service braking capability regardless of wheel-rail adhesion conditions, allowing ART technology to provide consistently high acceleration/deceleration performance under all weather conditions. A hydraulic disk brake system is also provided, but is normally used only for the final low-speed portion of the stop, by which time the kinetic energy has mostly been recovered.

- **Independence from Rail Adhesion is an important feature for Automated Systems**

Wheel spin / slide is very common on steel wheel, steel rail transit systems. In any climate that experiences a significant amount of rain, an elevated or at-grade rail system experiences low wheel-rail adhesion values a significant number of days per year. These conditions typically occur, for example, at the onset of rain. Pollution, spills, wet leaves or even pollen can cause low wheel-rail adhesion levels.

In a conventional rail transit system, spin / slide is inconvenient, but it is considered a fact of life. Streetcar or tram systems commonly operate on steep grades under poor weather conditions, and they do experience spin / slide issues, but the tram drivers are accustomed to the need for reduced speed, the need to apply sand, and the need to sometimes take multiple attempts to climb a grade. If they slide past a station stop point, they can usually perform a reversing maneuver, or the passengers can walk to the new door location.

Automated driverless urban transit systems, on the other hand, cannot tolerate any significant amount of spin / slide without significantly degrading system performance. Spin / slide events are particularly disruptive to service in such systems, a fact which may not be clear to those whose transit experience includes only systems with drivers. There are several reasons for this fact of life, including:

Short headways: One of the main advantages of full automation is the capability to operate short trains at short headways, thus providing better service (shorter waiting times) than conventional long trains. This improved service will, in turn, attract more ridership and revenue. Operating headways of 75 seconds are not uncommon; however consistent, reliable operation at such short headways is not compatible with reversing maneuvers or multiple attempts to climb grades.

The requirement for accurate positioning information: The automatic train control (ATC) system that controls a driverless vehicle needs to have accurate vehicle position information at all times. Most ATC systems rely on counting wheel revolutions as part of the process of determining a vehicle's position, thus wheel spin / slide injects errors that may be intolerable, resulting in emergency brake applications and hence disruption of service.

The requirement for stopping accuracy: An ATC system must be capable of stopping a train at a platform stopping point with a very small position error, especially when platform screen doors are in use. This requirement is incompatible with spin / slide.

Modern spin / slide controls can reduce the frequency and duration of spin / slide events, prevent wheel lockup and avoid wheel flats, but they cannot eliminate spin / slide and they are of no help when a vehicle needs to stop at a fixed position accurately. The only method by which such controls can avoid spin / slide is by reducing the rate of acceleration or deceleration, thus, in the case of acceleration, reducing performance, or, in the case of deceleration, extending the stopping distance. In either case travel time is extended.

- **Superior Grade Capability**

Another benefit of ART's independence from rail adhesion is its higher tolerance on the terrain. Clearly significant savings could be achieved using ART technology as a result of the reduced requirements for tunnels and the bridge structure.

- **Curve Capability**

The ART vehicle employs unique radial steering bogies incorporating both forced steering and self-steering concepts which enable a) the ability to operate on curves with radii as small as 50 m (35 m in the depot) to fit in a typical urban streetscape, and (b) low noise.

The bogie design is simple, lightweight and cost-effective, because the LIM propulsion system requires no gearboxes, drive-shafts, or couplings of any kind between the motor and the axles. The motor produces thrust acting directly on the reaction rail through magnetic fields.

The radial steering capability, as well as the absence of gearboxes, drive-shafts and related items, results in very low noise. The radial steering bogie eliminates flanging noise through curves.

- **Reduced wheel and rail wear with the Radial Steering Bogie**

Spin-off benefits of the radial steering bogie design include the fact that rolling resistance in curves is very small, and wheel wear is much reduced compared to conventional bogies. The fact that the wheels are not used to transmit propulsion forces or most service braking forces also contributes to their long life. Also, because flange wear is virtually non-existent and tread wear is very low, when wheel turning is required, the amount of material removed is limited to 1 – 2 mm.

The Vancouver SkyTrain system achieves a wheel life of five years (880,000 km based on an average of 170,000 car-km per year). This is remarkable considering that the ART vehicles use relatively small wheels (470 mm diameter for the ART 100 vehicles, 585 mm for the ART 200 compared with 780 mm for a typical metro car), which have minimal allowance for wear (the ART 200 wheels have an allowance of 14 mm radius for wheel wear, compared to 35 mm for a typical heavy rail metro).

- **Significant civil cost savings benefitting from smaller tunnels**

Compared to conventional rotary motor propulsion, the use of LIM propulsion technology results in a more compact bogie, which allows a lower vehicle floor. The standard ART vehicle has a floor height of 825 mm above top of rail, compared to 1100 mm for a typical rotary propulsion vehicle. This 275 mm reduction in floor height translates directly into a lower overall vehicle height, which can allow reduced tunnel diameter and corresponding reductions in the amount of material that has to be removed and disposed of during tunnel construction. Depending on the tunnel design (single track, dual track, cut and cover, with or without emergency walkway, etc.) and whether it is in solid rock or some other material, the savings due to reduced tunnel diameter can be very significant. Based on the minimum size of (single track) tunnel for both conventional and ART technology, the reduction in amount of material removed would be approximately 10,000 m3 per km of dual tunnel. The amount of tunnel liner material would also be reduced, by approximately 1,900 m3 per km of dual tunnel. These estimates are based on a 5.0 m finished tunnel diameter for ART, and 5.5 m finished tunnel diameter for conventional trains, with a 0.6 m thick tunnel lining.

Lightweight Vehicles resulting in less noise, vibration and less energy consumption

Low vehicle mass was one of the original design requirements of the ART vehicle development program. The use of LIM propulsion helped to achieve this requirement by allowing the use of smaller diameter wheels, a smaller bogie frame, and eliminating the need for gearboxes, drive-shafts, couplings and their associated bearings. Elimination of the driver's cab provides more passenger space per unit of vehicle mass. The carbody is a strong but lightweight welded aluminum structure. Comparisons of the ART vehicle with similar sized conventional transit vehicles show that the ART vehicle is approximately 24% less massive (1300 kg/m of car length compared to 1700 kg/m).

Lighter vehicles are inherently more energy efficient, and can potentially reduce the cost of elevated structures. There is also a benefit in reduced noise and vibration due to the fact that the vibration that is produced by the vehicle is excited by a smaller mass and is therefore less energetic.

Refer to figure 8 and figure 9 for ART vehicle weight and energy consumption comparisons.

- **Operation with LIM vehicles achieved low industrial operating cost**

Refer to figure 10 for the operating cost comparison of two Bombardier supplied LIM systems compared to 14 US systems. The source of the data is from FTA (Federal Transit Administration, US Department of Transportation). The comparison result shows that SkyTrain system has the lowest overall Operation and Maintenance cost per passenger carried, while JFK AirTrain system has lower Operation and Maintenance cost than that of eight US systems.

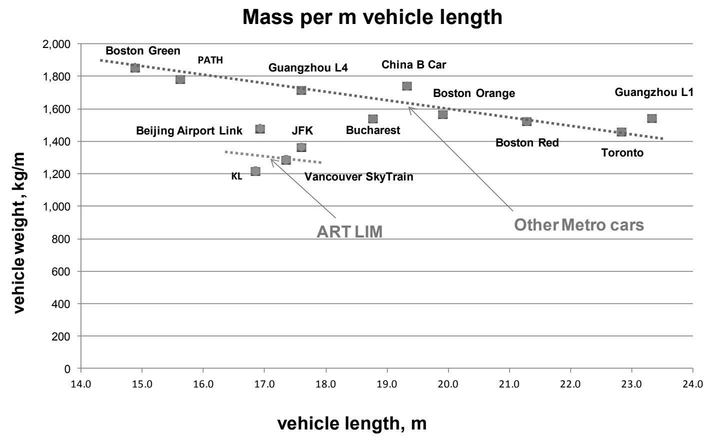
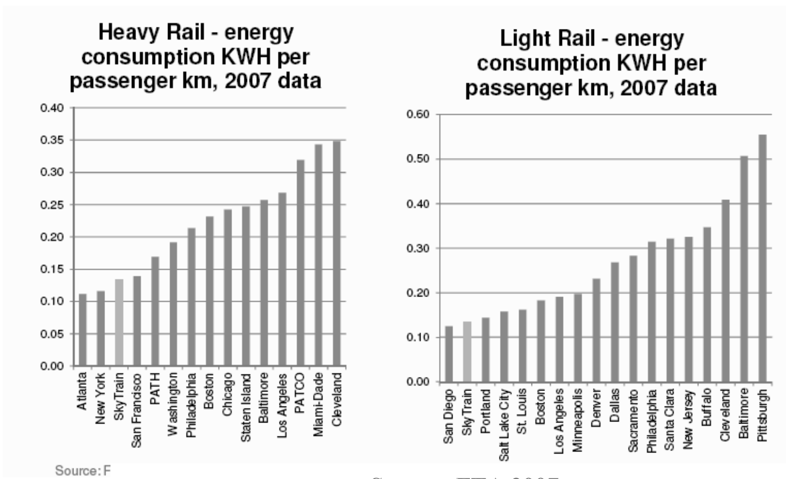


Figure 8. Vehicle Mass Comparison



Source: FTA 2007

Figure 9. ART Energy Consumption Comparison Compared to U.S. Systems

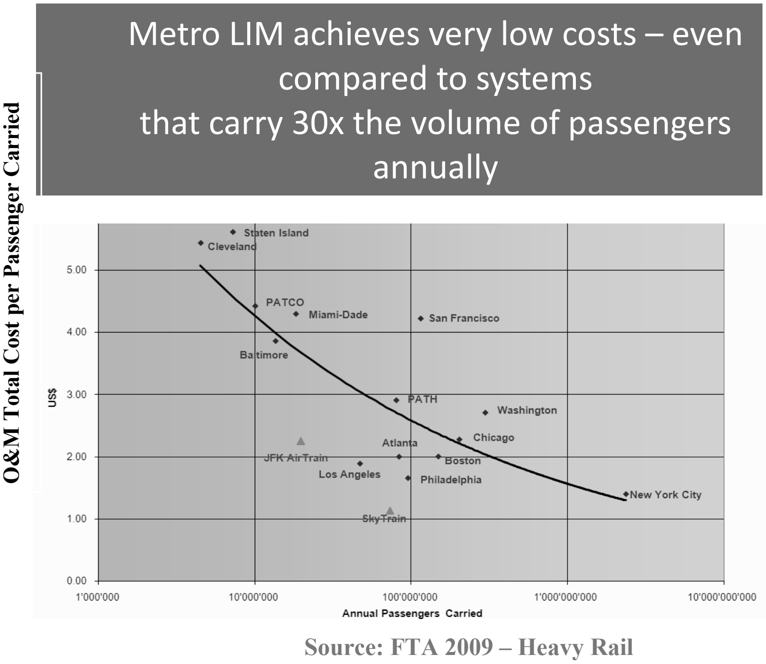


Figure 10. ART O&M Total Cost per Passenger
Compared to US Heavy Rail Systems

Conclusion

Bombardier's fully automatic, driverless, LIM propulsion, low profile steerable bogie ART vehicles provide the most energy efficient and low maintenance cost transportation system for medium capacity public transportation needs.

The ART system has unique advantages that contribute to consistent, weather and track condition independent operating performance which is very important for short headway, automatic train operation.

A low vehicle mass, smaller ART provides for lower energy consumption and the reduction of the size of the elevated guideway infrastructure and tunnels due to the smaller operating envelope. The lighter, steerable ART reduces noise and vibration transmission to the surroundings.

The employment of a radial steerable bogie and LIM propulsion enable the maximum flexibility in alignment route selection with the possibility of smaller design curves and up to 6.5% grades that provide the benefit of lower guideway construction cost without sacrificing the performance.

Bombardier continues to enhance the original benefits of ART vehicle with the latest technology. The newest generation ART vehicle – *INNOVIA* Metro 300 will provide customers with the combination of modern, attractive aesthetics and the best performance in its class.

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Personal Rapid Transit User Interface

Jenny A. Baumgartner, P.E., AICP[1] and Peter Chu, P.E., LEED AP[2]

[1]Manager of Engineering Projects, Lea+Elliott, Inc., 101 Montgomery Street, Suite 1750, San Francisco, CA 94104, (415) 908-6450; (415) 908-6451 (fax); jbaumgartner@leaelliott.com
[2]Project Engineer, Lea+Elliott, Inc., 101 Montgomery Street, Suite 1750, San Francisco, CA 94104, (415) 908-6450; (415) 908-6451 (fax); pchu@leaelliott.com

Abstract

PRT is an emerging technology with systems and test tracks in operation, under construction, and planned around the world. One aspect of the system that affects the passenger experience and can impact the success of a system is the user interface. The process used by passengers for fare collection and/or destination selection should be intuitive as well as efficient. This paper will review the "human factor" of PRT systems.

1 Introduction

Promising on-demand, point-to-point transportation, Personal Rapid Transit (PRT) systems have been the dream of futurists for decades. Characterized by small vehicles, on-demand boarding, and direct, non-stop origin to destination trips, the systems have the potential to improve patron wait times and overall trip speed, while minimizing infrastructure costs for operators. While technically feasible for decades, challenges both in technical complexity and social adoption have led to few systems actually being implemented. Over the last decade, however, decreases in the cost of computing and networking components have lowered the technological barriers to implementation, leading to a new crop of PRT installations.

As PRT matures, however, challenges common to the introduction of any new technology become evident. Like the early automobile—where different methods for acceleration, braking and steering were explored before the eventual adoption of the familiar wheel and pedals—the manners in which a patron interacts with a PRT system are untried and varied. Should audible progress be frequent and detailed, or only as necessary to reassure the patron? How often should the patron be prompted for input? Should a patron select their destination on-board the vehicle or car, or outside at a station kiosk? For that matter, what should constitute a station if the network is virtual, and a station is simply a set of coordinates for a specific curbside?

Questions such these, are the challenges faced by PRT that this paper will try to identify. These questions pose challenges, but also opportunities to develop seamless and functional interactions between system and patron. In the same way automobile user interfaces became standardized over time, the PRT interface is likely to become standardized as more systems are implemented. Identifying the challenges of interface design now can lead to identification of solutions and best practices in interface design in the future.

2 Sampled Systems

This paper investigates the user interface of several implemented PRT and intelligent transportation systems that incorporate interactivity into a patron's journey. The systems sampled range from an automated people mover that functions much like a rapid transit system, to an entirely autonomous small vehicle that provides point to point travel in a network, to a destination control suite for elevator networks in large buildings. Each system allows a patron to select a destination and be delivered to that destination with limited or no interim stops. Such demand management yields more effective use of resources for operators, and shorter wait times for patrons.

As of 2012, the authors had identified three PRT systems in operation, as well as one additional under construction. The systems formed the basis for the observations made in this paper and are described below:

2.1 ULTra PRT / Heathrow Airport, UK

Source: ULTra PRT

The Heathrow PRT is the first major implementation of the ULTra system that grew out of research at the University of Sheffield in England. Small and lightweight vehicles travel along a low-profile, grade-separated guideway, connecting London Heathrow Airport's Terminal 5 with two stations in a remote parking lot. All propulsion and switching functions are accomplished on board the rubber-tired vehicle with optical sensors that navigate the guideway edge curbs and provide feedback for vehicle steering and switching. This initial alignment is more linear or “line-haul” in its configuration than is typically envisioned for PRT, but will develop into more of a grid network with planned expansions. Vehicles are dispatched from stations where vehicles berth in a sawtooth configuration; outside of the berth, patrons use a kiosk comprised of a touch-screen to select their destination.

2.2 Vectus PRT / Suncheon, S. Korea

Source: Vectus PRT

The Suncheon implementation of the Vectus PRT technology is expected to be similar to the Heathrow PRT system: it will be an individual PRT system with small vehicles serving in-line stations, and providing point-to-point transportation. Scheduled for completion in 2013, the planned forty-vehicle system on 5 km of guideway serving two stations is expected to provide transport for three million passengers annually.

2.3 2GetThere / Masdar, U.A.E.

Source: 2GetThere

2GetThere recently installed an urban PRT system at Masdar City in Abu Dhabi. This application of PRT features two single-lane guideway loops with dual lane connection between the loops. Vehicles are guided by on-board maps, and error correction is provided by magnets installed at 4-m intervals along the guideway. Angled berths are utilized at the stations and destination selection occurs outside the berth using a touch screen.

2.4 Morgantown PRT / West Virginia University, USA

Source: Morgantown PRT

One of the earliest implementations of a PRT system is the five-station Morgantown PRT system located on the West Virginia University campus. This system, which entered operation in 1975, uses a patron's destination selection to group patrons into vehicles that travel directly from one station to another, bypassing any in-line station. The system prioritizes vehicle assignments based on demand, for example dispatching vehicles to a destination with 20 patrons waiting over a destination with 2 patrons waiting (although wait times are governed, ensuring that no patron waits more than a set time once a destination is selected).

The system uses stations and vehicles that resemble scaled-down versions of traditional rapid transit systems. The guideway for the rubber-tired vehicles is lighter than comparable steel wheeled systems, but includes more elements (communication, power distribution, physical guidance) than other more modern PRT systems.

The Morgantown PRT includes a barrier-type fare collection system, where under normal operating conditions, passengers swipe their student ID cards or pay cash and select their desired destination from the destination selection unit prior to entering the paid area of the platform. A display on the platform notifies passengers which loading area to proceed to.

2.5 Otis Elevator Compass(tm) Destination Management

The authors sampled the Otis Compass Destination Management system as an example of demand control systems that are increasingly being used for large buildings where it is prohibitively costly to have all elevators serve all floors. The destination management systems function much like group PRT systems, such as Morgantown, in that they solicit patron destinations in order to group patrons and assign them to an elevator car that serves their floor.

3 The PRT System User Interface

The PRT System user interface, for the purpose of this paper, is comprised of all elements with which a patron interacts over the course of a journey. Those elements are in many ways similar to the interaction on a scheduled transit system (where vehicles are dispatched based on a schedule, and make all stops along a given route) A PRT system adds the additional element of interactivity to the process of routing by allowing the patron to select a specific destination.

3.1 System Signage

Directional Signage
As with a scheduled system, the first element of a patron's journey in a PRT network is the directional signage throughout the system. Signage signals to the patron what is and is not part of the network by using consistent palettes, typefaces, language and convention—essentially creating the aesthetics for the network. In a PRT network, where the point of boarding is sometimes as simple as a specific portion of curbside, signage performs a critical component of the patron's way-finding. Directional signage, while often simple in nature, plays an important role in the patron's wayfinding process.

System/Network Maps
Once directed to the berthing location or boarding point for the network, the patron must identify their destination. Destination selection is in many ways the most critical piece of information for a journey on a PRT network, as it forms the basis for all future interactions with the system (all system confirmation requests and progress updates will be based on the decision). Additionally, once initiated, a journey is unlikely to be able to be cancelled, making proper destination identification increasingly critical as the duration of the trip grows.

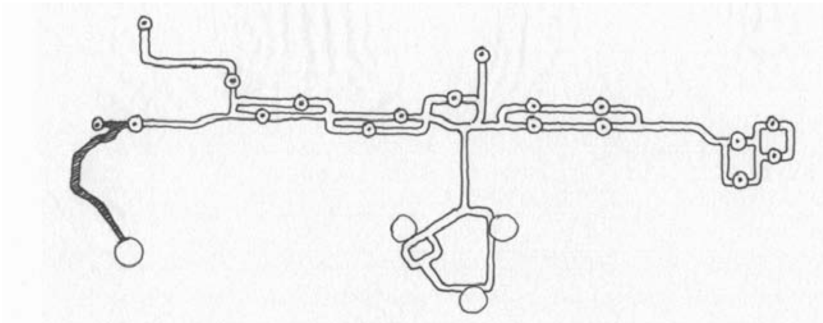

Figure 1: Proposed Heathrow PRT network. As the distance and duration of the journey grows, choosing the correct destination becomes imperative.

As with a scheduled system, the system map is likely to carry forward the branding elements of the directional signage to create continuity as the patron progresses along their journey on the network. Also like a scheduled system, the map is likely to emphasize the conceptual configuration of the system, rather than the actual geography it traverses, as the PRT network makes stops at specific locations.

While a scheduled system requires a system map at the platform and on-vehicle (and at fare collection if fares are collected and are distance based), a PRT network map is critical before fare collection and destination selection. Most PRT systems with a non-linear network are likely to incorporate the map as part of fare collection or destination selection in an effort to simplify the way-finding process. This can come in the form of displaying the PRT network map on a touch-screen that allows passengers to select their destination, which then prompts the user on the required fare. This can minimize the need for static signage at the station, although providing static signage can reduce congestion at stations by allowing patrons to identify their destination before boarding or approaching a kiosk. Once on board a PRT vehicle, the PRT network map can be shown for informational purposes and may be cropped to only show origin and destination, or may be overlaid with the vehicle's progress.

3.2 Kiosk / Destination Selection Unit

Some systems conduct fare collection and destination selection on-board the vehicle or car; others provide a Destination Selection Unit (DSU) at the station or berthing location, where destinations can be requested before a vehicle or car is present. The DSU may be as simple as several physical buttons mapped to stations or floors, or may be an interactive system that provides step-by-step prompts, enabling the patron to choose a destination. The DSU can be installed in a variety of places, from station entrances to platform, or may be incorporated into other system elements. Generally the configuration depends on whether the system is a group PRT system where multiple journey requests are combined into a vehicle trip, or an individual PRT system, where one journey request is assigned to one vehicle.

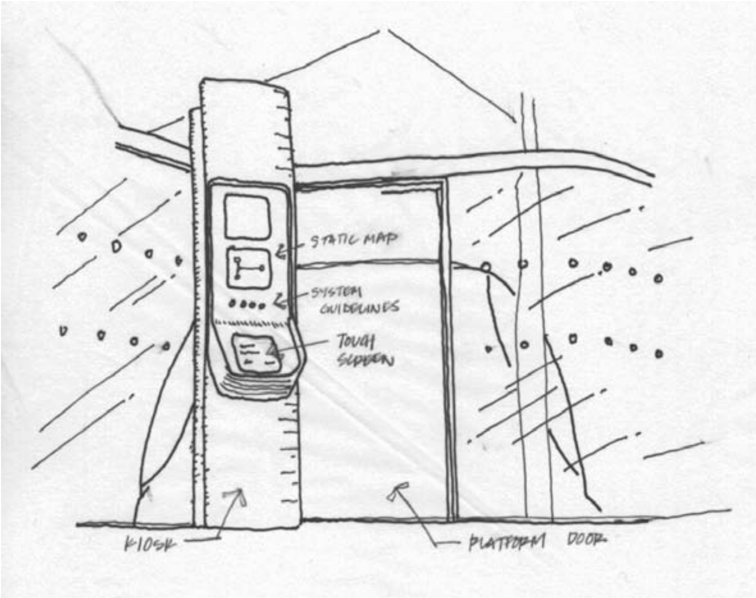

Figure 2: Heathrow PRT kiosk and boarding position

Some group PRT systems provide a central DSU where patrons request their destinations before being directed to a berthing location. For example, an elevator destination management system may direct all patrons to a single DSU, then direct them to a specific elevator car after their destination has been selected. This DSU can be simple, perhaps a touch-screen in a kiosk incorporating as little as a list of destinations, likely in the familiar format of the traditional elevator panel. It may also incorporate access control, requiring patrons to authenticate before providing the option of destination selection.

Other group PRT systems provide multiple DSU kiosks, usually at entrances into the system, associated with fare vending, or at the point of entry into a fare-paid zone. Such a system might be incorporated into a ticket vending machine, or into a turnstile or similar flow-control device. In each case, the system sums the demand for a station and dispatches an appropriate number of vehicles or cars; the patron queues in a central area and is notified by dynamic signage when a vehicle or car to their destination is available at a specific berth or door.

Individual PRT systems use on-board or berth-side destination selection. These DSUs are increasingly presented as touch-screens, either incorporated into the vehicle, or in a berth-side kiosk. An individual PRT must guide a patron (or party) through the process of identifying (and optionally paying for) a point-to-point journey. User interface is essential because this journey will be one that is longer than an elevator ride; a journey that is less easily cancelled and restarted as would an elevator trip.

Key functions of the berth-side kiosk are to display a map of the network, prompt a patron to select a destination, prompt the patron to confirm the destination, and to collect payment for the journey if fares are required. It also must direct the patron into the vehicle, or keep the patron apprised of progress if the system must dispatch a vehicle for the patron. Additionally, the kiosk may guide the patron through their journey, as well as describe what to expect, a feature that is important in environments where patrons are likely to be new patrons.

3.3 On-board User Interface Elements

The user interface continues inside the vehicle or car, where the functions of the user interface are to provide feedback to the patron that they have boarded the correct vehicle, to reiterate that the trip is progressing as desired, and to provide emergency assistance if necessary. As with other components, on-board user interface elements likely use "branded" elements to communicate continuity of the journey between berthing point or elevator door and the vehicle. Elements of the on-board user interface include:

Emergency Communication and Control
Because PRT vehicles function without operators onboard, the baseline for all onboard PRT user interfaces is a life safety connection to the system control center. This connection is used for emergency communication, and generally consists of a physical button that opens audio communication with an operator at the system control center. The button must be in a logical and immediately evident place, similar to emergency communication controls in scheduled transit systems or traditional elevators. It is often augmented with red paint or backlighting. In the event of a disruption to system operations, the audio channel may function as a public address system to keep patrons informed of any situation that has arisen.

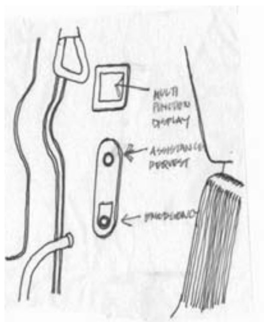

Figure 3: Ultra PRT Emergency Communication Panel

Progress and Status Information
Most PRT systems augment emergency communication controls with a display that shows the progress of the vehicle's travel, providing reassurance to the patron that the trip is proceeding as desired. This display may be as simple as a floor or station indicator in a linear system, or a lighted panel in a system with few stops. For universal accessibility, as with scheduled systems, the visual progress display can be augmented with audible announcements.

Newer systems consolidate the progress and status information with other system functions by using a display that serves multiple functions: In addition to displaying the current location of the vehicle (often displayed in plan form for a networked system, or as a station or floor indicator on a linear system) it can be used to solicit input from the patrons when necessary, or to augment the public address function of the audio channel when necessary by displaying instructions and diagrams.

The progress display is generally placed in a prominent place in the vehicle, either at the high-point of a seated patron's viewpoint (for example on the ceiling, as in a scheduled system) or near the emergency communications controls, in which case the display is usually integrated with the emergency communications controls and any other vehicle controls to form a "control panel" that conveniently collects the on-board elements of the PRT user interface.

Destination Selection
If destination selection does not take place outside the vehicle, destination selection can occur inside the vehicle, in much the way an elevator patron selects a floor. This destination selection can occur via physical buttons in a network with limited destinations, or as part of a multi-function display if the vehicle is so equipped.

The disadvantage of destination selection occurring inside the vehicle is that precious time can be exhausted in wayfinding while passengers are inside a berthed vehicle. Time spent wayfinding inside the vehicle diminishes the throughput of the station, resulting in lost capacity of the PRT system, which may particularly become a concern during peak hours.

Journey Initiation
In some on-demand systems, especially in those where the journey is longer rather than shorter, a patron must initiate the journey as a final confirmation that they do indeed intend to travel to the destination they have selected during the destination selection stage. Journey initiation can be accomplished via a soft button (usually part of the vehicle's multiple-function display, if so equipped), or via a physical button. The location of the button may be highlighted by backlighting, which, along with audible cues, indicate that this is the next necessary step of patron confirmation for the journey to continue.

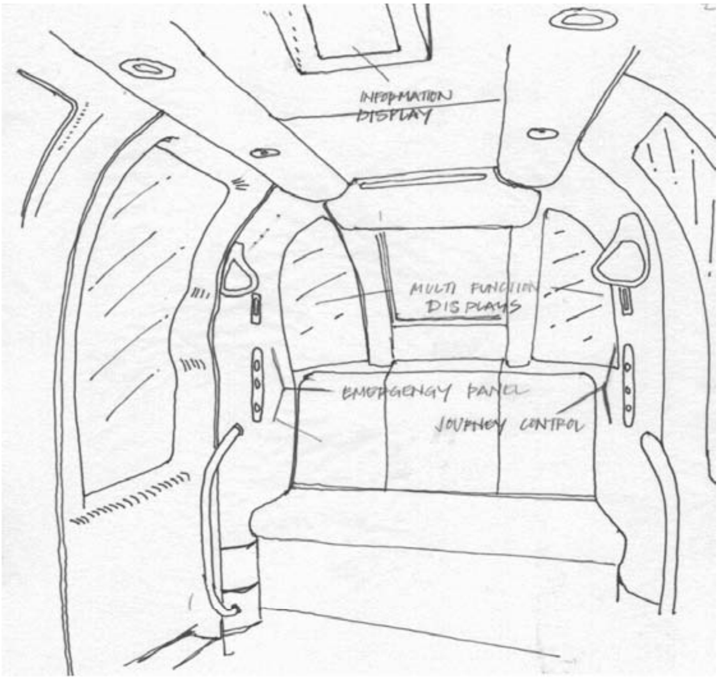

Figure 4: On-board elements of the ULTra PRT system

4 Sample System Walk-through

To demonstrate how the PRT interface elements come together to form the user interface, consider the following walk-through of a PRT system; in this case, London Airport's Heathrow PRT system.

A journey begins at Terminal Five, where the guideway deposits vehicles onto a floor of the parking garage, and a four-berth station is available to patrons. Directional signage in the terminals guides patrons to the station. Once in the station, patrons are guided to one of the (3 or 4) station kiosks, located on the narrow end of a saw-tooth berth. The kiosk consists of both static displays (system rules and guidance, as well as a map) as well as an LCD touch-screen, which is the primary means of interaction with the system at the kiosk. (Elements that appear on the on-screen display are displayed in the “Visual Interactions” column in Figure 5.)

Patrons are invited to begin by touching the screen, and prompted to choose their destination with on-screen buttons. Having selected a destination, the system cues the patron audibly to confirm their choice (audio cues are described in the “Audio Cues” column of Figure 5). If a car is present, the system provides audible and visual cues that the system is ready. A voice announces "I'm ready," and doors on the platform and on the vehicle open. Continuity between station and vehicle is provided by a flashing light inside the vehicle, which invites the patron in, as well as the same announcement ("I'm ready") broadcast inside and outside the vehicle.

Inside the vehicle, the user interface consists of panels on each side of each set of doors, as well as LCD screens on the ceiling and above each panel of controls. Emergency communications controls are located to the right of each door, while journey control elements (Close doors, Start, and Open Doors buttons) are located to the left. LCD displays mirror spoken announcements and show progress to the destination. Once inside the vehicle, the system audibly and visually prompts the patron to begin the journey. Flashing LED lighting directs the patron to buttons that must be activated; when pressed, the system confirms the initiation of the journey as well as the destination.

If the way is clear, the five-minute journey begins. The system confirms the destination by announcing the distance of the journey, including origin and destination. Should there be a delay in starting, however, the system provides feedback audibly and visually, announcing: "There is a slight delay. We'll be on our way as soon as possible." When the delay clears, progress is indicated with the announcement "We're on our way. Sorry for the delay." Each announcement is mirrored on the small LCD displays.

En-route, announcements are limited, although LCD displays indicate the vehicles progress from origin to destination. As the journey ends, the system makes several announcements to prepare the patron to disembark, with doors opening automatically at the destination station.

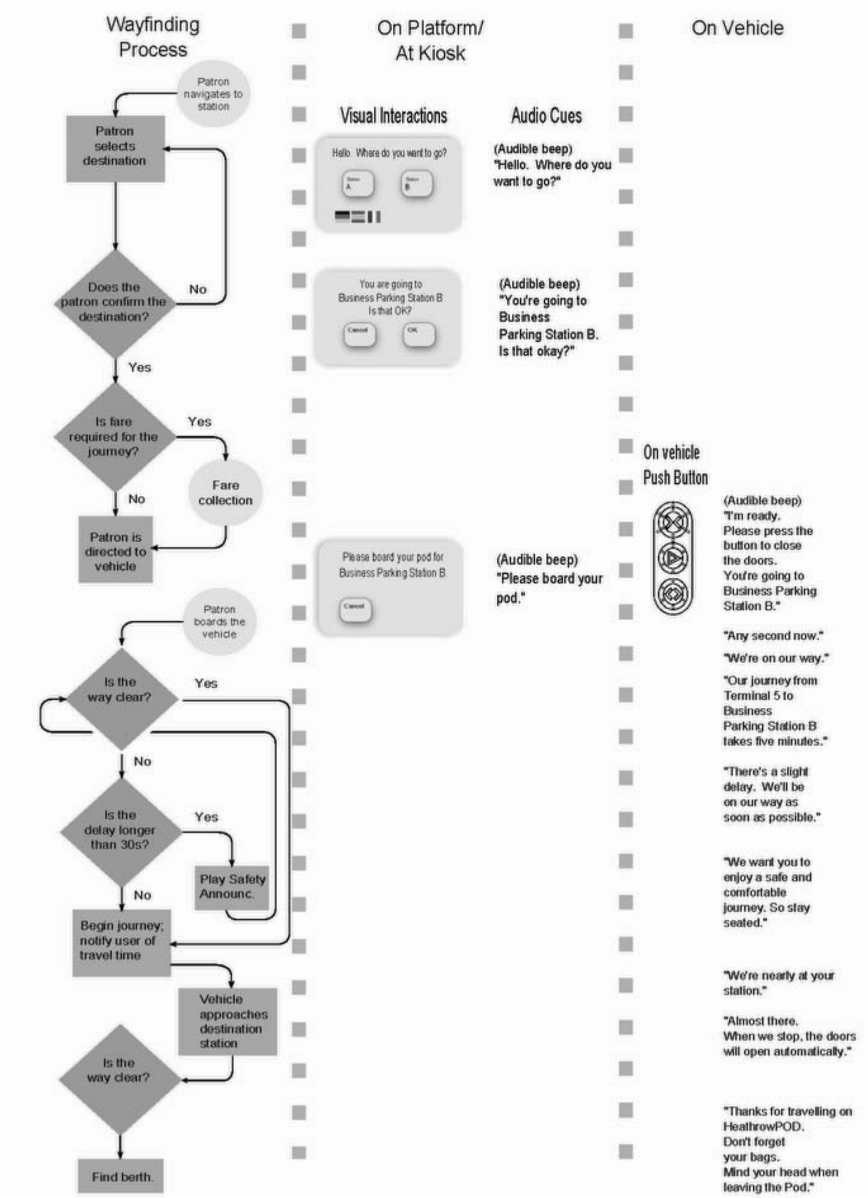

Figure 5: Audio and Visual Elements of the User Interface on the Heathrow PRT

5 Challenges

Early PRT systems earned their reputation as "horizontal elevators" through the simplicity of their user interfaces. While users were able to choose their destination, feedback received and interactivity beyond confirmation of destination selection were limited. In the Morgantown PRT system, for example, the user interface was limited to an elevator-like destination display panel incorporated into the turnstile, and lighted, but with static passenger information displays at each boarding area.

The simplicity of early systems was a direct result of several limitations placed on the system as a result of available technology. These included:

- Limited processing power of available computing components
- High cost of computing components
- Physical, low-speed communication
- Physical power distribution

As an example, the original Morgantown PRT system relied upon a 2400bps communication system – about a third the speed of a fax machine. Accordingly, the user interface was streamlined as much as possible to take advantage of any efficiencies.

In contrast, today's PRT systems are able to reap the advantages of great advances in technology, which has also drastically dropped in price. These include:

- Comparatively low cost components
- Easily scalable processing power
- High-speed wireless communications
- High-capacity rechargeable power sources

These changes make it vastly easier to create a system that requires less infrastructure, is less costly to implement, and that can be more closely tailored to the particular application or project. The increased flexibility available to designers, however, can create challenges in developing the optimal user interface, which this section will evaluate.

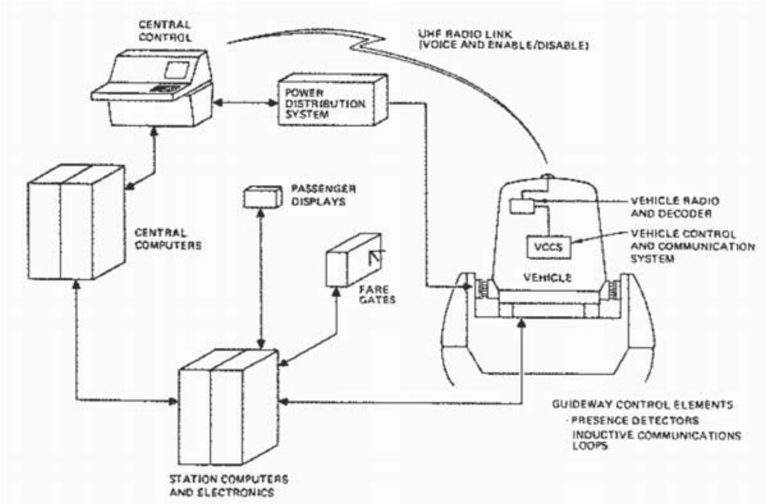

Figure 6: Sample PRT infrastructure and system components

5.1 Increased Complexity

As a maturing technology, PRT systems may cause some anxiety for first time users during their journey. Much of this may occur at the beginning of the journey due to the increased number of decision points and interactions as part of the wayfinding process. Part of this process will involve passengers identifying and selecting their destination within the system, paying the correct fare and validating media, and in some instances being directed to the correct vehicle or berthing station via audible announcements or visible displays. Once inside the vehicle, passengers will have the opportunity to confirm their destination by pressing a button to close the vehicle and station doors, thus initiating their journey.

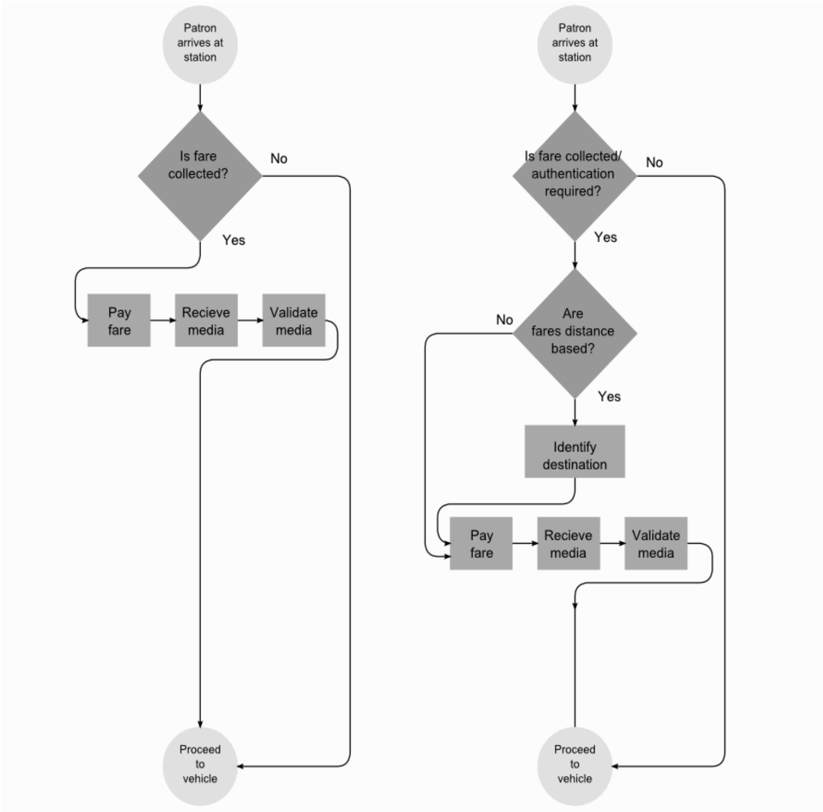

Figure 7: Passenger Wayfinding at a PRT Station.

Guideway configurations of a PRT system are typically envisioned as a network of individual loops, leading to some circuitous routes to get to a passenger's final destination. In order to provide peace of mind, appropriate feedback becomes significant during the journey process.

5.2 Providing Appropriate Feedback

While important to provide confirmation as reassurance to the patron that the journey is proceeding as desired, it can be easy to overwhelm the user with superfluous information. If a delay occurs at any point in the journey, intermittent updates and announcements should notify the passenger of the status. By the same token, too many updates can overwhelm and even exasperate a patron to an extent of detracting from the overall passenger experience on the system. Feedback should clearly differentiate between regular status updates and an emergency condition, notifying the passengers of the appropriate measures and actions.

5.3 Lack of Uniformity in System Components

The destination selection unit is an integral component of the passenger interface to the PRT system, and on-demand passenger service functionality. The destination selection process for conducting a PRT journey often mirrors that of interactions with other machines, such as ATMs. With few systems implemented, however, there are few purpose built interfaces for conducting the destination selection transaction, and manufacturers often have to build a solution from the ground up. There is varying software for destination selection units, but all should be software configurable to indicate various greetings and messages and allow the central control operator to change or add messages. Furthermore, the destination selection unit requires interfacing with the automatic train control system which automatically regulates the movement of all vehicles, including collision control, switching operations, overspeeds, acceleration, deceleration, etc. As the technology for these systems components become more battle tested and hardened on the project site, overtime, uniformity could naturally come to the forefront.

5.4 Functional Grouping

In group rapid transit systems, similar to the system which is currently in operation at Morgantown, functional grouping of passengers becomes a critical part of the process and the overall efficiency of the system. Group rapid transit offers the advantage of a higher capacity vehicle with point-to-point service, but presents the challenge of grouping specific passengers headed to the same destination to a specific loading area. At Morgantown, this wayfinding is achieved with variable message displays above each station berth that directs passengers to which loading area to proceed to.

As a system grows, the wayfinding becomes increasingly challenging, analogous with the number of destination stations and operating vehicles. A larger system may require multiple platforms per station to handle capacity, which would involve station signs either at ground or mezzanine level that direct passengers to their correct platform. This wayfinding can occur either before or after destination selection has occurred, but should be thoughtfully planned as well as intuitive for the passenger. Future expansions to the system should be accounted for in the early phases of the system and be detailed and flexible, allowing for long-term implementation.

5.5 Accessibility

Accessibility plays an important aspect in the user interface with the system and considerations need to be made to accommodate the elderly or those passengers with limited mobility. All elements of the journey should be examined—ingress/egress from the station and platform, destination selection for the visually impaired, level boarding onto the PRT vehicle, and adequate floor space within the vehicle for wheelchair access. PRT systems are being implemented worldwide and while accessibility standards vary from country to country, efforts should be made during planning and design, from both the supplier and owner, to ensure that any system elements requiring passenger interface meet minimum guidelines and international codes.

6 Conclusion

PRT systems are an emerging technology that has the potential to improve passenger wait times and overall trip speeds, while offering a futuristic and memorable experience for the passenger. A critical piece of this experience is how the user interfaces with the system and the potential affect it has on operational efficiency.

Key factors associated with the user interface include providing appropriate feedback and status updates, destination selection, wayfinding, passenger grouping, and accessibility. These aspects can present challenges during planning and development and should be carefully considered to establish a cohesive system and create a user friendly experience. The manner in which a patron interacts with a PRT system can leave a lasting impression for the user and efforts should be made to make the process both intuitive and streamlined.

The efforts made now to identify opportunities that create a seamless and functional interaction between system and patron, as well as enhance system operations, can pay dividends in the overall use of time, efficiency, and passenger experience in this promising and futuristic transportation alternative.

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The Track to Suncheon: Making APMs Intelligent

Martin Pemberton

Sales and Marketing Director: Vectus Ltd, Clifford Mill, Clifford Chambers, Stratford upon Avon, Warwickshire, UK; email: martin.pemberton@vectusprt.com

ABSTRACT

This paper will discuss the notion that the traditional concept of an APM can be developed from a simple line-haul system into a fully automated transit network (ATN) using smaller vehicles and more sophisticated control technology. Implicate in this ambition is the need to adopt a robust safety regime, which is not excessively complex or expensive to implement. At the present time, it is believed Vectus is the only vendor in the world offering a rail based PRT solution which conforms to internationally accepted mass transit and people mover standards for construction and safety.

These issues will be discussed within the context of the first commercial project being implemented by Vectus, in Suncheon bay South Korea, which will demonstrate the potential of this pioneering technology. Suncheon will showcase Vectus's design-led approach, working with world class partners such as Pininfarina in Italy, and lightweight vehicle engineering using state-of-the-art, carbon fibre composites and a revolutionary new type of space-frame bogie.

INTRODUCTION

Vectus can provide what in PRT speak is commonly termed the 'last mile', or perhaps several miles of transportation, say from a busy railway station, which might otherwise involve a taxi ride or a bus directly into a satellite area such as a housing estate or retail centre. Because the vehicles are small-scale and lightweight, they can be carried on a much smaller, (ideally elevated) track infrastructure, requiring minimal ground take and reduced power consumption. In terms of carrying capacity, Vectus is arguably the most cost effective public-transit solution, in comparison with say a monorail or light rail system, for moving up to around ten thousand passengers per hour. Thereafter, one needs to be considering a more traditional, mass-transit mode.

The road, or more correctly the track, to Suncheon began some time ago. As the PRT community is aware, Vectus has operated a test track in Uppsala, Sweden since 2007. It comprises 400 meters of track, three vehicles and one off-line loop with a station. The vehicles are all captive to the track and employ positive mechanical guidance using on-board switches instead of conventional track-switches – which are too slow to be practical for PRT headways. Although the test track was built using in-track linear motors, ostensibly to operate in an icy winter climate, the Vectus concept is adaptable to a variety of propulsion solutions including on-board LIMs and much lower cost, conventional rotary motors. It is this latter solution which is being used in Suncheon.

The first trial runs in Uppsala were made to verify the propulsion system and basic controls. Thereafter a rigorous programme of tests and verifications were performed, step by step, with increasingly more complex functionality to cover all aspects envisaged for a full commercial application. Most critically, this included the merging and braking of vehicles running at ever decreasing headways. This eventually led to the creation of a unique safety case and eventually the test track being fully approved by the Swedish Rail Agency for PRT operation with passengers.

PERSONAL RAPID TRANSIT VERSUS APM

PRT, or 'personal rapid transit', is a very broad, generic term which Vectus has more inherited rather than inspired. It has very academic roots, and depending upon one's experience and readings of past theories and demonstrations, it can engender very different understandings and pre-dispositions amongst colleagues in the transit industry per se. Indeed there are a lot of myths and prejudices about what PRT is capable of doing and what it might actually cost to realise a fully integrated system; one capable of demonstrating in reality, rather than forever in theory, just what this potentially ground-breaking new technology might really have to offer. The situation is not helped of course by the reluctance of vendors to expose their costing models (for obvious commercial reasons) and the reluctance of risk-averse customers to invest in new solutions, however big the claims, that are as yet unproven in the market place. It is the classic chicken and egg conundrum.

In the Vectus business model, the idea of creating a purely 'personal' transit system is not the main driver. Rather, we are looking for efficiency, flexibility, sustainability, low capital investment and above all, low operating cost. If we can afford passengers the luxury of travelling alone, just with friends or in family groups then this is a bonus - but it is not the absolute goal. In fact, when we look at most applications being considered for 'PRT' at the moment, there is frequently a need to offer mix mode running with both small and larger vehicles carrying up to 50 passengers at a time – GRT if you will – to help manage the peak hour loads. In many instances, we find in our emulations that a GRT vehicle is by far the most cost effective solution to moving large numbers of people between key nodal points in a large network. But then doesn't all this starts to sound a bit like APM territory?

So where is exactly is the difference? Where is the crossover? When does an APM start to become a GRT, or vice versa; and how big can a PRT vehicle be before it becomes a GRT? And is all this terminology maybe getting a little bit less relevant than before, in the same way that your mobile phone can no longer be described as simply a device for just making phone calls, and a personal computer is no longer just a big ugly box that sits on your desk – it can also be your phone, and your camera, and your games console?

By normal understanding, an APM is a line-haul transit, sometimes on rubber-tyres, sometimes with multiple cars, that essentially oscillates between two termini and maybe has one or more intermediate stops along the way. It requires only just enough intelligence to manage ATO (automatic train operation) type functionality without the need for a driver. However, there is usually no requirement to manage any other traffic, or to switch between lines, or to avoid any stations. So sometimes a PRT system, or perhaps a certain section of it, is performing the exact same function as a traditional APM. Under those circumstances, the safety regime for a vehicle performing APM duties is relatively straight forward compared with the complexity of navigating a full-blown network. That said, of course, safety is never to be taken lightly and is always a major cost element in the implementation of any new driverless system APM or otherwise.

INTELLIGENT CONTROL

Where Vectus starts to add value beyond the notion of simply running point-to-point, is the way that each vehicle controls its speed, position and direction, relative to all other vehicles on the system, as a method of optimising overall system capacity and efficiency. The methodology behind the Vectus control system, which will be deployed at Suncheon, can be divided into four key components: *distributed and scalable control, asynchronous control, dynamic moving block* and *optimal control*.

A distributed system means that the control is carried out locally, in pre-designated zones. If there is a fault, it only effects a small part of the system. The rest of the system will continue to work. With the distributed system there is no increase in the load for each individual control segment when the system is expanded.

With asynchronous control the flow of vehicles is handled as they travel along their path to their destinations. Merging of vehicles is managed as required on a local basis. Occasionally there may be a need to slow down to facilitate merging in switches; there may even be short queues along the route at times. Travel time may be prolonged by a few seconds, but the overall capacity of the system is maintained, which is essential to the overall ability to transport passengers during periods of high system loads.

A dynamic, moving-block vehicle protection system is superior to any fixed-block system, even if the fixed blocks are very short. It continuously updates each vehicle with information on the position of the one in front of it. With this information, each car can run, by varying its speed relative to the others, with the shortest allowed spacing based on the worst case braking performance. At lower speeds the vehicles run closer to each other; at higher speeds the distance is increased.

Then it is a matter of optimizing the logistics of the vehicles. Vectus has an adaptive-control which learns from travel patterns of traffic from previous days. This can be manually altered in the event of, for example delays in a train arriving at one station, or maybe special events where large crowds are generated. Another critical aspect of course is to ensure the effective management and distribution of empty vehicles.

These systems, in combination, are the building blocks in providing both safety and capacity within the Vectus system. It is easy to understand then why PRT technology is considered a quantum step beyond anything we currently have in operation in any of our cities around the world today. There are clearly niche applications for PRT, and potential customers are out there – although they may not know it yet - but there is, quite understandably, an air of caution amongst consultants tasked with analysing the opportunities and evaluating the various technologies on offer. One must remember that it is 45 years since the opening of the Victoria Line in London's Underground - which first heralded the concept of automatic train operation – and it is only now that we are finally able to say that driver-less mass transit systems have come of age and are an accepted norm. How long before the same can be said for PRT? We are already 37 years from the opening of Morgantown and so far only three commercial systems are reaching maturity.

It seems logical, therefore, that PRT should be seen as the natural evolution of APM, rather than as something totally distinct or indeed as a competitor technology. But somewhat disappointingly, to avid third party promoters of PRT anyway, all recent applications, including Suncheon, are not yet able to showcase the true potential of the technology. One might argue that current are really only demonstrating the ability of PRT to perform similar duties to an APM - albeit using a far more sophisticated safety and control regime. However, whilst these systems to date are not seen as being very ambitious (in terms of showcasing the ability of PRT to deliver high capacity, fully automated networks) they are the necessary first step in proving the underlying principles of PRT. They are also a valuable tool in helping to build confidence in the technology from both the operator and customer perspective. It is an incremental process, and what potential buyers of PRT require most of all, is some robust evidence of successful operational experience and longevity. In other words: some miles under the belt.

STANDARDS AND SAFETY

At present there are no internationally recognised, universal 'PRT standards' which can be applied to any system which purports to be PRT; but does there need to be? Certainly, within the US, there are initiatives to develop the ASCE APM standards to be be fully inclusive of PRT. However, in Europe and other parts of the world (which tend to follow the procedures and regulations originated in the EU), this may not prove viable as an umbrella standard. Moreover, one might are argue that the technological and operating differences between rubber-tyred PRT systems such as at Heathrow or in Abu Dhabi and a railway based solution like Vectus are sufficiently un-alike as to warrant a different approach. Therefore, the next few observations are made only in relation to the Vectus system and are not necessarily intended as a pan-industry solution.

It has been suggested that Vectus is really a very sophisticated light railway, much smaller scale and lighter weight, but never-the-less it is still uses solid wheels running on steel track. Certainly our engineers have been drawn mainly from the railway industry, having designed vehicles and systems and worked on safety cases and operating acceptance procedures for applications as wide ranging as LRT to the

London Tube. It will come as no surprise, therefore, that our starting point has been the standards and best practices already adopted and proven for light rail, mass transit and APMs – rather than to write completely new ones.

Whilst it is fair to say that to use railways standards in their entirety would be extreme over-kill, and in many cases not relevant, not to mention expensive, there are precedents within the railway culture for most eventualities that might occur on a PRT network. It is just a case of looking for them. Over the course of our development programme, and in consultation with third party consultants such as Lloyds Register, we have carefully selected those norms - either in totality or with self-nominated exemptions to specific, non-relevant clauses – and included those in our safety-case documentation.

Generally, our safety process follows the EU standard EN 50126/IEC62278 'Railways applications – specification and demonstration of reliability, availability, maintainability and safety (RAMS)'. All suppliers to Vectus must be familiar with the standard and follow the relevant parts of it. This is followed up closely throughout all lifecycle phases, both through specification of detailed requirements, a number of safety studies and risk assessments in all phases, thorough safety documentation of all deliverables, audits (internally and of suppliers) and a traceable system for verifications and validations.

In the test track project in Uppsala, the Swedish Rail Agency (SRA) reviewed all the documentation and held regular meetings with Vectus to make sure that the standard was followed throughout the system development, construction and commissioning introduced. This included using a third party for assessing the safety instrumented element of the system - which is the automated control and safety process.

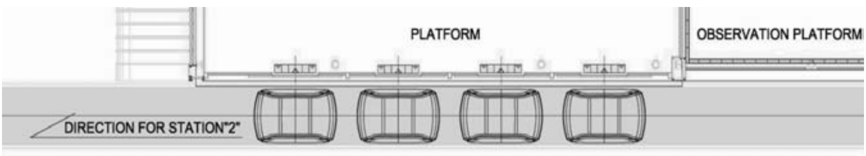
One specific area, however, where normal railway standards have not being wholly adequate is the control system. Here the safety elements utilise the same principles as any modern CBTC (Communication Based Train Control) system, like ERTMS for example, or a modern subway, however, Vectus employs a much more optimized and 'correct' safety approach covering not only the generation of a brake demand; but the whole chain from sensors to activators. The latter also involves a new approach for integration of the safety control aspects into both the track and the vehicles, which creates significant advantages, whilst being compliant with more generic and modern safety standards. So instead of using the traditional (and arguably less modern) railway standards such as EN 50128 ('Railway *applications. Communications, signaling and processing systems. Software for railway control and protection systems'*) and EN 50129 (*'Railway applications. Communication, signaling and processing systems. Safety related electronic systems for signaling'*) the IEC standard 61508 for *'Functional safety of electrical/electronic/programmable electronic safety-related systems'* was used. This standard is generic for all kinds of SIS (Safety Instrumented Systems).

In the overall approval process for Sweden, acceptance criteria for the Vectus system were established based on the principle that new systems shall be as good as or better than existing systems, against which the risk assessment was measured. The conclusions were that the risk for passengers and personnel was comparable with the best railway levels, and that the risk level for third persons was very low compared to other 'involuntarily' risks.

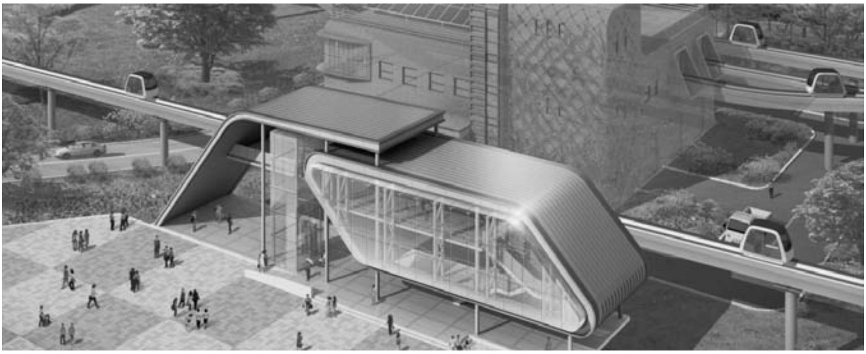
This exact process is now our blue-print for new projects, such as Suncheon, going forward. Once this is up and running, carrying passengers on a daily basis, it is our intention to publish a customer oriented guideline to these standards and processes as we have adopted them.

SUNCHEON PROJECT

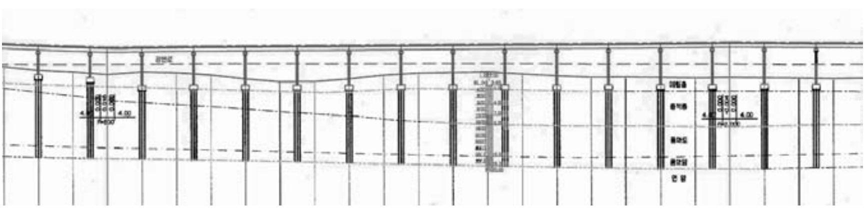
Following a successful four year period of testing and demonstration at the test track, Vectus has now moved forward very rapidly with building its first fully commercial system in South Korea. This is essentially a visitor transit between a park-and-ride location on the outskirts of Suncheon city, in the southern most part of the country, linking to a world famous wetlands and bird reserve in the Suncheon bay estuary. Here we will be operating 40 vehicles initially (and one maintenance vehicle) running between two stations, along five kilometres (end-to-end) of elevated, double track. The track has a full loop at either end with four on-line berths at each.



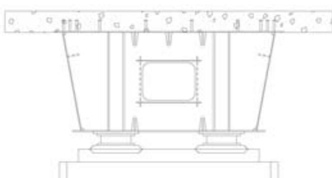
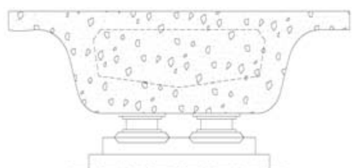
Adjacent to Station 1 (the Suncheon City end – see below) is located the Operations and Maintenance building. This houses the control room, vehicle storage (on the lower levels) a five berth daily maintenance area and a five berth, off-line, heavy maintenance facility. An average of three million visitors per year are expected to visit the Suncheon Wetland Park, once the new system is operational, and daily ridership is forecast at around 5,000 passengers per day.



The guide way itself is predominantly concrete using site-cast columns and pre-fabricated, pre-stressed beams of typically 30 metre spans – although we also have one 50 metre steel box-girder section over a river. Because the entire area is an earthquake zone and is also prone to occasional tornados, the construction has been very carefully engineered, with most of the column piling buried some 30 metres into the marshy terrain. Because, in most cases, the foundations are laid far under the top soil on top of the pilings, this has the effect of placing the bending moment from wind loading deep underground.



The track-work itself is manufactured from rolled steel profiles, mounted along the concrete structure and the entire railway is powered through a 500VDC system of continuous current collection located on both sides of the guide way. For this application, where there is no issue of track adhesion (in comparison with Uppsala, for example, which is prone to very icy winters), there is no necessity for using in-track linear motors at all.

Item	Steel Box	Concrete Beam
Upper Structure		

A prototype vehicle is currently in-build at our factory in the UK, with specialist components and sub-systems being supplied from Germany, Sweden and America. This car will first be statically tested in England and then delivered to our new test-track facility in Suncheon city – which is in effect the starting loop around Station One at the city end of the track. Following operational testing, and certification by the approval authorities, a further 39 vehicles (plus one maintenance vehicle) will be batch assembled in Korea and delivered for public service during 2013.

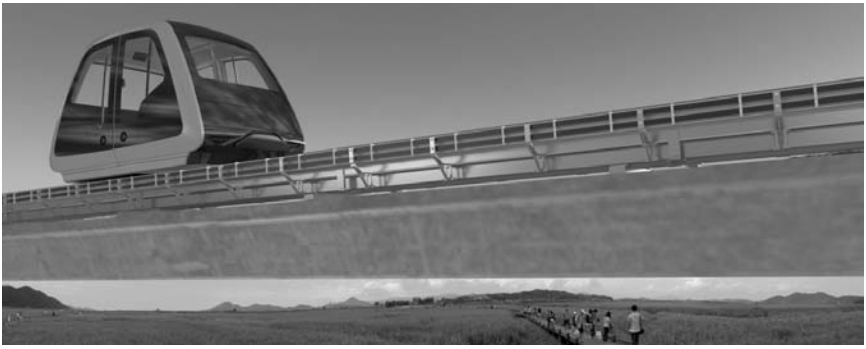
Station 2 awaiting the arrival of the first Vectus vehicle

DESIGN

It has been important from the outset to envision the Vectus offer as a turnkey transit solution, and not just a collection of vehicles running on a railway track. We understand that the passenger's interaction with our system is from the point where they first arrive at the station to the point where they exit at their destination. Consequently, we believe that 'design' is key to realising a completely seamless and comfortable journey experience.

In 2010, Vectus approached world famous design house 'Pininfarina' – probably best known for its work with Ferrari over the last 50 years or so - to be its design partner for all major components of the Vectus system including the stations, the track profiles and of course the vehicles themselves. With Pininfarina taking responsibility for the emotional and aesthetic elements, the underlying engineering of all the mechanical and electronic systems has been undertaken in-house by Vectus's own development teams based in Uppsala, Gothenburg in Sweden and in Stratford upon Avon, England.

In concept, the new Vectus vehicle is a modular design, which can be varied to carry anywhere between six and sixty passengers according to project-specific, operational requirements. Similar to a Formula One race car, all the body frames and panels are manufactured in carbon fibre composites. The main driver is strength-to-weight ratio in order to optimise performance and minimise energy consumption. Some of the mouldings are hollow, using the same 'monolithic' composite moulding technology employed in the making of wind turbine blades and bicycles frames, to provide the necessary high degree of structural integrity to meet safety requirements. For example, each entire side frame of the vehicle is designed as a structural ‘roll-bar’, and being hollow, also serve as concealed ducting for wiring and air-conditioning.

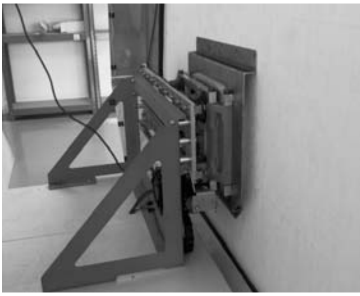
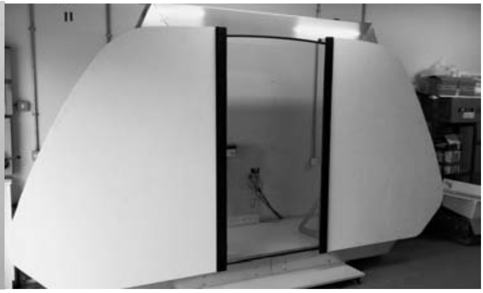


Both the smaller six passenger Suncheon vehicles and the next generation GRT cars, which are now on the drawing board, will draw from a common inventory of parts. So, for example, all line-replaceable units such as windows, doors, seats, lighting, air conditioning, control boxes and other major sub-assemblies will be largely interchangeable across all fleets of vehicles. This has the effect of creating volume, from a manufacturing standpoint, thereby reducing cost and improving reliability, availability and maintainability (RAMs) of equipment within the system generally – with a consequent reduction of risk.

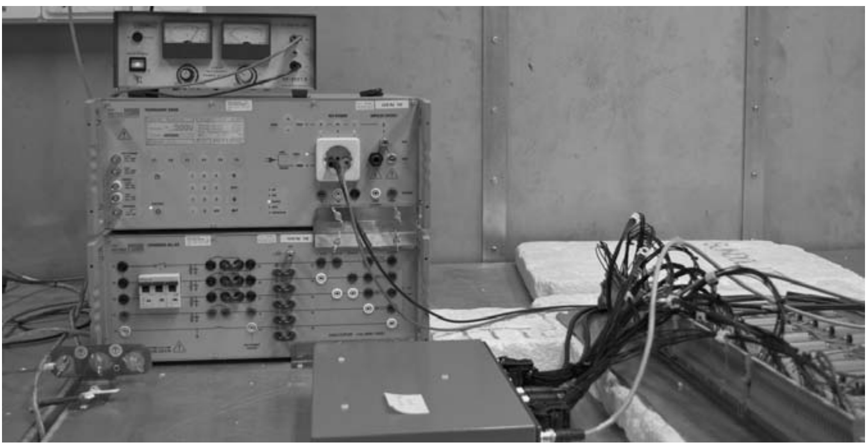
Another very good example of innovation within the Vectus vehicle is the drive bogie unit. Whereas the test track cars used a more simplistic, twin axle arrangement, the Suncheon vehicle has gone back to more traditional railway principles and reinvented the bogie in super light weight form. Almost unrecognisable for what it is, the miniature Vectus drive bogie is fashioned from a system of CNC-formed, high tensile steel tubular frames. These are soft-mounted together to form part of the primary suspension and then fitted with high-performance, automotive braking units borrowed from the race car industry together with secondary, air-bag suspension. Vehicle dynamics has been developed using state of the art simulation and calculation tools like *Gensys*, and ride quality improvements are significant.

Each bogie unit carries one permanent magnet 15 kW drive motor supplied by state of the art IGBT VVVF inverters. The motor is coupled to one pair of running wheels via a bi-directional limited slip differential. There is also a battery powered low speed drive for movement within the workshop (which does not have current collection) as well as the storage facility. The safety brakes are of the same principle as the test track proven units capable of retardation levels up to 5 m/s2 at any climatic condition.

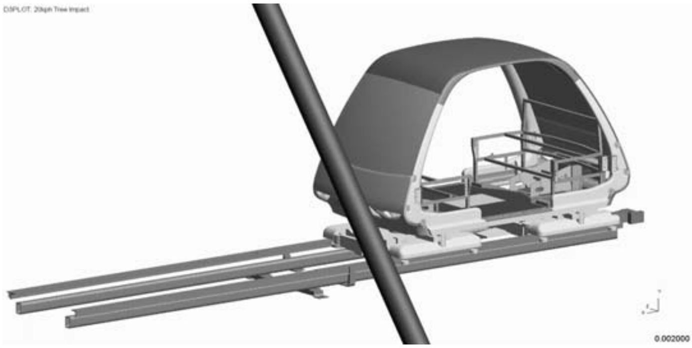
The door system, typically a problem area in most transit operations, is a totally new design which departs from the previous test track vehicles. The twin, slide-plug door wings (one pair per side) themselves are manufactured in very stiff, lightweight carbon fibre, and are actuated by permanent magnet linear motors in order to reduce the number of serviceable moving parts. These mechanisms have been rigorously life-tested, achieving over 1.5 million cycles with no stopping faults or maintenance required.

Located within the cabin is the vehicle control equipment, which is the heart of the Vectus system. This comprises two identical boxes, of different colour: the ‘vehicle controller’ and ‘safety controller’, each utilising high speed dual-core Power PC processors with cores running in lock-step mode in order to reach the required safety level. The controllers are rugged and run bare-board with real time software (no operating system) at SIL 3. They (orange box below) have been thoroughly tested under laboratory conditions prior to running a pre-series prototype on the track in Sweden. Similar controllers, albeit with different programming, are also used to control each designated track zone throughout the system.



Other aspects of the vehicle design, such as aerodynamics (CFD), structural integrity (FEA), fatigue and crash-worthiness have all been undertaken using standard automotive computer modelling techniques to optimise the design and ensure passenger safety. The following illustration, for example, simulates a collision with a fallen object such as a tree on the track.



In terms of the passenger environment, the vehicles take a further cue from the automotive industry by introducing the options of heated windows all round (to eliminate fogging); a heated floor and seat to warm the interior, and a powerful air conditioning system.

CONCLUSIONS

So what conclusions can be drawn from this first commercial installation by Vectus?

Firstly, that Vectus is, in effect, an autonomous, micro light rail or *intelligent people mover*, which aspires to meet, at scale, all the safety and operational standards required of a traditional guided transit system. The major value-added, is that a large number of small vehicles - and potentially a mix of small and larger vehicles in the future ranging from six to sixty passenger capacity - can all operate simultaneously on the same network, operating on relatively short headways down to three to four seconds. They can go point-to-point (that is they do not need to stop at intermediate stations) and waiting times are reduced to an absolute minimum.

Secondly, as we now hope to demonstrate in Suncheon, Vectus is most definitely one method, the missing link if you like, by which transport planners can finally realise a low cost, fully integrated, multi-modal transport system. It is not intended to be 'mass-transit' or compete with long distance public transport services such as commuter rail; rather it is designed to enhance and improve the viability of such networks by providing feeder lines and links into areas where 'heavy rail' and metro (in inverted commas) would otherwise be too expensive to install and operate.

Thirdly, that the new Suncheon vehicles are state-of-the-art in people mover technology showcasing innovations in bogie design, lightweight vehicle structures, passenger door actuation, system safety and control and last but not least, advanced, elegant styling. Because they are lightweight and (being rail based) are able to use simple current collection infrastructure, they have by default unlimited range and can accommodate the most powerful HVAC equipment, where required, to operate in extremes of ambient temperature.

So overall, we suggest perhaps that Vectus is really the beginning of a next generation of APMs - with added intelligence - having the ability to navigate a complex network, using different size vehicles, as well as perform more traditional line-haul duties where required.

In other words: an Intelligent People Mover for the twenty-first century – *an IPM.*

Personal Rapid Transit – computer simulation results and general design principles

W. Choromanski, Ph.D., D.Sc.[1], I. Grabarek, Ph.D., D.Sc.[1], J. Kowara, MSc. [1], B. Kaminski, Ph.D.[2],

[1] Faculty of Transport, Warsaw University of Technology, Koszykowa 75, 00-662 Warsaw, POLAND; PH (+48) 22 2345409; FAX (+48) 22 6286491; e-mails: wch@wt.pw.edu.pl, ig@wt.pw.edu.pl, jkowara@wt.pw.edu.pl,
[2] Institute of Control and Industrial Electronic, Warsaw University of Technology, Koszykowa 75, 00-662 Warsaw, POLAND; PH (+48) 22 2347615; FAX (+48) 22 2346023; email: kaminskb@isep.pw.edu.pl,

ABSTRACT

This article applies to the new transportation system PRT – Personal Rapid Transit. Personal rapid transit (PRT), is a public transportation mode featuring small automated vehicles operating on a network of specially-built guide ways. PRT is a type of automated guideway transit (AGT), a class of system which also includes larger vehicles all the way to small driverless subway systems. In PRT designs, vehicles are sized for individual or small group travel, typically carrying no more than 3 to 4 passengers per vehicle. Guide ways are arranged in a network topology, with all stations located on sidings, and with frequent merge/diverge points. This approach allows for nonstop, point-to-point travel, by passing all intermediate stations. The point-to-point service has been compared to a taxi. This article concerns the methodology of designing such a system. Works on this type of system is carried out, inter alia, at the Warsaw University of Technology under the project "Eco-Mobility".

1. INTRODUCTION

Selected elements of the PRT system will be presented; among others, the designs of the cabin, the power system and vehicle propulsion system. Particular attention has been paid to customize the system to transit the elderly and disabled, as well as to the principles of passenger interface design. The interface performs a very important role, since the PRT system is a system of APM (Automated People Movers) and there is no driver in the vehicle. There will also be shown some computer simulations relevant to the analysis of traffic and some external influences on the PRT vehicle.

2. THE RESEARCH METODS

The work used the V-model to design mechatronic systems, and the PRT transportation system is undoubtedly such a system. The aspects presented will be:

a) the mechanical systems of vehicle and track; b) the propulsion and power supply systems; c) the computer system d) legal and economic aspects. In the design process there has been a strong emphasis on inclusion in the construction of the principles of ergonomics and the needs of disabled and the elderly people. CAx software and simulation techniques have been used as a basic research technique.

2.1. Mechanical systems of vehicle and track

Research of the mechanical systems include:

- Passenger cabin – stylish and functional design
- Vehicle guidance system with switchless guideway
- Analysis of motion and external influences on the PRT vehicle

Research on the track system was presented previously at the 13 International Conference of Automated People Movers, 23-26 May 2011 in Paris [CHOROMANSKI].

2.1.1. Passenger cabin design

Research on the passenger cabin system takes into account following aspects:

- Usability
- Safety
- Environment
- Business

According to above aspects the pods should be:

- small (as possible within comfort)
- modularly built
- easing infrastructure flexibility
- equipped with standarized interfaces with infrastructure

Additionally in the cabin system, the subsystems such the following can be identified:

- Chassis frame
- Doors
- Seats and support system for wheelchairs users
- Passenger interface
- Equipment and installations
- Body panels
- The integration of the above mentioned systems

All of the subsystems were built and simulated with the aid of computer models (see Figure 1). Selected results are described and presented in chapter 3.1.

Figure 1. The computer model of supported PRT vehicle

2.1.2. Vehicle guidance system with switchless guideway

Research on the vehicle suspension and guidance system with switchless guideway takes into account laboratory tests on small scaled physical vehicle and computer simulations.

The purpose of the construction of the scale model is a representation of the dynamic effects in vehicle motion on straight and curved track, in the range of acceleration, passing through the junction and deceleration.

In general, the basic equation of motion is expressed as the balance of forces applied to the system, for similarity there is a need to specify the k_F scale factor for all the forces included in the equation (1).

$$m\ddot{x} + c\dot{x} + kx = F \qquad (1)$$

in a polar system we accordingly get the equation (2)

$$I\ddot{\theta} + c_T\dot{\theta} + k_T\theta = T \qquad (2)$$

where: m- mass,
I – moment of inertia,
c, cT – damping coeficients,
k, kT - stiffness coefficients,
F – operating forces,
T – applied torque.

For the scale model we accordingly receive.

$$m\ddot{x}\left(\frac{k_m k_l}{{k_t}^2}\right) + c\dot{x}\left(\frac{k_c k_l}{k_t}\right) + kx(k_k k_l) = F(k_F) \quad (3)$$

$$\left(\frac{k_m k_l}{{k_t}^2}\right) = \left(\frac{k_c k_l}{k_t}\right) = (k_k k_l) = (k_F) \quad (4)$$

Using the above specified scale factors we obtain the equation (5) and (6), the fulfilment of those ensures the similarity of scale model.

$${k_l}^4 = k_c k_l = k_k k_l = k_F \quad (5)$$

$$k_c = {k_l}^3,\ k_k = {k_l}^3,\ k_F = {k_l}^4 \quad (6)$$

To obtain the full similarity, the scale factors should be specified for the forces acting between the wheels in contact with the track, where describing and defining these forces requires knowledge of the equations that describe the impact of the selected type of contact. For wheels with polyurethane tread application, the work is in progress.

Finally, it has been developed a scaling strategy, indicated with S4, the results of which are shown in Table 1.

Table 1. Scale coefficients for the adopted scaling startegy indicated with S4

Sn.	Dimension related:	Values of scale coefficients	Symbol
1	Length	4	k_l
2	Time	2	k_t
3	Density	½	k_ρ
4	Frequency	½	k_f
5	Surface	16	k_A
6	Capacity	64	k_V
7	Mass	32	k_m
8	Velocity	2	k_v
9	Acceleration	1	k_a
10	Inertia forces	32	k_F
11	Moments of inertia	512	k_I

Table 2 shows a set of dimensions for a full scale and for a 1:4 scale model.

Table 2. Comparing the selected parameters values for the full scale vehicle and 1:4 scale model

Sn.	Parameter:	Full scale:	Model 1:4
1	Vehicle mass	1250 kg	~39 kg
2	LIM mass	300 kg	~9,5 kg
3	Resistance to motion (without track slope)	2000 – 2750 N	62,5 – 86 N
4	Maximum velocity	13,5 m/s	6,75 m/s
5	Operating velocity	2,5 m/s	1,25 m/s
6	Wheel tread	800 mm	200 mm
7	Wheel base	1800 mm	450 mm
8	Support wheels diameter	400 mm	100 mm

9	Support wheels width	100 mm	25 mm
10	Minimal guideway radius	5 m	1,25 m

Within the ECO-Mobility project, a unique laboratory test stand for PRT system research has been designed and made.

2.1.3. Analysis of motion the PRT vehicle

In order to allow simultaneous activities of team members working on different components of the system, a set of parameters and assumptions was created in relation to vehicle movement profile. Table 3 shows set of parameters (named C1) related to movement resistance of the vehicle. For a defined set of parameters, load profile characteristics were calculated, taking into account typical operation of the vehicle: acceleration to a maximum speed, travel at a maximum speed and deceleration to a full stop (see Figure 2.). Acceleration and deceleration rates were defined according to comfort and safety of the passengers.

The parameters of C1 set are describe in the Table 3 below.

Table 3. Parameters set (named C1) used for calculation of resistance to motion of the PRT vehicle

Sn.	Symbol	Parameter	Value	Unit
1	m	Overall vehicle mass	1250	kg
2	Vmax	Maximum velocity	13,5 (48,6)	m/s (kph)
3	w	Limiting guideway gradient	10	%
4	ρ	Air density (T= 273 °K, p= 0.1Mpa)	1,226	kg/ m2
5	A	Cabin front surface	2,5	m2
6	Cx	Cabin shape factor	0,65	-
7	Vw	Face wind speed	13,5 (48,6)	m/s (kph)
8	f	Rolling resistance coefficient	0,012	-

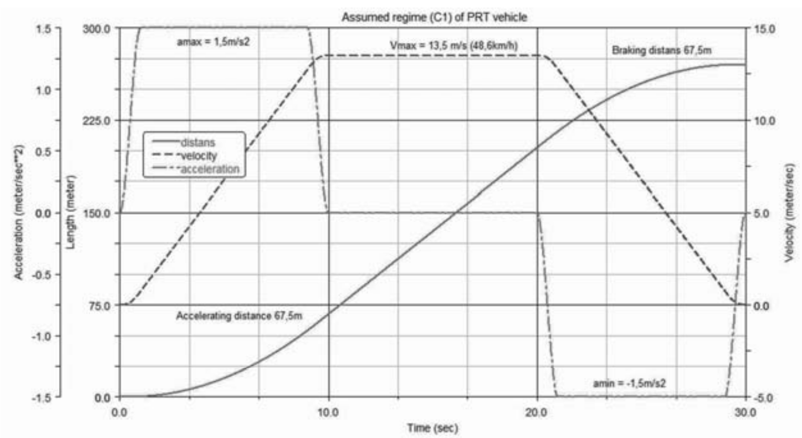


Figure 2. Assumed regimes of motion the PRT vehicle

Using the above motion conditions, the demand for the driving force and the linear motor power of PRT vehicle has been determined.

2.1.4. Analysis of selected external influences on the PRT vehicle

Within the range of calculation of the support frame of PRT vehicle cabin, two types of analysis were conducted – static and dynamical (modal). The static calculations aim was to examine the behavior of the design for several loads variants, including the determination of torsional stiffness. The values of stresses at the critical locations were referred to the basic value defining the material strength.

Modal analysis provided the information on the dynamic characteristics of structural elements at resonances, and thus aids in understanding of the detailed dynamic behaviour of these. The results were compared with the likely types of extortions to indicate a potential resonance in the structure working range.

Within the range of aerodynamic effects on the cabin construction a Computational-fluid-dynamics CFD model of PRT vehicle was built. The calculation conditions were determined for different flow directions and the velocity of the medium (i.e. air), the pressure and velocity distributions, which will become loading (pressure) for the strength calculations supporting the vehicle frame and the door frames. At the same time, the CFD calculations provide the image of pressure distribution on the external surfaces of cab panels, this defines the optimum position of the inlets and outlets of the air conditioning and ventilation.

The basic values of the base wind speed and the wind speed pressure were determined in accordance with the applicable standard. (See Figure 3).

Strefa	$v_{b,0}$ (m/s)	$v_{b,0}$ (m/s)	$q_{b,0}$ (kN/m²)	$q_{b,0}$ (kN/m²)
	$A \leq$ 300 m	$A >$ 300 m	$A \leq$ 300 m	$A >$ 300 m
1	22	$22 \cdot [1 + 0{,}0006\,(A - 300)]$	0,30	$0{,}30 \cdot [1 + 0{,}0006(A - 300)]^2$
2	26	26	0,42	0,42
3	22	$22 \cdot [1 + 0{,}0006\,(A - 300)]$	0,30	$0{,}30 \cdot [1 + 0{,}0006(A - 300)]^2 \cdot \left[\frac{20000 - A}{20000 + A}\right]$
UWAGA: A – wysokość nad poziomem morza (m)				

Figure 3. The basic values of the base wind speed and the wind speed pressure in the zones. Source – PN-EN 1991-1-4:2008 standard.

The selected values of analyses were presented in the paragraph 3.1.

2.2 Propulsion and power supply system structure

Topology of the proposed propulsion power and supply systems directly reflects the agreed concept of the developed PRT system, which assumes use of autonomous vehicles where individual are able to select a route and control their movement. Thus, the guide way contains highly simplified, almost passive components of the power train. Conversely, the vehicle carries sophisticated control and power circuitry. Another feature, which distinguishes the proposed concept is the application of the linear induction motor together with a hybrid power supply of the vehicle. This employs contactless energy transfer together with the supercapacitor energy storage.

Figure 4 shows a block diagram of the proposed power train for developed PRT system. The system is divided into two parts: stationary located on a guide way and the mobile located on a vehicle.

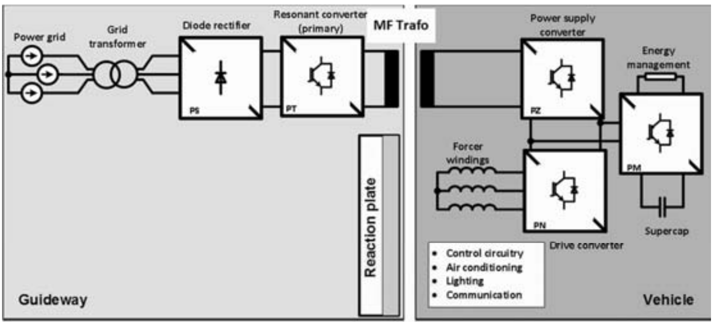


Figure 4. Block diagram of proposed propulsion and power supply system

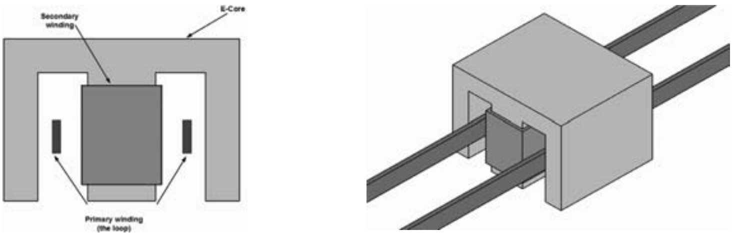
Stationary part contains mainly elements of the power supply system, which are: power grid connector, matching transformer, diode rectifier and primary side of the contactless energy transfer system. A reaction plate of the linear induction motor, used for vehicle propulsion is placed on a guide way, additionally.

The vehicle carries the secondary side of the contactless energy transfer system, vehicle energy management system and primary winding of the linear induction motor, together with motor inverter.

2.2.1 Contactless Energy Transfer (CET) system

Figure 5 shows the concept of a transformer [PEDDER], where primary winding, in the form of a loop, is distributed along PRT guide way. The E shaped core, with secondary winding, mounted on the center column creates energy pickup and it is placed on the vehicle.

Primary winding is supplied with sinusoidal current. In order to provide the required magnetic coupling, the frequency of the current should be in the range of tens of kilohertz. Respectively, due to primary winding distribution, the current amplitude should range hundreds of amperes. Since the vehicle must cover guide way junctions or following sections of the primary winding, the core of the pickup must be open, to enable safe operation in that areas. As a result, the magnetic circuit of the transformer is characterized by significant amount of leakage inductance. Therefore, in order to transfer the required amount of active power to the vehicle, significant reactive power must be delivered to the magnetic circuit, at the same time. This problem was solved by putting a compensation network made of capacitors, in series with the primary loop. The capacity of the network is selected to meet the resonance criteria for supplying current frequency. As a result, reactive power is exchanged between the capacitors and the leakage inductance of the transformer and does not need to be delivered by the converter. Such an arrangement improves operational conditions of the supplying inverter, because it can operate in soft switching mode, which substantially reduces heat losses generated in power electronics switches.



a) Front view b) Side view

Figure 5. Concept of contactless energy transfer system for PRT

During travel, the vehicle can slightly change its position relative to the transformer primary winding, due to not perfect surface of the track or especially when covering difficult sections of the track, like junctions or turns. Thus, the magnetic circuit of the transformer will change, loosing its resonance condition. As a result power transfer will be impeded. Such changes can be detected by the control circuit and loop current frequency can be adjusted to avoid this situation.

Application of contactless energy transfer introduces significant advantages to conventional vehicle supply system based on pantographs, such as

- Increased immunity to weather conditions
- No electric arc
- Practically maintenance free system
- Reduced risk of electric shock to the users

In order to reduce the power rating of the Contactless Energy Transfer System a hybrid solution was proposed, which utilizes a supercapacitor as an energy storage located on the vehicle. The storage delivers peak power to the propulsion during acceleration and takes back the energy recovered during regenerative breaking. In addition, it allows travel of the vehicle through track sections, where usage of contact less energy transfer is difficult or impossible like track junctions or hard turns.

2.2.2 Linear Induction Motor drive for PRT vehicle propulsion

It was decided to use a Linear Induction Motor (LIM) for vehicle propulsion. Figure 6 shows a cross section of flat type linear induction motor used in proposed PRT system concept.

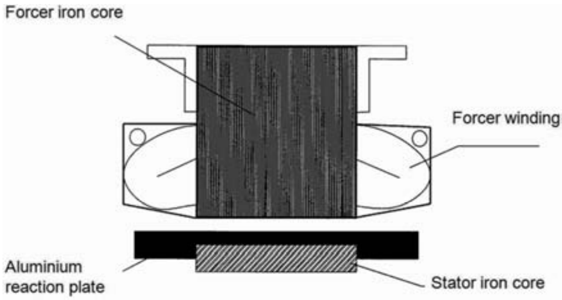


Figure 6. Cross section of a Linear induction motor

The motor forcer is located on the bottom of the vehicle and contains copper windings wound on a magnetic iron core. The winding is supplied from the microprocessor controlled power electronics inverter, which allows smooth control of a thrust force during acceleration, steady state and deceleration. Energy recovery can be controlled, additionally. An aluminum reaction plate, together with the stator core are located on the vehicle track.

Application of this type of the propulsion provides the following benefits related to use of conventional rotary motors to the PRT system:

- Direct source of thrust/breaking force
- Low sensitivity to the environmental conditions like icing/snow or rain
- Low maintenance cost
- Low noise
- Increased reliability

Some difficulties are associated with linear motor application, which are: reduced efficiency, high attraction force between the forcer and the stator core, motor magnetic circuit end effect and variable airgap. High attraction force require higher strength of vehicle suspension, but can stabilize the vehicle during turns. Motor magnetic circuit end effect and variable airgap lead to performance deterioration of the thrust force production, but can be compensated by the control scheme. Finally, increased energy cost maybe compensated by reduced maintenance effort.

2.3. Ergonomic designing of vehicle PRT passenger space

The research presented in this paper refers to designing of vehicle PRT cabin, fitted to the needs of the potential users. This group is varied from the point of view of dimensions, ages and abilities. Knowing the differences and needs meant they could be taken into account in the cabin design. The PRT vehicle is remote control, that is why the passengers should only make some manual steering actions during the trip. The projecting process of the functional and ergonomic vehicle required a considerable amount of reserch and analysis, inter alia:

- Questionnaire/expert-based surveys (the disabled people were the group of experts),
- Anthropometric verification of vehicle passenger space, from the point of

view users dimensions,

- Analysis of manual handling possibilities of touch screen interface (simplicity and intuitiveness of interface handling will vivificate with ready-made interface with the participation of different groups of users).

A questionnaire-based survey included two groups of people who are moving on the active wheelchairs. The first group size was 12 people, the second – 15 people. The analysis of the level of efficiency of the manual handling among the disabled respondents revealed some small difficulties, but generally there was no problem with manual operations by the upper limbs. The computer dummy man, based on Catia software and direct methods were used in the anthropometric verification. Both, the dimensions of the smallest individuals (C_5 ♀) and the largest ones ($C9_5$ ♂) taken into account. In this case the largest analyzed person was C95 man , sitting in the wheelchair, the height of which was 52 cm (according to the standards). The interface design demanded the initial dimensional and availability areas on the touch screen analysis in order to allow people with lower efficiency of the upper limbs correct handling.

3. THE ANALYSIS OF RESEARCH RESULTS

3.1. Selected results of the mechanical systems

In order to verify the proposed PRT mechanical concept a series of simulation tests were performed.

3.1.1. Strength analysis of PRT vehicle cabin frame

The worst case for the important frame elements occurs when the frame is twisted, subjected to the wind force (pressure), during braking or driving around the curve. The selected results presents Figure 7.

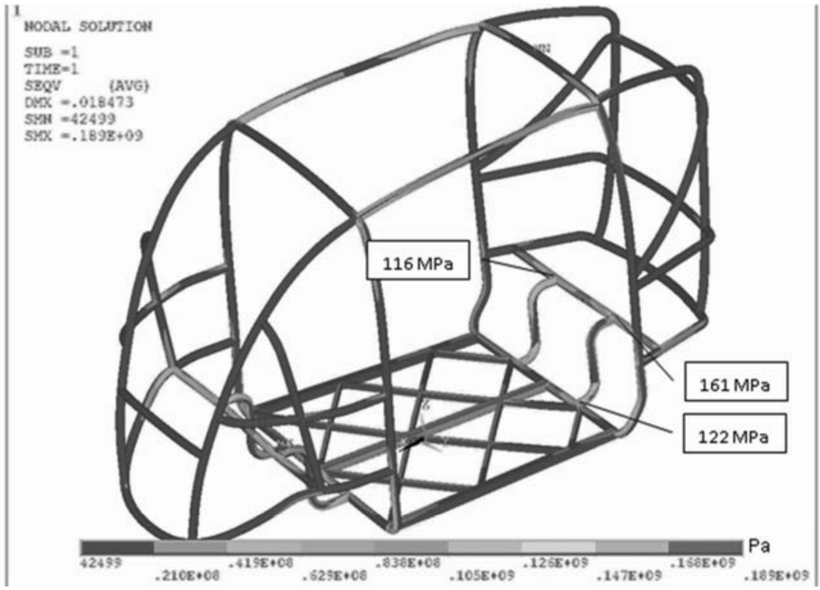


Figure 7. Mean stress distribution- (torsion case)

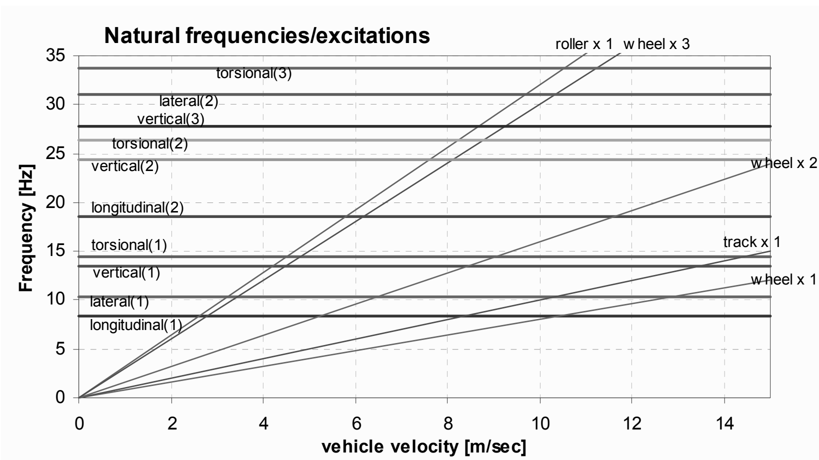


Figure 8. Frame natural frequencies and possible excitations

3.1.2. Analysis of Computational-fluid-dynamics

The maximum value of the gust is 26 m/s (93.6 kph). It has been assumed that the top speed of blow is 100 km/hr. At the same time, it has been assumed a maximum speed of vehicle is 50 km/hr. The following are some cases that correspond to the states of motion (see Figure 9 and Figure 10)

Figure 9. Case A – speed of 25 kph, steady state, no gust, a case verifying a pressure distribution at lower speeds

The case E (see Figure 10) corresponds to the situation when the vehicle is stationary and it is a subject to the side gust of the maximum speed.

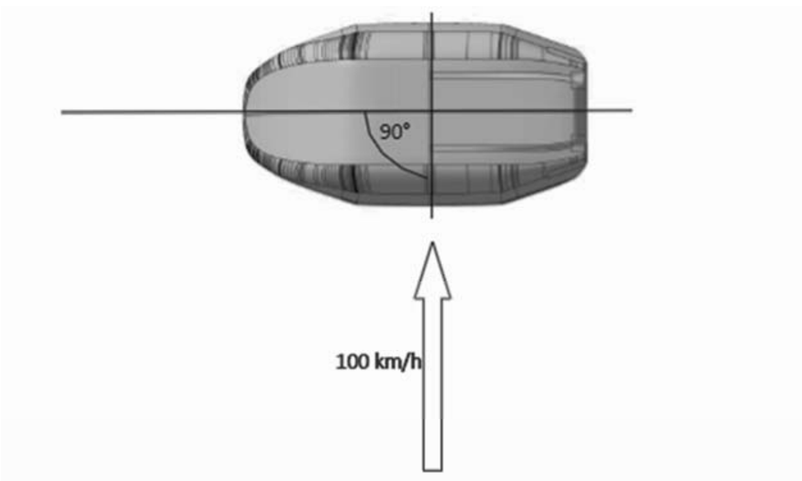


Figure 10. Case E – vehicle speed of 0 kph, the side gust value of 100 km/hr.

The selected results as below (see Figure 11 and Figure 12).

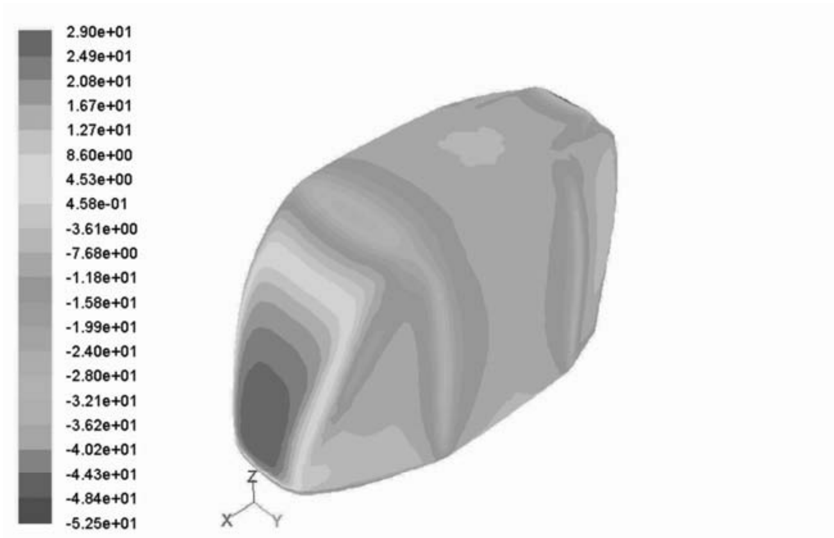


Figure 11. Case A – Contours of static Pressure (Pascal)

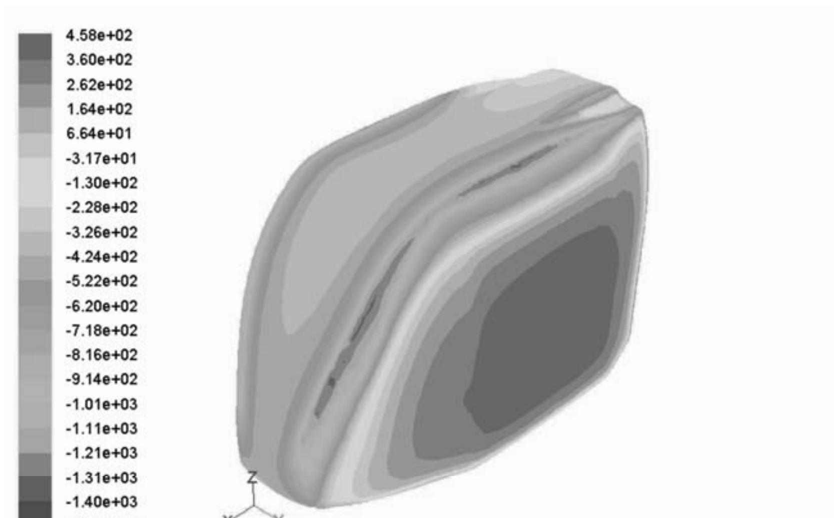


Figure 12. Case E – Contours of static Pressure (Pascal)

3.2 Propulsion and power supply system structure - Simulation and experimental tests

In order to verify the proposed PRT power train concept a series of simulation and experimental tests were performed.

3.2.1 Contactless energy transfer

Figure 13 shows the schematic of the scaled laboratory model of CET. It should be noticed, that figure 13, shows a variant of the CET, where the matching transformer is located at the high frequency side. As a result, the size and a cost of this element can be significantly reduced.

The setup is supplied from a variac through a simple diode rectifier. Thus, smooth input voltage regulation for the resonant converter is possible, for experimental purpose. The capacitor network was located on the input of the matching transformer. Thus, leakage inductance of both transformer and the loop are compensated. A single 3.5 m loop was interchangeable and was constructed using different types of copper conductors like litz wire or copper pipes.

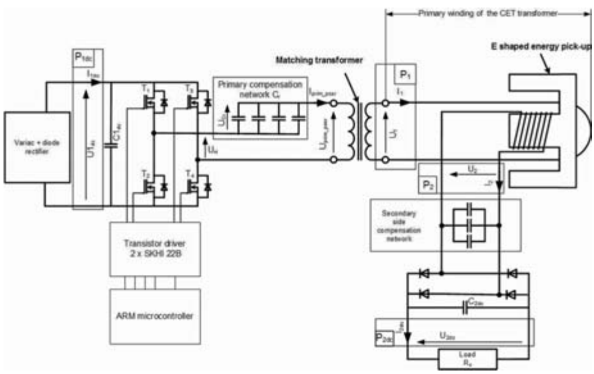
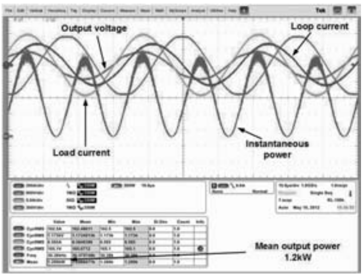


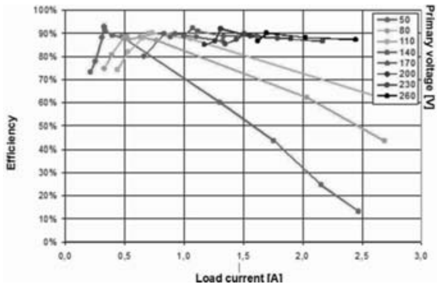
Figure 13. Schematic of Contactless Energy Transfer System scaled laboratory model

An E shaped pickup was able to be moved along and in the direction perpendicular to the axis of the loop. The output section of the system contain secondary side compensation capacitors together with diode rectifier and variable resistor load. The output circuit models drive inverter. The setup allows the measurement of the power flow at different points of the system, which in turn allows verification of energy transfer efficiency. Moveable E-Shaped energy pickup simulates movement of the vehicle, which causes the loop to move inside the pickup. Finally, the system is controlled by a real-time control scheme, implemented on an ARM type microprocessor. The main objective of the controller is to measure state of the circuit and adjust loop current frequency, so the resonance is always maintained.

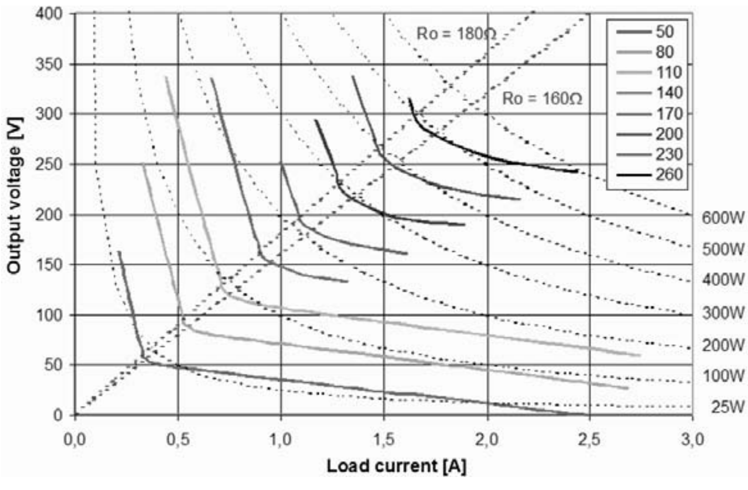
Figure 14 presents selected results taken from measurements of the laboratory setup. Correct operation of the CET system is shown on figure 14a. The resonant converter operates at 30.4kHz, loop current amplitude is 186 A rms. The output voltage is 185 V rms and the transferred power is 1.2 kW.



a) Maximum power output test of the scaled model 1.2kW



b)Transformer efficiency characteristics



c)Output characteristics of CET system

Figure 14. Selected waveforms and characteristics taken from experiments on a scaled laboratory model of Contactless Energy Transfer system.

Figure 14b shows set of CET transformer efficiency characteristics measured for different supplying voltage amplitudes. Finally, the last figure presents set of CET system output characteristics.

It can be seen from the results presented that the CET is able to provide efficient power supply for the PRT vehicle.

3.2.2 Simulation of the linear induction motor drive

Selected control method (FOC) for linear induction motor drive uses dynamic state estimator based on machine equivalent circuit. Thus one of the simulation tests objective was to evaluate the linear induction motor equivalent circuit, which takes into account end effects. The model was proposed by [DUNCAN]. Additionally, performance of the Field Oriented Control Method (FOC), with the modified machine state observer [LIU], was evaluated. For this case, a simulation model in MATLAB/SIMULINK was created as shown in Figure 15. Linear motor equivalent circuit model parameters were obtained from motor laboratory tests.

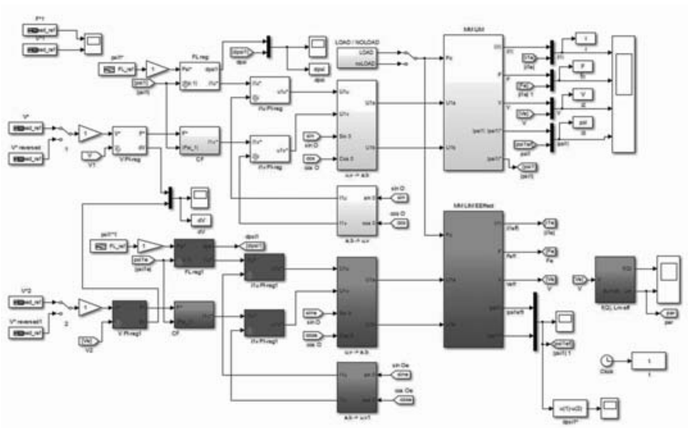
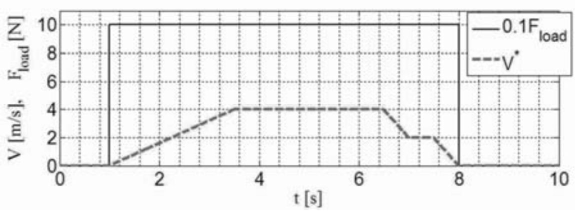


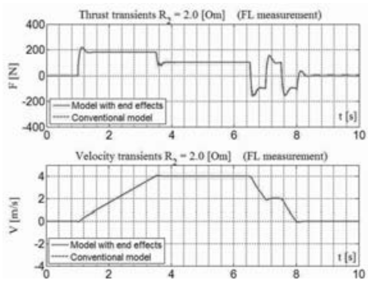
Figure 15. Simulation model of Linear Induction Motor drive taking into account end effects

The circuit on the upper part of the figure (light color filled blocks), contains the equivalent circuit without modeled end effect. The equations of the model are identical to the classic rotary motors. The block on the lower part of the figure, represents the extended model, which considers end effects phenomena.

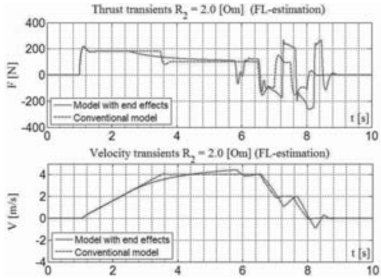
Figure 16 shows an example of simulated performance of the control method, as well as state estimator for both linear motor models.



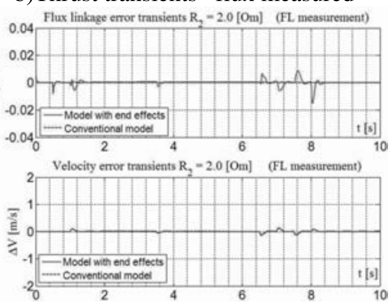
a) Motor velocity and load profiles



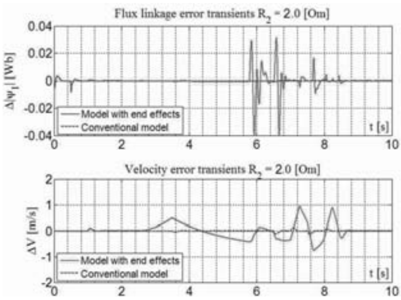
b)Thrust transients –flux measured



c)Thrust transients –flux estimated



d)Flux and velocity error transients – flux measured



e) Flux and velocity error transients – flux estimated

Figure 16. Results from a simulation experiment showing performace of FOC control method with/without state estimator accounting end effect

It can be shown from simulation experiments results, that extending linear machine model by equations describing end effect phenomena, may lead to drive performance deterioration in a form of thrust force oscillations.

3.3 Ergonomic designing -the analysis of research results

As a result of both research and analysis, the design procedure of the ergonomic vehicle design was defined and the initial assumptions were made regarding construction and ergonomics. The assumptions, aimed at adapting the vehicle to people with different levels of physical ability, were created on the basis of opinions of experts recruited from the group of disabled people. When designing the interior and the equipment of the PRT vehicle's cabin, the following anthropometric parameters should be considered:

- The user's position/preferred wheelchair's position – forward-facing
- The forward grip reach
- Securing comfortable drive
- Measures of potential users, both with high level of physical ability and the ones on wheelchairs.

Assuming that passengers' seats can face each other and can be folded down only in case they are backward-facing, the wheelchair can be put in two positions after it is fixed inside the cabin. In both cases the wheelchair is fastened to seats' backrests and in each of them it is being situated slightly differently in relation to the cabin's equipment, especially the screen, that is, passenger's interface. This situation has a considerable influence on determination of cabin dimensions, securing the access to key elements of its equipment. The Figure 17 presents the project of seats' configuration inside the cabin and the wheelchair position, elaborated with the help of CATIA software.

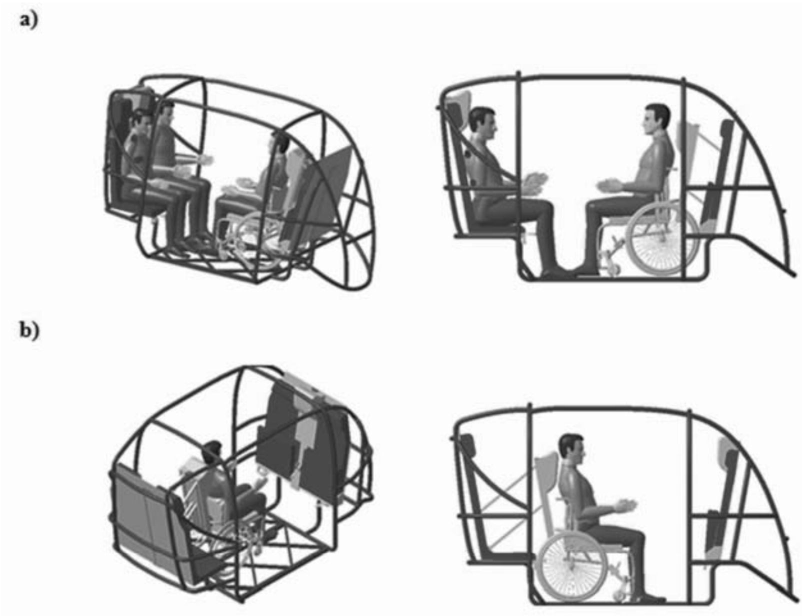


Figure 17. Location of the wheelchair inside the cabin of PRT vehicle: a) forward-facing b) backward-facing.

With the use of computer dummy man, the cabin space available for all PRT passengers has been marked. Securing the screen accessibility to the smallest person on the wheelchair, that is C_5 ♀, is in this case a sufficient condition. Installation of two screens, situated on opposite walls, will enable their handling with the use of the right hand, depending on the wheelchair position in relation to driving direction. The Figure 18 presents the reach are for the smallest person on the wheelchair.

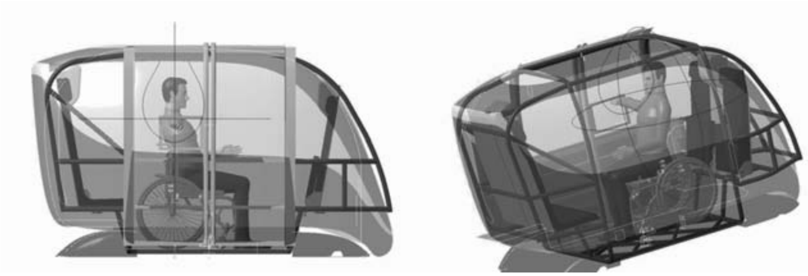


Figure 18. The position of two passenger's interface screens

The key functionality of the touchscreen (steering device) is to allow as many people as possible to select their destinations. The interface is located inside the cabin so that the passengers are able to change their destinations at any time. The key assumptions behind the service methodology and graphical layout are as follows:

- Finding source of information
- Discerning information
- Understanding information or a signal.

In order to enable finding and understanding the information, its screening has to be legible. Securing the detection of the information will result in high level of understanding and intuitive use of graphic interface. The graphic elements of the screen (icons, symbols) has been accompanied by adequate comments, so that a wide group of users, including elderly, could use it in an easy and comfortable way. The fact that the user can predict the reaction of the graphic interface to his previous actions proves its intuitive use. It results in efficient and comfortable use of the programme and the lack of additional user's manual and, consequently, the need for teaching the user. The interface consists of a number of screens: welcome screen, screens for selecting destination, screen confirming the choice of final destination and screen active between the stops. The Figure 2.z. presents function buttons of the touchscreen as well as sample of screens appearing while choosing the final destination of the journey.

Figure 19. Function scheme of the screen and examples of interface screen

4. CONCLUSIONS

The PRT network could be considered as an alternative transportation system, particularly in the urban areas or where the transportation infrastructure (roads, railways, etc.) is poorly developed. The work has demonstrated that the PRT network can effectively replace the current operating transportation systems. In Poland, local installations of PRT networks are planned in several urban conurbation and in selected areas of special character (i.e. in national parks).

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PRT (Personal Rapid Transit) computer network simulation, analysis of flow capacity*

Włodzimierz Choromański[1], Wiktor Daszczuk[2] ,Waldemar Grabski[2], Jarosław Dyduch[1], Mariusz Maciejewski[1], Paweł Brach[1]

[1]Warsaw University of Technology, Faculty of Transport, Koszykowa str. 75, 00-662 Warsaw, Poland, PH (+48)222347311, FAX (+48)224256543, email: prof.wch@gmail.com

[2] Warsaw University of Technology, Institute of Computer Science, Nowowiejska str. 15/19, 00-665 Warsaw, Poland, PH (+48)222347432, FAX(+48)222346091, email: wbd@ii.pw.edu.pl

ABSTRACT

Transportation problems of large urban conurbations inspire search for new transportation systems, that meet high environmental standards, are relatively cheap and user friendly. The latter element also includes the needs of disabled and elderly people. This article concerns a new transportation system PRT - Personal Rapid Transit. In this article the attention is focused on the analysis of the efficiency of the PRT transport network. The simulator of vehicle movement in PRT network as well as algorithms for traffic management and control are presented. The proposal of its physical implementation are also included.

INTRODUCTION

In Warsaw University of Technology, a project on Personal Rapid Transit (PRT) (Irving at al. 1978, Andreasson 2010) is under development (Choromański et al. 2011a and 2011b, Daszczuk et al. 2011).

Personal Rapid Transit (PRT), is a public transportation mode featuring small automated vehicles operating on a network of specially-built guide ways. PRT is a type of Automated Guideway Tansit (AGT), a class of system which also includes larger vehicles all the way to small driverless subway systems. The whole system is electrically supplied.

In PRT designs, vehicles are seized for individual or small group travel, typically carrying no more than 3 to 4 passengers per vehicle. Guide ways are arranged in a network topology, with stations located on sidings, and with frequent merge/diverge

* The research is rried out under the project ECO-mobility co-funded by European Regional Development Fund under the Operational Program Innovative Economy

points. This approach allows for nonstop, point-to-point travel, bypassing all intermediate stations. The point-to-point service has been compared to a taxi.

There are three kinds of nodes in the PRT network: stations, capacitors and intersections.

Stations are places where passengers book their trips and board the vehicles, or wait for vehicles in a queue if there are no empty vehicles on a station. A capacitor is a source of vehicles (and sometimes may serve as a parking place). Intersections are threefold: “fork” (diverge), “join” (merge) and “junction” (such intersections are for technical purposes only).

It is assumed that a vehicle has its own control unit, which is linked via radio network with control units of other vehicles and nodes (capacitors, stations and “join” intersections). Radio connections are established to vehicles and nodes that are closest to the vehicle, i.e. not farer that specified distance. This makes a subnet “visible” to the vehicle, the edge of which is called “a horizon”. The horizon distance should be chosen carefully, too large causes too much information to be transmitted (and routing problems), too small results in reduced safety of the traffic.

A vehicle gets information about current parameters of movement of preceding vehicles: their positions, velocities and mode of operation (acceleration/ constant velocity/ deceleration/ friction braking). From an intersection controller a vehicle receives the decision on priority of crossing the intersection.

Among other mechanical, electrical and transportation research goals, simulation of PRT network is performed, on two abstraction levels:

- Coordination level is “behavioral simulation”. On this level, algorithms for following a route, keeping up, coordination on “join” intersections, joining the traffic and similar are tested for effectiveness.
- Management level is “statistical simulation”. Simulation experiments identify the impact of various parameters of management algorithms (mainly of empty vehicle management and dynamic routing) on the passenger comfort (trip time and queue size).

There are several PRT simulators available (Castangia and Guala 2011, Zheng, Jeffery and McDonald 2009, Andreasson 2010, Hermes, Beamways, RUF), yet the authors have decided to build the project’s own simulators. It seems that these simulators are more advanced. They permit the analysis of different algorithms of the management and the steering in the traffic management of empty vehicles. The simulators allow to analyze various network topologies PRT, as well as to analyze the sensitivity of the system PRT to variation of different parameters values.

THE STRUCTURE OF THE PRT NETWORK

A typical structure of PRT network is assumed (Andreasson 2010), which consists of network nodes and segments connecting the nodes. Repertoire of nodes is: capacitors, stations and intersections. Stations and capacitors have one entry and one exit.

A station has internal structure shown in Fig. 1. There are two types of stations: in-line (following the FIFO rule) and stub-berths (vehicles must move back to dock in berth).

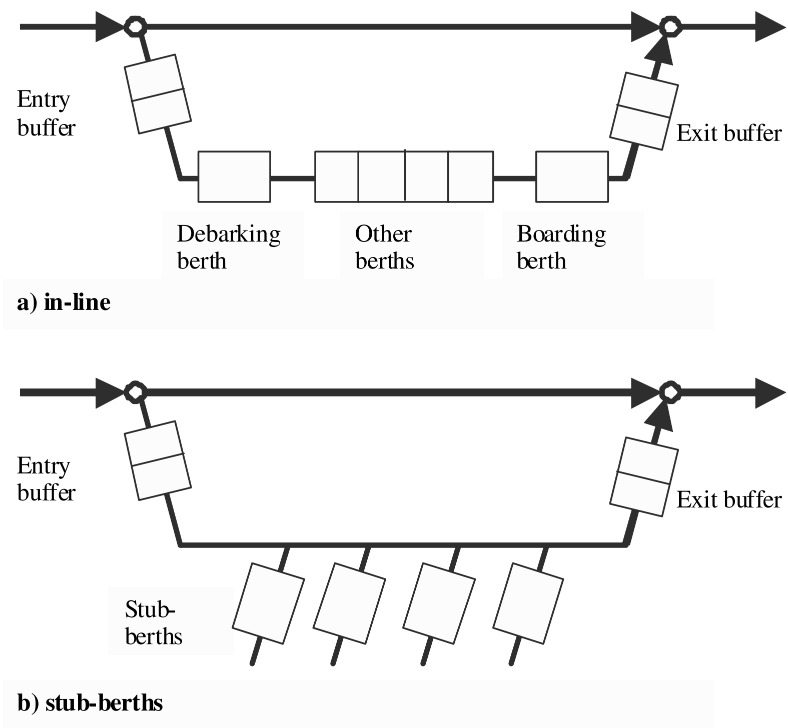

Figure 1. station types.

Nodes are assumed to be zero-sized, although they have internal structures necessary to model behavior: parking places (berths), entry and exit buffers, passenger queues etc. A station is characterized by its type (in-line/stub-berths), entry and exit buffer sizes and a number of berths. A capacitor has only one parameter – a number of parking places.

Segments connect the nodes (capacitors, stations and intersections). The parameters of a segment are: length and maximum velocity. Highway segments connect intersections only, while road segments may end at capacitors and stations as well.

Dynamic objects are vehicles (starting from capacitors) and passengers (appearing in stations).

Vehicles realize trips between capacitors and/or stations. The parameters of a vehicle are: capacity, maximum velocity, maximum acceleration and deceleration, minimum inductive deceleration, maximum friction deceleration (emergency brake) and minimum separation between vehicles. The characteristics of a passenger group (performing a common trip) are group cardinality (1-4 passengers) and the target station.

THE MODEL

The control algorithm of the PRT network is divided into lower, coordination level, and upper, management level:

- On the lower level (coordination) two algorithms are defined: keeping up, and coordination on “join” intersections (joining the traffic is realized as a special case of “join” intersection).
- On the upper level is empty vehicle management and dynamic routing algorithm are defined.

Coordination algorithms use several movement parameters: maximum velocities on individual sectors of segments, and parameters of vehicles: maximum velocities, maximum acceleration and deceleration, minimum deceleration, separation between vehicles. These algorithms are described in next sections.

The basic behavior, including rules of movement inside capacitors and stations, and rules of movement along the track, as well as keeping up rules, are fixed in the simulator. The routing is based on Dijkstra’s algorithm, although parameters of routing are defined for the model.

The structure of the network (nodes and segments), type of individual stations (in-line/stub-berths), capacity of nodes, number of vehicles, boarding and debarking times as well as distribution of passenger group cardinality are constant during the single simulation. Some values may be defined to be valid in specific periods (i.e. mean input of passenger groups and origin-destination matrix) or to occur in specified while (i.e. change of maximal velocity of a segment).

A lot of traffic parameters (concerning both levels of control) are definable by the author of the model, but they stay constant during single simulation experiment.

TWO APPROACHES TOWARDS PRT SIMULATION

Two independent simulators have been built, each one constructed on different principle. They are:

- Event-driven based simulator,
- Cellular automata based simulator.

Both simulators use the same model of PRT network (Andreasson 2010) and the same base parameters to allow distinct comparison of the results and verification of both of the simulators. The former simulator is more accurate, while the latter one is much faster.

Also, both simulators are micro-simulated. In the event-driven simulator, segments are divided into sectors (number of sectors is a parameters of a segment). The second simulator is based on cellular automata, every automaton corresponding to a sector.

The parameters of the model and traffic (i.e. boarding time, mean input, acceleration etc.) and the parameters of the coordination and management algorithms conform the (quite long) vector of values. Together with the structure of the network, the parameters conform a hierarchy of design steps, from most general to most detailed:

- network structure: nodes, segments;
- network elements characteristics: station types, number of berths, velocities, separation, capacity of entry and exit buffers, cardinality of passenger groups, etc.;
- acceleration and deceleration, general velocity limits, boarding and debarking times, origin-destination matrix;
- parameters of empty vehicles management, priority rules and dynamic routing;
- number of vehicles and their individual characteristics (velocity limits);
- passenger input (general or for individual stations) and origin-destination matrix in various times of day.

The parameter vector may be used co compare various network structures, various station and segment characteristics, or particular network in which empty vehicles management parameters or dynamic routing parameters vary. Some research is described later.

EVENT-DRIVEN SIMULATION ENVIRONMENT

The coordination is performed in a event-driven way, which is a typical solution (Anderson 1998, Lopez et al. 2008). As the behavior or a vehicle may change during the movement along a segment, the decision was made to divide segments into sectors. Therefore, events in our simulator are: passing connections of sectors and starting some actions in capacitors/stations – passenger group occurring, coupling of passenger group with a vehicle, beginning of boarding or debarking, start form parking place etc.

The simulator is split into two layers: the upper layer (called “UI”) allows to build a model, set its parameters and to perform simulation experiments. The lower layer (called “external simulator”) implements control algorithms. Both layers are written in C#. An exact interface is defined between the simulator layers, which allows to define user’s own control algorithms.

In every situation requiring a decision (for example start of movement, time of passing a sector), UI calls external simulator and acts regarding obtained decision. Therefore, UI is used as simulation engine, animation engine and statistics collector. Also, in UI are included procedures for model definition. External simulator prepares decisions on every changing of state of a vehicle, i.e. coupling passenger group with a vehicle, start boarding, enter the buffer, start moving along a sector, time of passing a sector etc. The whole simulation environment is called Feniks 3.0.

The manner the simulation runs is called microsimulation (Daszczuk at al. 2011, Fox 1999, Casas 1999, Gabard 1999), i.e. every detailed decision (micro-step) is under control.

EVENT-DRIVEN SIMULATION - COORDINATION - MOVEMENT ALONG A TRACK

It was decided that a vehicle moves along a track with maximal possible velocity. A "horizon" is a distance prior to the vehicle, which is observed by it and in which network nodes and other vehicles influence the behavior of the vehicle. A track prior to the vehicle is assumed empty if there is no vehicle, "join" intersection or capacitor or station closer than horizon.

The velocity on an empty track is a minimum of the three limits: maximum velocity for the vehicle, maximum velocity for the segment, maximum velocity for the sector. The actual velocity is limited additionally by the acceleration of the vehicle (the vehicle might not reach its maximal available velocity at a given moment) and by deceleration of the vehicle together with velocity limit on the next sector. Velocities, acceleration and deceleration are parameters of coordination algorithm. During a movement along a track, a distance called "separation" is kept. Static separation defines the minimum distance between vehicles standing one after another. On the move, the minimum separation and current maximum velocity are counted that guarantee safety, i.e. stopping after the preceding vehicle in *static separation* distance if preceding vehicles starts to decelerate of brake at the moment.

If there is a "fork" intersection ahead, the solution is simple: the vehicle takes into account only the outgoing track following chosen way (left or right). The other outgoing track is not analyzed.

If a capacitor or a station is in the horizon, and the vehicle "wants" do enter the capacitor/station, it must reach the zero velocity in a point of diverging from the track to the capacitor/station (capacitors and stations are zero-sized, although they have internal "logical" structure required to play their roles). If a vehicles wants to "drive through" a capacitor/station, it runs with maximal allowed velocity, except a situation where another vehicles wants to join the traffic (this case will be discussed later).

The exception from the above rule is when all the parking places in a capacitor/station (and entry/exit buffers) are occupied – in such a case the vehicle must stop before capacitor/station instead of exactly in the point of the capacitor/station.

The most complicated case is keeping up, when a preceding vehicle is found inside a horizon. The vehicle keeps the velocity (or slows down) that guarantees stopping safely after preceding vehicle even if it starts to brake.

EVENT-DRIVEN SIMULATION - COORDINATION - BEHAVIOR ON "JOIN" INTERSECTIONS

The main principle on "join" intersections is based on "allocating" the intersection to one of approaching vehicles (other considered principles require much more information sent between vehicles and intersections). The rules are: if a vehicle is in the distance of horizon before a "join" intersection, then it communicates with the intersection controller and:

- if the intersection is allocated to a vehicle on the other track leading to the intersection, the considered vehicle is planned to stop prior to the intersection (if the other vehicle is on the same track, normal keeping up is executed);
- otherwise the intersection decides to which vehicle it should be allocated (depending of priority rules, which are parameters of coordination algorithm).

Joining the traffic (from a capacitor or a station) is very similar, just the point of the capacitor on the track (or the point of the station) is treated as intersection, and it is being allocated to a vehicle on the move or to a vehicle joining the traffic, depending on priority rules (parameters of coordination algorithm).

The simulation is event-driven, i.e. the vehicles are moved from one discrete position to another. The positions are connections of sectors and various places inside capacitors and stations (parking positions, entry and exit buffers etc.). Examples of the decisions made by simulator are

- coupling of passenger group with a vehicle;
- beginning of boarding or debarking, start form parking place, entering the buffer, passing a connection of sectors, stopping at connection of sectors;
- decision on time of passing a sector (calculated by the algorithm presented above).

The Simulator plans the vehicle movement precisely (not approximate). Even in a single sector, the vehicle may accelerate, after that drive with constant velocity, then decelerate. The operation of the simulator is similar to the analog simulator (although the simulation is event-driven).

CELLULAR AUTOMATA SIMULATION ENVIRONMENT

Cellular automata system is a structure defined by a matrix of cells and their states, transitions and the rules of those transitions (Nagel and Schreckenberg 1992). Automata in such form are a mathematical models that construct an environment for a bigger, discrete classes of models, because all the structures describing them are discrete.

Each simple cellular automaton consists of n-dimensional, discrete matrix of cells. Each cell is the same (is a copy of the previous cell) and the whole space of the matrix must be filled with the cells put next to each other. Each cell has exactly one state from the finite number of available states. Transition of each cell takes place based on the same, precisely defined local rules (homogeneity), that depend only on the previous state of the cell and states of finite number of neighbouring cells. Transition is discrete and happens at the same time for all cells (parallelism). In the cellular automata, a cell is finite automaton.

In order to model the PRT network and traffic a more elaborated adaptation of cellular automata has been chosen – directed graph that represents the infrastructure.

The computational model is a directed graph, in which the nodes are the hubs and the edges between the nodes are the segments. Each node and edge has all the parameters that describe a given element (length of the segment, direction of movement, maximum allowed velocity, etc.). Each edge is tied to a discrete model of a segment, which is represented by 1-dimentional array. Every cell represents one unit of segment.

Each junction is represented as one cell. In a given unit of time, in a given cell, there can be only one vehicle. The cell can have one of two available states – empty or occupied by a vehicle. Each vehicle in the model moves with a velocity from the range $0 \ldots V_{max}$.

In the simulator a topographic model has been implemented, that consists of 2-dimentional, regular and discrete cell matrix. This model is a layer of abstraction over the directed graph. In the graph the nodes are the elements of the segments and the edges define the direction of movement between the nodes. Each node represents exactly one cell in the 2-dimentional matrix.

The configuration describing the infrastructure and the initial state of the environment – location of the vehicles, stations and capacitors and the passengers is one of the parameters of the model. The simulator uses and optimal-path algorithm to define a route to the target station. Such an approach allows for a dynamic control of the vehicles during the movement and is an excellent template of the real life movement of the PRT vehicles.

CELLULAR AUTOMATA SIMULATION – MOVEMENT IN THE NETWORK

After defining all the elements of the cellular automata, the rules of transition can be applied on the cell matrix. The transition process can be split into several parts (Schadschneidert and Schreckenbergt 1993, Li et al. 2001). Initial state, as mentioned previously, is a the definition of the initial conditions of the cell. Usually those are neutral states, that do not cause any conflicts.

Update of the automata matrix is a walkthrough sequence of steps for each cell according to the instructions below:

1. Verification of the transition rules – in this step a current state of the cell is verified along with the states of the neighbouring cells and other parameters of automaton
2. Neighbours verification – during this step a verification of any conflict states of the neighbouring cell takes place. If there are any conflicts they have to be resolved according the predefined rules
3. Verification of boundary conditions – verification of the cell at the borders of the matrix. They can be removed (absorbing closed neighborhood) or new ones can be created (periodic neighborhood)
4. Verification of number of iterations- if this is a finite automaton, with predefined lifecycle than in this step it is check whether the transition should stop.

In the case of the implemented PRT model, the update of the model consists of the following steps (each is performed in parallel for all vehicles in the environment):

1. *Acceleration*: if the speed of the vehicle V is smaller than the maximum, allowed speed (for a vehicle or road segment) and if the distance to the next vehicle is bigger then $V+1$, than the velocity is increased by 1, e.g. $V:=V + 1$
2. *Deceleration*: if the vehicle at the position I, with velocity V, sees a vehicle at the position i+j, for j smaller or equal to v, then the speed is reduced to $j-1$, e.g. $V:= j-1$
3. *Randomization* (optional): with a probability p_1, the velocity of a vehicle is reduced by 1 (if bigger than 0), e.g. $V:=V-1$
4. *Randomization* (optional): with a probability p_2, vehicle breaks down for a time period J, e.g. the velocity of vehicle is 0 for J units of time
5. If in the next unit of time vehicle will drive through a junction, following conditions are verified:
    a. If there is no conflict on the junction, e.g. there is no other vehicle coming to junction in the same time do nothing.
    b. Otherwise define the order of the vehicles (using weighs-based function). The priority vehicle does nothing (drives through the junction) and the other one slows down, letting the priority vehicle to drive through
6. *Movement*: move vehicles V cells in the direction of movement

SIMULATION RESEARCH

As an example of research work, a simulation experiment with PRT network saturation is presented. A PRT network structure as presented in Fig. 2 s assumed

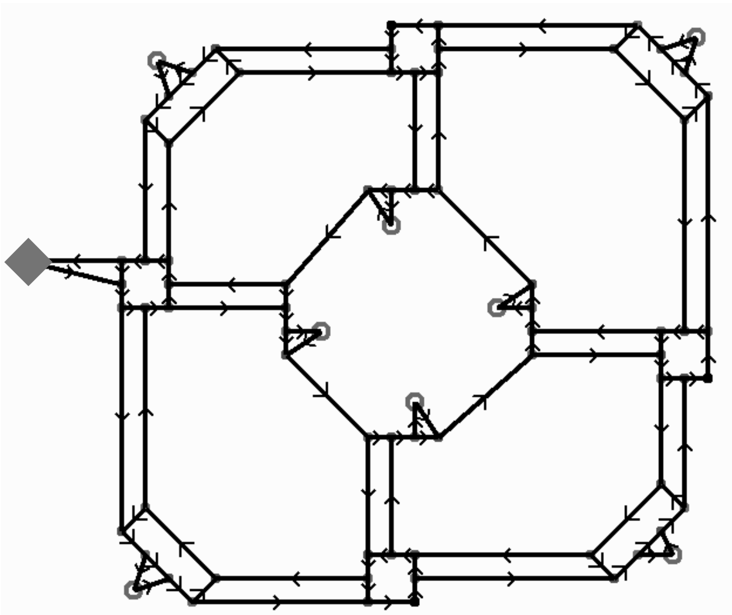

Figure 2. A PRT structure for simulation experiment.

(used also for other experiments). Circles represent stations (eight) while diamonds represents capacitors. The main parameters of the network are:

- total tracks length 6064,5m,
- 12 vehicles,
- 4 passengers in every trip,
- all stations of in-line type,
- 4 berths on each station.
- maximal velocity 14m/s,
- maximal acceleration and deceleration 2m/s^2,
- boarding and debarking times 10s.
- minimal separation 4m (event-driven simulator) and 2m (cellular automata simulator),
- passenger input differ in specific simulations,
- trip destination chosen randomly,
- empty vehicles management algorithm: if a vehicle stays in a station for longer then 120s, it is moved to the capacitor (*timeout* 120s). During this time it may be

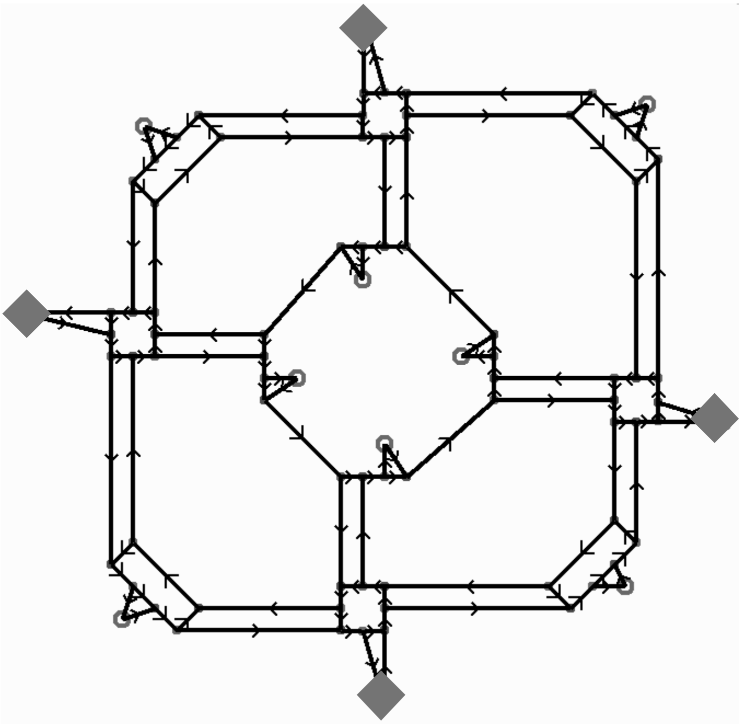

Figure 3. Modified PRT system.

called to other station (in which a passenger waits) or expelled (if other vehicle approaches the station and there is no free berth for it).

The model (as with every model) has its saturation point, i.e. maximum number of trips per hour (with its structure, number of vehicles etc.). It defines maximal throughput of the network: maximal number of passengers that may be moved to their destinations. If the average passenger input is less than saturation, a passenger waits for a vehicle on a station for given (average) time. If a saturation is reached, or the average input is greater than saturation, every passenger waits longer than its predecessor (passenger queues rise to infinity).

The idea of the experiment is as follows: a vehicle standing in a station for longer than 120s is moved to the capacitor, but the distances to the capacitor vary from station to station. It is expected that if we use 4 capacitors containing 3 vehicle each, regularly placed in the network, instead of one capacitor containing 12 vehicles (see Fig. 3), saturation should occur for higher number of trips per hour than in former network (in Fig. 2). Therefore, waiting time according to input growth should rise less.

Five input values (applied to every station) were tested: with mean time between groups 120s, 60s, 45s, 30s and 15s. Each simulation 4 hours of simulated time.

The results are collected in Table 1. The left hand part is for event-driven simulator, while the right hand part is for cellular automata simulator. We see that the saturation occurs about mean time 45s (between passenger groups occurring).

Table 1. Passenger waiting time and station queue length vs. passenger input in various conditions (number of capacitors and passenger input), two simulators compared; timeout 120s

event-driven simulator			**cellular automata simulator**		
	avg waiting time [s]			avg waiting time [s]	
avg input [s]	1 capacitor	4 capacitors	avg input [s]	1 capacitor	4 capacitors
120	22,51	20,27	120	24,93	21,88
60	59,40	58,15	60	68,29	67,20
45	435,95	440,32	45	451,43	460,73
30	2599,52	2586,12	30	2723,48	2712,47
15	4893,61	4882,92	15	5162,98	5145,65
	avg queue length [pass.groups]			avg queue length [pass.groups]	
avg input [s]	1 capacitor	4 capacitors	avg input [s]	1 capacitor	4 capacitors
120	0,19	0,17	120	0,22	0,20
60	0,97	0,95	60	1,08	1,05
45	9,58	9,67	45	10,43	11,02
30	85,22	84,90	30	94,59	93,41
15	324,73	324,24	15	340,97	338,35

The results show that our assumption was naive: the difference occurs for low input rather than for high input.

The research was repeated for shorter timeout: 30s. It was expected that the difference (1 capacitor vs. 4 capacitors) will be greater (as the vehicles are more frequently moved to capacitors). The results are collected in Table 2.

Table 2. Passenger waiting time and station queue length vs. passenger input in various conditions (number of capacitors and passenger input), two simulators compared; timeout 30s

event-driven simulator			**cellular automata simulator**		
	avg waiting time [s]			avg waiting time [s]	
avg input [s]	1 capacitor	4 capacitors	avg input [s]	1 capacitor	4 capacitors
120	31,32	28,46	120	33,38	29,03
60	60,14	58,80	60	69,73	65,33
45	448,32	435,28	45	464,74	461,84
30	2599,52	2589,60	30	2832,62	2801,98
15	4893,61	4882,92	15	5129,77	5113,54

	avg queue length [pass.groups]			avg queue length [pass.groups]	
avg input [s]	1 capacitor	4 capacitors	avg input [s]	1 capacitor	4 capacitors
120	0,26	0,24	120	0,29	0,25
60	0,98	0,96	60	1,12	1,06
45	9,85	9,57	45	11,54	11,47
30	85,22	85,01	30	95,53	93,78
15	324,73	324,24	15	339,63	335,39

The results are as expected, i.e. the difference (occurring for lower input only) is greater than in previous research.

It should be explained why the hypothesis (that saturation point will rise for 4 capacitors) was wrong. The reason is that when the input is high, vehicles often take passengers and vehicles seldom are moved to capacitors, so the location of capacitors is not important.

IMPLEMENTING PRT STEERING AND MANAGING ALGORITHMS IN PHYSICAL MODEL OF PRT NETWORK IN LABORATORY ENVIRONMENT

In parallel with developing logical model of the PRT network, a physical one is being built on the Warsaw University of Technology. It implements the algorithms described in the former chapters. The security and safety of PRT system is governed by a central computer control and dispatch system. The system consists of layers containing following subsystems (Fig. 4):

- dispatcher system – DS.
- central control system – CCS
- area control system – ACS
- radio communication system – RCS
- vehicle control system – VCS

The main task of the dispatcher system is the facilitation of the monitoring of the

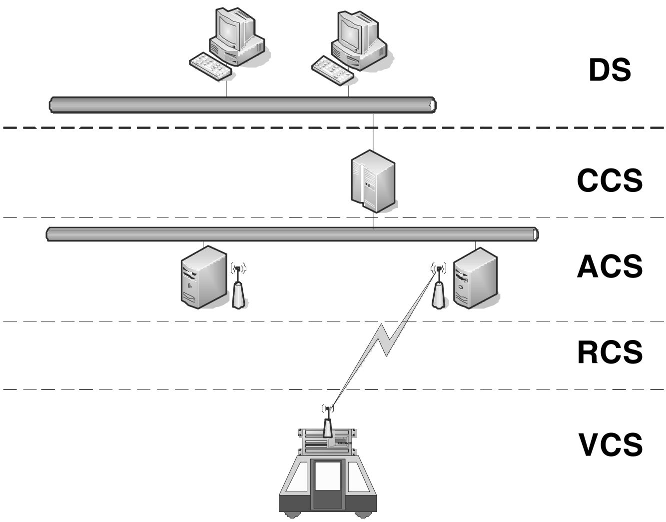

Figure 4. Structure of the steering system of PRT.

whole system by the maintenance personnel. The PRT system is fully automatic and during regular operation no human intervention is required. In case of emergency the personnel can switch to manual control. Dispatchers monitor the current state of the traffic, power system, data transmission and proper operability of computer systems. Dispatchers can mark any component as faulty and plan maintenance tasks. The steering and controlling system is equipped with surveillance video. The video cameras are mounted on the stations and PRT vehicles. Both the stations and vehicles have systems enabling instant contact with the dispatchers In case of emergency dispatchers have direct live feedback from each vehicle. The video and voice transmissions are recorded and archived.

At the infrastructure level the system is redundant, therefore provides the continuous operability in case of failure of single components of the system. The transmission system also provided redundant connection in case of failure.

Central control system is of distributed type - different functions are deployed on different steering layers. Central CCS system manages the vehicles. It sets the routes, assigns vehicles to the orders and manages free vehicles. Performance and optimization of that part of the system is analyzed in the simulation environments. Optimization aims at the defining most efficient ways of movement in PRT network in terms of travel and waiting time as well as the energy efficiency. System react to emergency and faults situation by dynamically reassigning routes. Each change in the traffic situation is archived with a frequency of 100ms. The archived materials are available for analysis, elimination of bottleneck and errors in the system.

Area control systems have the tasks of controlling single moving vehicles, controlling the traffic on the stations and assigning right-of-way on crossroads. The whole system is divided into areas that are manages by dedicated computers. The central system collects information about location of each vehicle and distributes it to all area computers. The right-of-way algorithms are parameterized and can be adjusted according to the traffic state in specific areas. ASC does not assign or manipulate routes. In case of emergency of CCS, the ASC directs the vehicles to the nearest station or evacuation points according to predefined scenario. If the connection with specific vehicle is lost, the ASC marks corresponding area as unavailable in order to maximize the safety of all participants.

At the infrastructure level ASC is redundant. Additionally the information about movements and state of a vehicle is distributed to corresponding are computer as well as to neighboring ones. Such setup assures that in case of emergency one of the neighboring computers can take over the control of the area.

The main tasks of vehicle control system is communication with area control system, marking the position of the vehicle, assuring the safe distance to closest vehicle , maintaining a safe velocity, monitoring of the door controlling system, air conditioning, lightning, etc. VCS facilitates the voice and video communication between vehicles and dispatchers. Each vehicle is equipped with displays showing the current state and location of vehicle. Passenger can alter the target station at any moment and a new route will be assigned. During the trip the main display can present commercials and news information. VCS monitors the operation of the engine, breaking and power systems.

Communication between PRT vehicles and ACS is facilitated by digital transmission system. The vehicle is in range of two independent base radio stations in any point of the network. The transmission system is implemented in accordance with European standard EN-50159. Data transmission is encoded and encrypted to disable access to the systems by undesirable individuals. Implementation of the European standards EN-50126, EN-50128, EN-50129 ensure highest safety, reliability and maintainability of the whole system. All the critical technical components are configured in fail-safe technique, using 2 out of 2 model.

CONCLUSIONS AND FURTHER WORK

The results from simulation experiments show that the simulation environment is useful for comparison of various conditions of network operation.

In future, the comparison of various network structures, management algorithms and other features may be performed from various points of view, for example from passenger, network administrator or network maintenance engineer point of view.

The very wide set of output parameters measured give the possibility to observe the behavior of a PRT network from that outlined or other points of view. For example, trip time may is measured in three various ways:

- *gross time*: time including boarding and debarking (passenger point of view);
- *buffered time*: time since end of boarding till start of debarking (includes times the vehicle stays in entry and exit buffer of stations – network administrator point of view – he/she does not care about boarding and debarking);
- *net time*: from start of movement after leaving origin station to stop of movement at destination (network maintenance point of view);

A detailed log of events may be also obtained, which allows to build simulation statistics viewed from other points of view.

Using the simulators, various design aspects may be viewed as complex optimization tasks. For this purpose, “unit costs” of all PRT elements (1m of the track, 1 vehicle, 1 berth in a station, 1 intersection of every type etc.) and PRT services (1m of a travel, 1 day of vehicle technical maintenance and amortizement, etc.) must be specified. Then, optimal usage parameters (passenger waiting time, effective travel velocity, average travel delay to optimal travel time) or maintenance parameters (daily vehicle distance, full/empty travel ratio etc.) may be identified in simulation experiments.

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APM and Other Driverless Systems for Integrated Urban Planning and Sustainability

Tim Zhang[1]

[1]Tim Zhang, Bachelor of Science in Engineering, MBA, Manager Marketing, Bombardier Transportation, Systems Division; P.O. Box 220, Station A, Kingston, Ontario, K7M 6R2, Canada; Telephone: 613-384-3103 Extension 4732; Fax: 613-634-5321; Email: tim.zhang@ca.transport.bombardier.com

Abstract

This paper provides an overview of how APMs and other driverless systems integrate with other forms of transit and how they support sustainability and smart growth.

Cities today face the challenges of increased traffic congestion and tighter budgets. Urban planners are increasingly facing the demand of planning infrastructure with sustainability and energy savings in mind. Mobility, as one of the key components for urban planning, is increasingly demanded as a result of demographic changes. In addition, the travelling public is more concerned than ever with the environmental impact of their transport choices. Transit users are demanding more integrated systems, user-friendly interfaces and improved services.

APM and other driverless systems have played key roles in the sustainable development of airports and cities. This paper discusses how various forms of driverless systems integrate with other forms of transit systems, and why driverless systems should increasingly become transportation solutions for urban planners in the planning of tomorrow's mobility network.

Bombardier, as a pioneer of driverless systems, has been enthusiastically embracing these economic and environmental trends. Its products are designed with sustainable mobility in mind. Its R&D is increasingly focusing on those goals. Key features of Bombardier's driverless systems, such as fully automated unattended operation, short trains with frequent service, low weight, optimized energy consumption, high reliability and availability, and the use of recyclable materials all support the goal of sustainable mobility.

Various aspects of transit planning such as route selection, transit technology selection, extension / expansion plans, and procurement method all have direct impacts on capital costs, operational costs and energy consumption. Today there are various forms of driverless systems available for policy-makers/planners to choose from to achieve the optimized results that will ultimately benefit customers/citizens.

Introduction

Cities today face the challenges of increased traffic congestion and tighter budgets. Urban planners are increasingly facing the demand of planning infrastructure with sustainability and energy savings in mind. Mobility, as a key component of urban planning, is more and more demanded as a result of demographic changes and technology advancements. In addition, the travelling public is more concerned than ever with the environmental impact of their transport choices. Transit users are demanding more integrated systems, user-friendly interfaces and improved services.

Population Growth and Public Transport Riders

In general the world population has been increasing and is projected to continue to increase. Cities today face the challenges of increased traffic congestion as a result of population growth and demographic changes.

It is important to have a better understanding of the users of public transportation in order to understand if population growth has a direct impact on public transportation ridership growth. According to an APTA (American Public Transportation Association) public transit passenger survey, the majority of public transit users are in the age group between 15 to 54 years. Both a 1992 survey (Figure 1) and a 2007 riders survey (Figure 2) confirmed that. This is reasonable, because this population group includes students who go to school every weekday and employees who go to work every weekday.

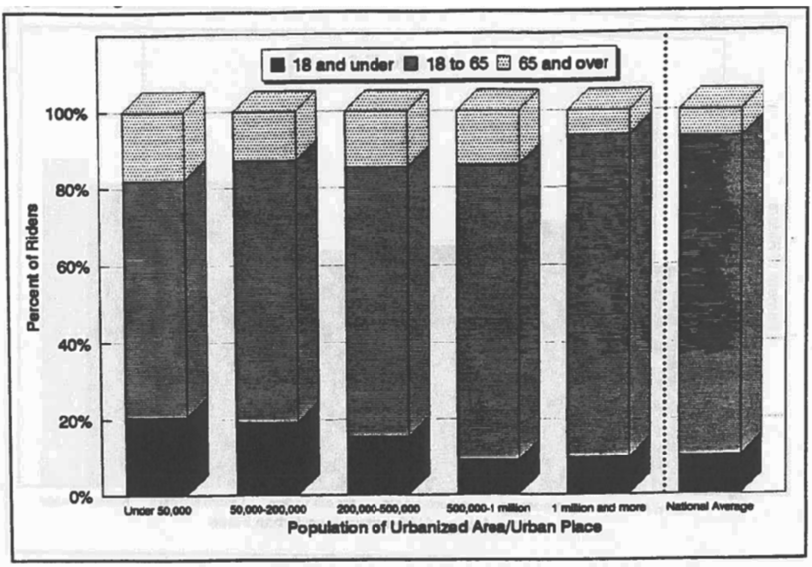

Figure 1 Age distribution of Riders, APTA Survey 1992 [1]

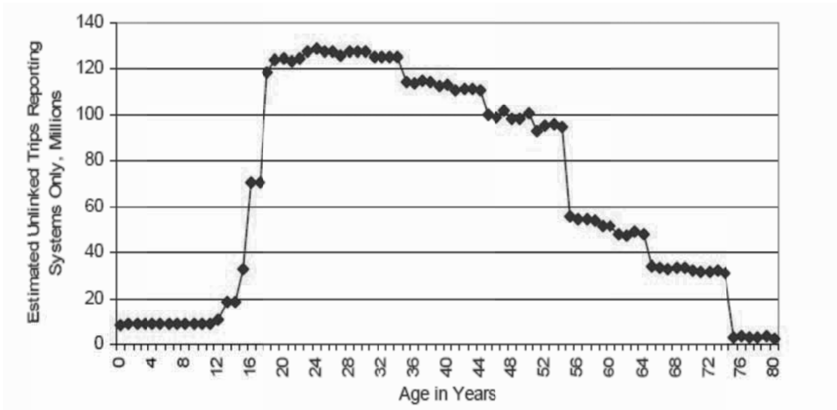

Figure 2 Age distribution of Riders, APTA Survey 2007 [2]

The next question to consider is how the demographic distribution in the population will look in 10 years, when the current main pool of riders will be 10 years older. Would the population in the age group of main ridership source increase with the overall population? U.S. census data (Figure 3 and Table 1) is used for analysis to provide an answer to those questions.

Apparently the answer is not simply to shift the current distribution by 10 years, because there are other changes to the population such as immigration, emmigration, deaths, etc. For the purpose of this paper the historical trend from 2000 to 2010 is used to predict the 10 years after [3].

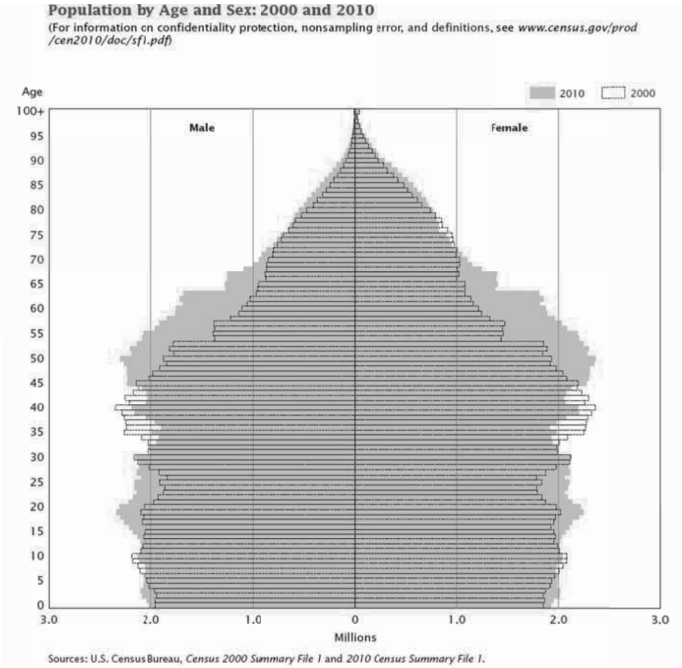

Figure 3 Population by Age and Sex: 2000 and 2010 [3]

The age group of 20 to 54 is chosen to study demographic changes for the future because this group is the consistent main source of ridership. As demonstrated in Table 1 below, the growth ratio of 2010 over 2000 is used to predict the population for that age group in 2020.

	2000	2010	ratio 2010/2000	2020 Projection assuming the same ratio
under 5	19,175,798	20,201,362		21,281,775
5 to 9	20,549,505	20,348,657		20,149,772
10 to 14	20,528,072	20,677,194	1.08	21,783,056
15 to 19	20,219,890	22,040,343	1.07	21,824,924
20 to 24	18,964,001	21,585,999	1.05	21,742,806
25 to 29	19,381,336	21,101,849	1.04	23,001,707
30 to 34	20,510,388	19,962,099	1.05	22,722,096
35 to 39	22,706,664	20,179,642	1.04	21,971,022
40 to 44	22,441,863	20,890,964	1.02	20,332,501
45 to 49	20,092,404	22,708,591	1.00	20,181,355
50 to 54	17,585,548	22,298,125	0.99	20,757,159
55 to 59	13,469,237	19,664,805	0.98	22,225,315
60 to 64	10,805,447	16,817,924	0.96	21,324,793
65 to 69	9,533,545	12,435,263	0.92	18,155,225
70 to 74	8,857,441	9,278,166	0.86	14,440,818
75 to 79	7,415,813	7,317,795	0.77	9,545,107
80 to 84	4,945,367	5,743,327	0.65	6,016,133
85 to 89	2,789,818	3,620,459	0.49	3,572,606
90 to 94	1,112,531	1,448,366	0.29	1,682,067
95 to 99	286,784	371,244	0.13	481,778
100 and over	50,454	53,364	0.05	69,473
	281,421,906	308,745,538		333,261,488
20 to 54	141,682,204	148,727,269		150,708,646

Table 1 Population for main Rider sources

The conclusion of this analysis is that the population of the main source of riders will roughly stay the same, around 1% more than 2010. Then the question is "Do we still have a problem if the main ridership source segment of population is not really growing"? Or "Can we do with the current transit services as provided"?

To answer those questions we need to study ridership growth trends. If ridership keeps growing, which means more people choose to use public transportation, then we will still need to provide more public transportation services.

Ridership Trend

APTA/FTA ridership data is used here to evaluate trends in ridership. The rail ridership used includes light rail and heavy rail (metro). Commuter rail is not included.

As Figure 4 shows, overall urban public ridership grew but saw some decrease since 2008 due to the recession. From the same figure we can also see the different patterns of ridership for rail and bus. Ridership for bus didn't really grow and it dropped sharply in the recession.

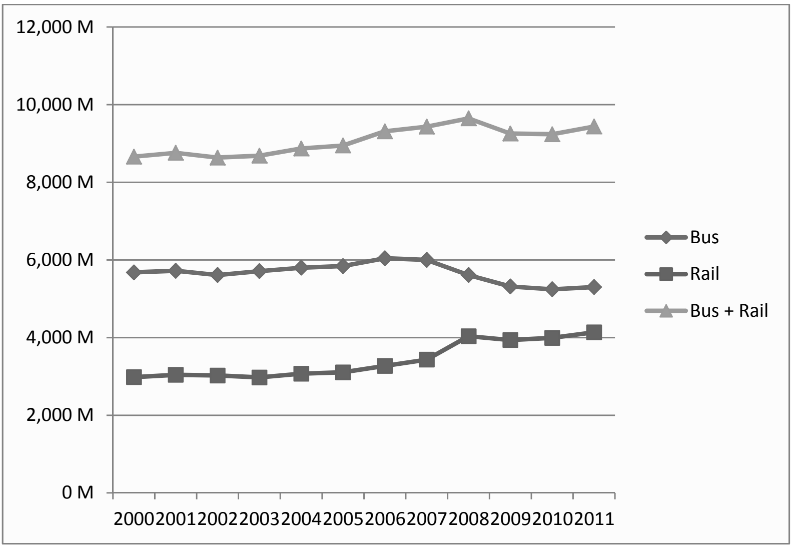

Figure 4 Ridership (passenger trips) trend [4]

Rail mode ridership has increased in the last 10 years. The recession did affect the ridership somewhat, but it has been steadily increasing in contrast to the bus ridership decline. Clearly rail is the preferred mode for riders. The reason presumably is that rail is more reliable, faster and more comfortable. As the Transit Oriented Development model shows in the U.S., rail, because of its permanent infrastructure, attracts more development investment and thus more riders as well.

From 2000 to 2010 rail ridership had a 34 % increase. Based on this, the estimate for ridership growth over the next 10 years is around 20% after removing the population increase effect during the 2000 to 2010 period.

The conclusion is that the population providing the main source for ridership is going to be steady with a slight increase, but the percentage of people who choose to take rail will continue to increase. This poses a great challenge for city planners in transportation planning and also for transit agencies in their planning for future operations.

New Trends in Transportation Preferences

There are other trends that may also impact ridership growth and public transportation services. With the popularity of smart phones and social media, especially with the younger generation, more and more young people prefer to use public transportation than driving. The reason, obviously, is that they can continue to use their smart phones on trains without safety concerns. If the trend continues as they age, it would have a significant impact on ridership growth, which would also increase the demand for public transportation.

The older segment of population does not form a large portion of public transportation ridership, at least they don't have great impact on peak hour demand because they don't have to travel during rush hours. However, this group is going to grow because of the baby boomers who will move into this age group (see Figure 3). Public transportation is also the main means of transportation for some of them because they give up driving as they grow older. Some specific needs such as wheelchair access will become more important as a consequence. Rail transit can easily provide convenient and reliable level boarding.

Sustainable Transit Modes

The increasing preference of rail may also have something to do with environmental impact awareness. Passenger rail is generally powered by electricity, which doesn't produce CO_2 emissions at the point of use. Diesel busses, which are used for the majority of bus fleets, are obvious contributors to the CO_2 emissions of a city, and thus are seen as less desirable.

Rail transit can provide much higher capacity than bus. Trains also provide better ride quality and more reliable service, which may also contribute to the significant ridership growth over bus. As previously mentioned, rail transit lines attract more property investment, which can also help to sustain them due to increased population density.

Benefits of Driverless Systems

There are significant benefits associated with driverless systems. Firstly, they reduce the costs of operation and maintenance. Drivers are not needed, which saves operating costs significantly. Secondly, they provide operational flexibility. An operator can change number of operating trains based on passenger demand without the need to adjust staffing, because drivers are not needed. Thirdly, energy consumption is reduced. Driver behavior has significant impact on energy consumption. A driverless system eliminates the (unnecessary) driver's impact on energy consumption, and therefore the system can be confidently designed based on the lower energy consumption predicted by advanced energy management simulations.

Fourthly, safety is improved. Many train accidents are caused by careless driving or impaired driving. Using automated systems eliminates these causes.

Finally, customer service quality is improved. More frequent service (shorter headway) is a benefit of using of short trains. For a system with drivers, frequent trains are not efficient because of the need for drivers, which has a significant impact on operation costs. For a driverless system staff can also be dedicated to support passengers either in the stations or in the trains if necessary.

The Role of APMs and Other Driverless Systems

APMs and other driverless systems have played key roles in the sustainable development of airports and cities. A range of technologies including APM, driverless monorail, driverless light metro and heavy metro is available, each having its optimized application. These technologies can integrate with light rail, bus and other transit modes to form a network of transportation solutions for a city or region.

APM systems (rubber-tired automated people mover systems) have been implemented in many places in the U.S. and other parts of the world, especially at airports. APMs can also be implemented for urban environments. Miami and Singapore are examples. There are also a number of APM systems in light metro applications in Europe and Asia, such as the VAL systems in Lyon, Lille and Rennes.

Driverless monorail technology is similar to APM technology because it also uses rubber tires. Monorail is unique because of its futuristic look, slim beam and fast implementation. It is a technology that provides a very good urban fit because the beams can be fabricated off-site, thus reducing the time of road closures for construction. It also has the low noise, high grade and small-radius curve features that make it a good fit for urban applications.

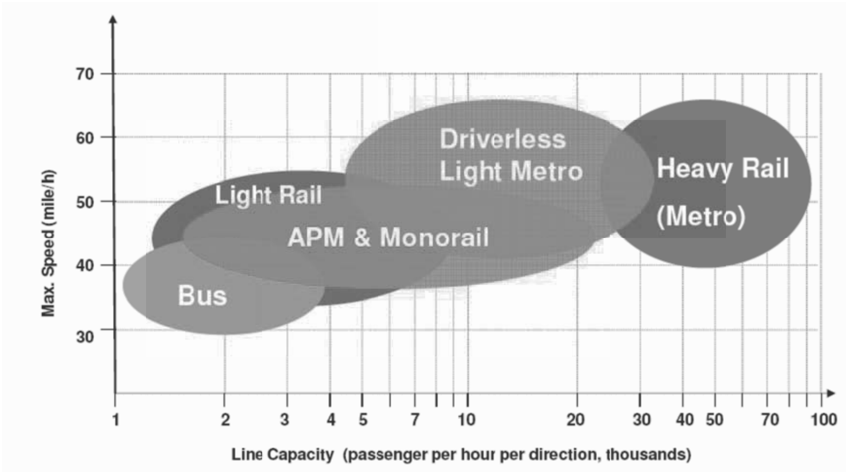

Figure 5 Urban Rail Transport Chart

The driverless light metro concept was initiated as a cost-efficient urban rail transit solution by Bombardier in the 1970's. The rationale for the driverless light metro is that it saves significant cost compared to heavy metros, which typically have long trains and usually involve long portions of expensive underground tunnel. For medium sized cities or transit lines with medium capacity requirements, heavy metro is not an economical solution because there isn't sufficient ridership to support the system. Light metro using elevated guideway is an economical alternative for the medium capacity requirement because it is considerably less expensive to construct elevated guideway than underground tunnel. It is equally important to offer good service to attract riders, thus the train frequency has to be high. It is not economically viable to offer light metro systems with drivers on board and offer very high frequency service because of the resulting labor cost. The solution is to employ driverless short trains that operate at high frequency.

From Figure 5 we can see that bus is optimized for low capacity systems. It has its ideal application in low density areas where it is not possible to justify the initial capital investment in a rail system.

As Figure 5 shows, APM, driverless monorail, and light metro fill the capacity gap between bus/light rail and heavy metro. They can work together to provide the most efficient urban transportation solutions.

APM, light metro and monorail can be applied for line-haul systems, which serve as a backbone of transit, or as circulators for an airport or city downtown, or as collector/distributors that link main stations with other lines or modes of transport, or as an airport link such the JFK AirTrain in New York.

Bombardier Embracing the Trend - Design for Environment

Figure 6 Bombardier INNOVIA 300 Products – Metro, APM and Monorail

Bombardier, as a pioneer and leader in driverless systems, has been enthusiastically embracing recent economic and environmental trends. Its products are designed with sustainable mobility in mind. Its R&D is increasingly focusing on those goals. Key features of Bombardier's APM and other driverless systems, such as fully automated unattended operation, short trains with frequent service, low weight, optimized energy consumption, high reliability and availability, and the use of recyclable materials all support the goal of sustainable mobility.

Bombardier's new generation driverless system is called *INNOVIA* 300, which includes *INNOVIA* APM 300, Metro 300 and Monorail 300. The 300 products are the result of the evolution of previous generations of products. The latest technologies have been used to continue the sustainable themes such as low weight, low energy consumption, high reliability and availability.

Bombardier has also developed advanced energy management technologies such as wayside energy storage units EnerGstor and an energy management simulation tool, which is used to optimize the energy efficiency of transit systems. Those are all compatible with *INNOVIA* 300 systems.

Transit Technology Selection is an Important Part of Urban Transportation Planning

Various aspects of transit planning such as route selection, transit technology selection, extension/expansion plans, and the chosen procurement method all have a direct impact on capital costs, operating costs and energy consumption. As mentioned, a range of technologies including driverless light metro, monorail and APM are available, from which policy-makers/planners can choose to achieve the most efficient results. Urban planners should therefore be aware of the available alternative technologies, and the need of integration of the various systems into one seamless network.

It is important to understand the relevant characteristics, such as grade and curve capabilities, of the available transit technologies and then plan the system infrastructure accordingly. APM or Monorail technologies can easily climb grades of up to 6%, and thus a transit line along a 6% grade can be planned without using tunnel sections. APMs can negotiate 22 m curves, and transit-grade monorails can negotiate 46 m curves. These features can be exploited by routing the system using tight curves in city streets and around buildings. This eliminates the need to use tunnels, or to find alternative (longer) alignments. It is important to consider these features in the early stages of a project planning. They will reduce the capital cost significantly, and in many cases they can reduce the length of line, and thus the travel time, energy consumption and operating costs.

Linear Induction Motor (LIM) rail technology uses conventional steel wheel and steel rail but it can operate safely and reliably in low-adhesion conditions, and in winter conditions with ice and snow. The reason that LIM technology provides this capability is that it doesn't depend on rail / wheel friction to accelerate and decelerate. LIM technology also has excellent small-radius curve and high grade capability. The Vancouver SkyTrain Expo Line and Millennium Line use LIM technology (Bombardier INNOVIA Metro or ART), which has provided 27 years of best-in-class reliable and efficient operation. New York, Yongin, Detroit, Kuala Lumpur, and Beijing and Toronto also have Bombardier's *INNOVIA* Metro LIM systems in operation.

Operating Budget Constraints

As we know, every city in the world is facing operating budget constraints, because there are always competing priorities for a city. Also as mentioned, driverless transit systems provide the benefit of lower operating costs. Figure 7 is a comparison of U.S. heavy rail systems with Vancouver SkyTrain and JFK AirTrain, which are driverless light metros.

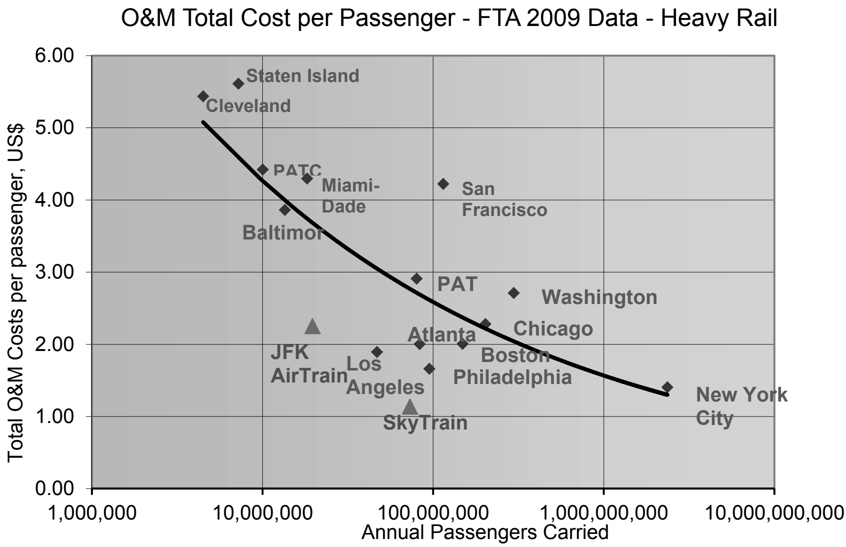

Figure 7 O&M Costs Comparison – Driverless vs. Other Metro

It is very clear from the figure that driverless technology provides significantly lower operating and maintenance costs for a system of similar size. The comparison with light rail systems gives a similar picture.

Project Procurement

Driverless transit systems are technologically complex, with many interdependent subsystems, and thus to successfully implement them it is recommended to procure them as turnkey systems. The JFK AirTrain and Vancouver SkyTrain are good examples. In a turnkey procurement approach one party/consortium has the responsibility to deliver the whole project. The scope and responsibility are therefore very clear for system delivery. This approach can also mitigate scope and budget creep. The price is fixed for the system supply and also for operation and maintenance (O&M) if O&M is part of the scope. The turnkey approach can also result in a shorter implementation time than a "sum of the parts" procurement, because the procurement process is under one single contract. The project delivery schedule can also be optimized because the consortium has all the scope under its control. The "one stop shop" model also gives the contractor the opportunity to design the system as a whole and optimize the system, thus providing the best service quality.

Conclusion

To address mobility issues and budget constraints, it is to the benefit of planners and cities to consider a wide range of driverless transit system technologies including APM, monorail, and automated light metro. The most efficient technology can be selected based on the specific needs of a city, the specific requirements of a line, and certainly the capital costs, O&M costs and environmental impacts.

Driverless systems should increasingly become transportation solutions for urban planners in the development of tomorrow's mobility network. Various aspects of transit planning such as route selection, transit technology selection, extension / expansion plans, and procurement method all have a direct impact on capital costs, operational costs and energy consumption. To achieve sustainable mobility it is important to consider the selection of transportation technology at a very early stage of urban planning.

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Calculating the Capacity of Automated Transit Network Systems

Jefferson H. Davis, P.E. [1], **Gregory W. Love** [2], **and Matthew Sturgell, P.E.** [3]

[1] **Senior Associate,** LEA ELLIOTT, Transportation Consultants
44965 Aviation Drive, Suite 290, Dulles, Virginia 20166
PH (703) 537-7406; FAX (703) 968-7888; Email: jdavis@leaelliott.com

[2] **Manager of Engineering Projects,** LEA ELLIOTT, Transportation Consultants
5200 Blue Lagoon Drive, Suite 250, Miami, Florida 33126
PH (305) 929-8114; FAX (305) 500-9391; Email: gwlove@leaelliott.com

[3] **Manager of Engineering Projects,** LEA ELLIOTT, Transportation Consultants
44965 Aviation Drive, Suite 290, Dulles, Virginia 20166
PH (703) 537-7424; FAX (703) 968-7888; Email: msturgell@leaelliott.com

Abstract
Calculating the passenger carrying capacity of transportation systems is an important and necessary process to determine if a proposed system can be expected to meet design requirements related to passenger demand. The analysis and calculation must consider many factors that influence the final passenger carrying capacity of a transportation system, such as safe separation distance, operational headway, average speed of the vehicles, the vehicle control system design, track alignments, ride comfort criteria, dwell time, and system operating modes. While this paper discusses systems with off-line stations and pinched loop systems with in-line stations, the methodologies discussed are applicable when analyzing the capacity of different transportation technologies and networks.

Introduction

It is important and necessary to perform an analysis to estimate the Passengers Per Hour (PPH) for planned Automated Transit Network Systems (ATNS) to determine if the proposed design and configuration will provide adequate service for the estimated passenger demand. The final PPH is dependent on the number of passengers each vehicle can comfortably carry and since this varies based on the interior design of the vehicles, and an assumed passenger density, this paper will focus on the sustainable flow of vehicles past a fixed point on the guideway, i.e. Vehicles Per Hour (VPH). The final estimation of PPH can then be calculated using the estimated VPH.

It is important to note that the determination of the sustainable VPH for a given system is based on the minimum sustainable headway which is different than calculating the minimum achievable headway. The minimum achievable headway typically only exists between stations on track sections without interferences, such as active diverges and merges. However, the minimum sustainable headway considers all the sections of track, including conflict points such as diverges, merges, station stopping areas, and turnbacks. The section with the longest headway determines the minimum sustainable headway for the system.

The VPH can be calculated as:

$$VPH = \frac{3600\ seconds\ per\ hour}{T_H} \qquad \text{Equation 1}$$

Where:
T_H = Headway in seconds

Issues to consider when analyzing and estimating VPH for a given system include:

- Safe separation distance; the distance between two successive vehicles which provides sufficient separation to avoid collisions and is calculated using:
  - Vehicle normal acceleration rate
  - Vehicle normal deceleration rate
  - Vehicle maximum deceleration rate, also known as Guaranteed Emergency Brake Rate (GEBR)
  - Vehicle maximum speed
  - Vehicle control communications delay between vehicles
  - Vehicle control system design including processing time
  - Safety distance; a distance added to the rear bumper of leading vehicles as a safety margin
  - The last known position of the rear bumper of a lead vehicle
  - Assuming that vehicle to vehicle collisions are not allowable
- System alignment or topology
- Operating mode

The safe separation distance is used to determine the minimum achievable headway.

For the purposes of this paper the following is assumed:

- Single vehicle consist; a passenger carrying unit that can operate individually
- Moving Block control system using Communications Based Train Control technology whereby the locations of all vehicles are known to the control system within centimeters
- Normal deceleration rate is the rate used during station stops and is based on ride comfort criteria
- Emergency deceleration rate (GEBR) is the rate used by vehicles when an unsafe event is detected and is greater than the normal deceleration rate.

Vehicle Design Characteristics, Safe Separation Distance, and Operational Headway

Nominal or sustained operational headway is the time measured between the same point on successive vehicles passing a fixed guideway location for a period of time equal to or greater than one Round Trip Time. This includes the time between the rear bumper of lead vehicles and front bumper of trailing vehicles (safe separation distance) plus the time for the front and rear bumpers (length of vehicle) to pass the fixed location.

The GEBR is the minimum deceleration rate a vehicle will achieve given single point failures on the vehicle or worst case track conditions. The determination of the GEBR is beyond the scope of this paper, but will be used in the calculation of the safe separation distance.

The vehicle control communications time delay is dependent on the specific implementation and is one of the following:

1. For self-propelled vehicles using a wayside control system the total time is calculated as the sum of the following:
    a) Time to communicate the application of emergency brakes from the vehicle to a wayside controller
    b) The processing time of the wayside controller
    c) Time to communicate the application of emergency brakes from the wayside controller to following vehicles
2. For vehicles with onboard distance measuring devices it is the processing time onboard the vehicle to detect that the distance to a lead vehicle is less than the minimum separation distance
3. For vehicles utilizing a common propulsion system such as Linear Induction Motors (LIM) or cable propelled it is the time to detect an event requiring emergency brakes

For the purposes of this paper it is assumed that the position, within centimeters, of the rear bumper of lead vehicles is continuously transmitted to a wayside controller and that the transmission delay is short with respect to maximum speed of the vehicles, i.e. vehicles cannot travel far between position update transmissions.

The vehicle control system processing and application time is the sum of time to detect an event requiring the application of emergency brakes on the vehicle, the time taken by following vehicles to process stop commands, and the time to fully apply the brakes.

For the purposes of this paper it is assumed that following vehicles must be decelerated in a manner to avoid a collision with a lead vehicle. Therefore a ‘safety distance’ behind the lead vehicle rear bumper will be included in the safe separation distance.

There are two general philosophies regarding the separation distance between vehicles:

1. Following vehicles use the last known location of the rear bumper of a lead vehicle minus a safety distance as the stopping point. This design philosophy is commonly referred to as “Brick Wall Stop”. The ASCE APM Standard (ASCE 21) requires “Separation assurance shall provide protection against rear-end collisions for following trains by maintaining a zone at the rear of each train that

continuously provides sufficient stopping distance for the following train assuming that the train ahead can stop instantaneously". Refer to Figure 1.

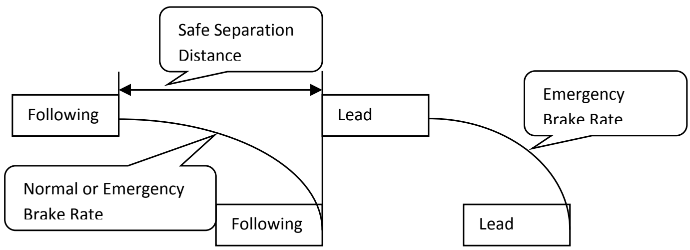

Figure 1 – Last Known Location of Rear Bumper Used as Stopping Point

2. Following vehicles use the calculated or projected location of where the rear bumper of a lead vehicle will be as the stopping point and is referred to as "non-Brick Wall Stop". The calculation of the stopping point is based on the lead vehicle's last known location, speed, an assumed deceleration rate, and a safety distance. Refer to Figure 2.

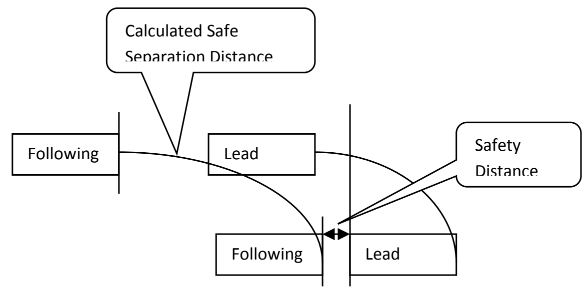

Figure 2 – Calculated Location of Rear Bumper Used as Stopping Point

Additional design criteria that affect the safe separation distance are:

- What deceleration rate should following vehicles use; normal or emergency?
- The design of the alignment including diverges and merges, loop versus pinched loop.

If a lead vehicle initiates emergency brakes and following vehicles should decelerate at a 'normal' rate (the same rate used during a normal station stop) the vehicles will be separated farther apart than if following vehicles should decelerate at an emergency rate.

For systems with off-line stations the separation distances between vehicles is affected by vehicles diverging off the mainline to off-line stations and merging onto the mainline from off-line stations. For pinched loop systems the sustained separation distance is affected by the turnback time at the end or terminal stations. These factors are discussed in more detail in a following section.

A general equation to calculate the theoretical minimum allowable headway between two successive vehicles traveling on the same alignment is:

$$T_H = T_D + \frac{V_i}{2*a_f} + \frac{D_s}{V_i} + \frac{L}{V_i} - \frac{V_i}{2*a_l} \quad \text{Equation 2a}$$

Where:
T_H = Headway
T_D = Communications Time Delay
V_i = Initial Velocity of Vehicles (assumed to be equal for all vehicles)
a_f = Deceleration rate of the following vehicle
a_l = Deceleration rate of the lead vehicle
D_s = Safety Distance Behind Rear Bumper of Lead Vehicle
L = Length of Vehicles (assumed to be equal for all vehicles)

Note that D_s, Safety Distance Behind Rear Bumper of Lead Vehicle, is included to account for failure modes or factors that reduce the brake rate or failures on following vehicles such as overspeed detection and reaction times.

Any uncertainty regarding the transmitted location of the vehicle versus its' actual location is not included in the above equation since it is assumed that this value is low (within centimeters) in comparison to other factors. However if it is desired to include a term for position uncertainty then Equation 2a may revised as follows:

$$T_H = T_D + \frac{V_i}{2*a_f} + \frac{D_s}{V_i} + \frac{L}{V_i} + \frac{PU}{V_i} - \frac{V_i}{2*a_l} \quad \text{Equation 2b}$$

Where:
PU = Position Uncertainty

The derivation of the minimum headway equation is beyond the scope of this paper.

Equation 2 may be simplified by making certain assumptions regarding brake rates and communications time delays. It is extremely important to review and fully understand the implications of any simplifying assumptions. For example, Equation 2a could be simplified if it is assumed that the deceleration rates on lead and following vehicles are equal, i.e. $a_f = a_l$. However, this means that if lead vehicles decelerate at the emergency brake rate following vehicles must also decelerate at the emergency brake rate. If it is also assumed that $D_s = 0$, then for control systems designed using this assumption, if lead vehicles decelerate at a rate higher than assumed, i.e. $a_f < a_l$, vehicles may collide since the spacing and timing between vehicles is too short to allow for variances in braking effort.

Note that this paper assumes that $D_s > 0$ since, as described above, variances in brake rates between vehicles can lead to vehicle to vehicle collisions during an emergency braking event if $D_s = 0$ or if D_s is not long enough to account for any variance in the brake rates.

For vehicle control systems designed to use the last known position of the rear end of the lead vehicle, i.e. "Brick Wall Stop", Equation 2a is simplified as follows:

$$T_H = T_D + \frac{V_i}{2*a_f} + \frac{D_s}{V_i} + \frac{L}{V_i} \qquad \text{Equation 3}$$

For alignments with off-line stations the normal speed for mainline vehicles may need to be reduced or headways increased in the areas of diverges and merges. To use the above equations in diverge and merge areas, they need to be changed in accordance with the design criteria for diverge and merge areas. This is discussed in more detail in a following section.

Track Alignments Studied
This paper will discuss systems with off-line stations and pinched loop systems with in-line stations.

Systems with Off-Line Stations
The minimum headway equation, Equation 2a, is not applicable to vehicle headways through diverge and merge areas since a vehicle's stopping point can be any of the following cases:

1. For systems with track mounted switches, a switch not aligned in the desired direction of travel (fixed stopping point)
2. The diverge/merge area occupied by a lead vehicle (fixed stopping point)
3. Any vehicle beyond the diverge/merge area in the desired direction of travel (fixed or moving stopping point depending on actual conditions)

Case 1 above is only applicable to systems with vehicle technology that utilizes track mounted switching. In this case the minimum sustainable headway becomes more complicated since following vehicles must be stopped or slowed down to allow for a switch re-alignment or spaced far enough behind a lead vehicle to allow for the switch re-alignment without impacting (or minimal impact to) the vehicle's speed. Therefore, for systems with track mounted switches it is not practical in areas surrounding diverges and merges to use headways based on the calculated location of a lead vehicle since a switch re-alignment may be required between a lead vehicle and a following vehicle. This re-alignment requires that following vehicles use the switch area entrance as the fixed stopping point rather than the calculated stopping point of the lead vehicle.

Case 2 above covers the condition where a part of another vehicle is protruding into the diverge or merge area and therefore it is not safe for a following vehicle to enter.

Case 3 above covers the condition where a vehicle is allowed to enter a diverge or merge area, so therefore its' stopping point becomes the rear of any vehicle beyond the diverge or merge area in the desired direction of travel.

Diverge and merge areas may increase the minimum sustainable headway throughout the system since vehicles exiting or entering the mainline will need to go through a curved section of track and therefore may need to slow down in order to maintain ride comfort criteria. The difference between mainline speed and the reduced speed in curves in diverges and merges depends on the curve radius and maximum allowable acceleration and jerk rates experienced by passengers.

In addition, depending on the distance between the station stopping locations and diverges, vehicles may need to slow down prior to entering a diverge area in order to not exceed the normal deceleration rate regarding station stops. Similarly, depending on the distance between the station stopping location and merge area, vehicles entering the merge from the off-line station may be running much slower than mainline vehicles, and therefore vehicles on the mainline will need to be either slowed down or held back in order to allow for merging vehicles to enter the mainline and accelerate to normal mainline speed.

Depending on the alignment the general equation to calculate the theoretical headway between two successive vehicles in diverge and merge areas is one of the following:

1. For systems using track mounted switching approaching a diverge (Cases 1, 2, and 3) the theoretical headway is (regardless of the type of control system):

   $$T_H = T_S + \frac{V_S}{2*a_f} + \frac{D_S}{V_S} + \frac{L}{V_S} + \frac{L_S}{V_S} \qquad \text{Equation 4}$$

   Where:
   L_S = Length of Switch
   T_S = Switch movement time: The time to move the switch includes the time to unlock, detect unlocked, physically move the switch mechanism, detect the commanded position, lock, and detect locked. (T_S = 0 for vehicle mounted switching)
   V_S = Maximum allowable velocity through the switch area; a) For vehicles on the mainline and travelling through the switch in the normal (tangent) direction, V_S = mainline velocity, b) For vehicles travelling through the switch area in the reverse (turnout) direction, V_S = maximum allowable velocity through the switch curve, typically less than mainline velocity.

2. For systems that do not use track mounted switches (vehicles with onboard switching) and the last known location of lead vehicles (Cases 2, and 3), vehicles approaching a diverge with a vehicle ahead of it in the desired direction of travel the theoretical headway is:

   $$T_H = T_D + \frac{V_S}{2*a_f} + \frac{D_S}{V_S} + \frac{L}{V_S} \qquad \text{Equation 5a}$$

3. For systems that do not use track mounted switches (vehicles with onboard switching) and the calculated location of lead vehicles (Cases 2, and 3), vehicles approaching a diverge with a vehicle ahead of it in the desired direction of travel the theoretical headway is:

   $$T_H = T_D + \frac{V_S}{2*a_f} + \frac{D_S}{V_S} + \frac{L}{V_S} - \frac{V_S}{2*a_l} \qquad \text{Equation 5b}$$

Pinched Loop with On-Line Stations
The minimum headway equation, Equation 2a, is not applicable to sustained vehicle headways for systems with on-line stations since vehicles need to decelerate to a stop, dwell within the station berth long enough for passengers to transfer, and then accelerate to leave the station. This stop and go action results in a significant increase in minimum sustainable headways, especially if vehicles are spaced far enough apart such that the stopping point for following vehicles is the station berthing position.

For pinched loop systems with on-line stations the minimum sustainable headway through the station areas can be calculated as follows:

$$T_H = T_{DT} + \frac{V_M}{2*a_f} + \frac{D_S}{V_M} + \sqrt{\frac{2*(L_V+D_S)}{a_f}} \qquad \text{Equation 6}$$

Where:
V_M = Maximum allowable velocity on the mainline
T_{DT} = Time the vehicle is stopped in the station (dwell time)

Note that Equation 6 can be used to calculate the minimum sustainable headway for a Loop System with in-line stations.

In addition, the minimum sustainable headway between successive vehicles for Pinched Loop Systems is limited by the time it takes for vehicles to approach, enter, stop, and exit the turnback station. This headway through the turnback station can be estimated as follows:

$$T_H = T_S + \frac{V_S}{2*a_f} + \frac{D_S}{V_S} + \frac{L_S}{V_S} + \frac{V_S}{2*a_f} + T_{DT} + \frac{V_S}{2*a_f} + \frac{L_E}{V_S} \qquad \text{Equation 7}$$

Where:
V_S = Maximum allowable velocity through switch area
L_S = Total Length of switch area
L_E = Total distance the vehicle must travel in order to clear the switch area

The maximum allowable velocity is primarily determined by the maximum allowable lateral acceleration passengers can experience and curve radius in the switch area.

The total length of the switch area is determined by the physical envelope of the vehicles such that if a portion of a vehicle extending into the switch area could impact other vehicles the entire switch area is considered occupied. The total switch area is also known as the “interlocking” area.

The total distance a vehicle must travel in order to clear the switch is determined by vehicle length such that the rear of the vehicle must be clear of the switch area before the switch is considered as unoccupied.

It is important to note that for Pinched Loop Systems the minimum sustainable headway time will generally be determined by Equation 7.

Factors Affecting System Capacity

This section discusses the actual or effective capacity of the ATN System determined by the number of passengers per hour entering one station and exiting another. The actual throughput capacity of the total System is affected by many factors either directly or indirectly, and therefore is not determined solely by the minimum achievable headway or time between vehicles.

Systems with Off-Line Stations

Systems with off-line stations have a total effective capacity limitation governed by how many vehicles can enter an off-line station area. Once this limit is reached, additional vehicles with routes to enter the station area must either stop and wait for a berthing position to become available, which will also stop traffic on the mainline behind them, or bypass the desired station and go around the loop until a berth will become available prior to the next approach. Since vehicles stopping prior to the station diverge will block mainline traffic, system designers have proposed that vehicles unable to completely exit the mainline should bypass the station, go around the loop, and try again. A term used to describe this bypass action is 'wave-off'.

Therefore, for any given station design, once the berthing capacity has been reached there may be wave-offs of any other vehicles, and these wave-off vehicles will take up space on the mainline, reducing the capability for other vehicles to enter the mainline track.

When vehicles exit the mainline into the off-line station area they create gaps and if these gaps are not taken by vehicles entering the mainline from the station, these gaps lower the effective VPH. For vehicles entering the mainline from a station, if a sufficiently long gap between mainline vehicles is not available the control system will slow down or stop mainline vehicles in order to allow merging vehicles to enter the mainline. Both of these actions act to reduce the maximum theoretical VPH.

If the maximum speed through the diverge and merge switch areas is less than the mainline speed, the maximum theoretical VPH is reduced to allow exiting vehicles to slow down to the diverge area speed and to allow space for entering vehicles and time for the entering vehicles to accelerate.

The effective VPH considering these factors could be estimated as follows:

$$VPH_E = PT_{VM} * VPH_{VM} + PT_{VSD} * VPH_{VSD} + PT_{VSM} * VPH_{VSM} \quad \text{Equation 8}$$

Where:

VPH_E = Effective Vehicles per Hour

PT_{VM} = Percent of time vehicles operate at maximum or mainline speed

VPH_{VM} = Vehicles per Hour with vehicles operating at maximum or mainline speed

PT_{VSD} = Percent of time vehicles operate at diverge switch speed

VPH_{VSD} = Vehicles per Hour with vehicles operating at diverge switch speed

PT_{VSM} = Percent of time that vehicles operate at merge switch speed

VPH_{VSM} = Vehicles per Hour with vehicles operating at merge switch speed

Empty Vehicle Movements

Some systems are operated as or designed for demand response, meaning that vehicles do not depart a station unless requested by a passenger. Vehicles approaching a station designated by the passengers need an empty berthing position. To create an empty berth for an incoming vehicle, an empty vehicle at the designated station may be commanded to depart. Alternatively, empty vehicles may need to be sent to stations with passenger trip requests. In either event empty vehicles must enter the mainline track and these empty vehicles reduce the space available for vehicles carrying passengers, which reduces the actual passenger carrying capacity of the System.

Summary

This paper has presented an overview of some of the factors affecting the actual passenger carrying capacity or Vehicles per Hour, of an ATN System. These factors included minimum allowable spacing between vehicles for safety reasons and switch areas. Each of these factors interact with the overall System to reduce the capacity of the System, and must be considered when calculating or estimating the effective minimum sustainable headway, which in turn is used to calculate passengers per hour.

For transportation systems with point to point service, the final effective passengers per hour capacity should be reduced to account for empty vehicles required to be on the track as well as the possibility of vehicles circulating around the system with passengers that were unable to enter their selected destination station due to unavailable berthing positions.

This paper presented some of the theory to use when performing an analysis of the minimum sustainable headway, and given the many different possible variations of alignments it is not possible to use any one set of equations for all Systems.

Finally, it should be noted that operating transportation systems at the minimum headway is not advisable since any disruption in vehicle movements quickly affects following vehicles and leaves very little time for the Central Control Operators to react.

Simplifying the Measure of Service Availability

Charles P. Elms[1]

[1]Consultant, 104 Beaver Glen Ct., Morrisville, NC 27560; PH 919-469-2390; email; cpelms@peoplepc.com

ABSTRACT

The following paper provides a simplified measure of the service availability of an APM system, which produces the same results as the more complex measure presently being used by the industry. Service availability can be simply, directly and accurately measured according to only the two parts of the APM system that passengers encounter for service – the trains and the stations. Indirectly, the simplified measure takes into account the reliability of the APM subsystems and components – i.e, trains, train control, traction power, auxiliary power, station equipment, guideways and guideway equipment, etc. Only two types of events are necessary to be counted – downtime of the cars of a train and downtime of station platform doors (or the platforms where there are no platform doors).

While the methodology that follows was developed for APM systems it is applicable to all modes of public transport.

1. SERVICE AVAILABILITY DEFINITION

Service Availability (A) is generally defined as follows:

$$A = MTBF / (MTBF + MTTR) \tag{1}$$

where,

MTBF is a mathematical expression for the mean time between failures of the APM system to provide passenger service and

MTTR is a mathematical expression for the mean time for the APM system to restore passenger service.

The measure of Service Availability is calculated over a specific time period. The calculation is generally equivalent to the actual operating time (scheduled operating time minus the accumulated downtime) divided by the scheduled operating time. Typically one counts the downtime of the system, or major subsystems that provide passenger service, when service is not available.

Service Interruptions are those events or failures that prevent passenger use of the system or system subsets as intended. Service interruptions are defined and weighed in accordance with their relative importance. At a minimum the following types of service interruptions are to be included.

(1) Unscheduled stoppage of one or more trains;

(2) Unavailaility of trains, vehicles or cars within a vehicle or train;

(2) Rerouting of trains due to equipment malfunction so that any stations normally served are not served;

(3) Station Platform, or Door, malfunctions that prevent passengers from entering or exiting trains at stations in automatic operation; and

(4) Malfunctions that result in potentially hazardous operations

Exceptions are generally provided where the service interruption is not due to the fault of the APM system as follows:

(1) Malfunctions that result in an interruption of normal passenger service for a specified interval of time (Grace Period).

(2) Malfunctions or disruptions due to vandalism, passenger misuse of the system, or passenger-induced delays.

(3) Disruptions caused by unauthorized intrusion of persons, animals or inanimate objects into the system.

(4) Disruptions due to external causes, including loss of primary power, police or security directives, force majeure, or environmental conditions beyond specified limits.

(5) Disruptions for special training, guideway inspections or extended repair purposes that have been arranged in advance.

2. MEASURE OF SERVICE AVAILABILITY USED IN THE INDUSTRY

The most prevalent measure of Service Availability used in the industry is that which has been specified by Lea+Elliott in its performance specifications for APM projects, summarized as follows:

$$A(i) = A_m(i)\, A_f(i)\, A_s(i) \qquad (2)$$

where:

A(i) is the system Service Availability for the Period i,

$A_m(i)$ is the Service Mode Availability for the Period i,

$A_f(i)$ is the Fleet Availability for the Period i, and

$A_s(i)$ is the Station Platform (or platform door) Availability for the Period i.

Service Mode Availability for a period of operation is defined by:

$$A_m(i) = (MTSi - MTDi) / MTSi \quad (3)$$

where:

MTSi is the total schedule time for a mode during Period i and

MTDi is the total time that the scheduled mode is totally down, i.e., no trains are in service. While this was the original intent of the Lea+Elliott specification there is some confusion of the definition of a Service Mode Downtime event. The confusion in the Lea+Elliott specification lies with the wording for a Service Mode Downtime event that implies a downtime event begins when one train has failed, yet other trains may still be in proper service and ends when all trains have resumed normal operations. This confusion results in an undue penalty while a single train is failing; which was not intended when the procedure was first developed and can also result in double counting of train (car) failures.

Fleet Availability is defined by:

$$A_f(i) = (FTSi - FTDi) / FTSi \quad (4)$$

where;

FTSi is the total car time scheduled for the total operating fleet of trains during Period i, where the car is the smallest passenger carrying unit, and

FTDi is the total downtime of cars of the scheduled operating fleet during Period i, where cars are not available for passenger service due to failures an/or cars are taken out of service.

Station Platform (or platform doors) Availability is defined by:

$$A_s(i) = (STSi - STDi) / STSi \quad (5)$$

where;

STSi is the total time scheduled for passenger station platforms (or platform doors) Period i, and

STDi is the total downtime of passenger station platforms (or platform doors) where such are not available for use by passengers during Period i because of failure and/or have been taken out of service.

Compensation for Degraded Service is provided by defining specific degraded service modes that can be operated in the event that a scheduled service mode is totally down and service cannot be resumed in the scheduled service mode within a reasonable period of time. For such events a K-factor is defined for each degraded service mode that is factored against the calculated service availability for the degraded service mode. K-factors are ratios of the quantity and quality of delivered passenger service of a degraded service mode to that of the scheduled service mode, which is always less than 1. The K-factor for the scheduled service mode is 1.

System Service Availability is generally measured over a defined period (i.e., day, week, month, year) as defined by:

$$A = \Sigma_i K_i T_i A(i) / \Sigma_i T_i \quad (6)$$

where:

A is the system service availability,

K_i is the K-factor for the specific service mode operated during Period i,

T_i is the time of Period i that a specific service mode is operated, and

A(i) is the service availability of the specific service mode during Period i.

3. OTHER MEASURES OF SERVICE AVAILABILTY

Other measures of service availability have been employed in the industry. Three measures [1] have been defined as follows:

Tier A Approach – Headway Based

$$A – (SOT – D) / SOT \quad (7)$$

where;

SOT is the scheduled operating time and

D is the downtime. Down time is measured as the delay in on-time operating headway caused by an event where the operating headway exceeds the scheduled headway by a specified threshold. The downtime event begins when the headway threshold is exceeded and ends when the scheduled operating headway is restored.

This measure is totally service performance based and does not account for partial failures of parts of trains, station platforms, or station platform doors. As such it does not indicate the reliability of the system equipment. It also is not an accurate performance measure for service availability. For example, the failure of a part of a train, such as an inaccessible car, is not reflected. Trains can continue operating at the scheduled headway while one or more trains could have inaccessible cars, yet the measured service availability is unaffected.

Tier B Approach – Train and Station Based

$$A = MTBF / (MTBF + MTTR) \tag{8}$$

where:

MTBF is the meantime between failures of the scheduled operation of trains or stations.

MTTR is the mean time to restore scheduled operation after a failure event.

SOT is the scheduled operating time during the operating period.

NF is the number of failures during an operating period. Train failures are unscheduled stoppages of a train or a train makes an incomplete trip on a scheduled route. The failure of a train door or a station platform door that blocks passenger use during a station dwell is also a failure event.

TTR is the time to restore normal operation of a train, a train door or a station platform door after a failure event. For an unscheduled stop of a train the TTR begins when the train reaches zero speed and ends when the train restarts. For an incomplete trip the TTR begins when the train ceases its trip on the route and ends at the time when it was scheduled to complete the trip on the route. In the case where the train fails to stop a station the TTR begins when the station is bypassed and ends at the start of the dwell at the next station stop. The TTR for a blocked train or station platform door begins at the moment during a dwell that blockage occurs and ends when the train departs the station. When multiple failures occur simultaneously during the same incident, or due to the same malfunction, the total TTR begins at the earliest start time and ends at the latest end time of the simultaneous failures.

This approach accounts for the reliability of the two main subsystems with which passengers interface for service – trains and stations. However, the failure of a train door and station door are given undue importance equal to that of a train failure in the measure of TTR. No provision is made for the number of doors of the trains or the number of station platforms encountered on a route, resulting in giving undue weight to such failures in the summation of all TTRs during the period. This inadequacy might be rectified by the inclusion of “door factors” that would be factored against the specific door TTRs as follows:

Train Door Failures

$$TTR = (1/TD)\ TTR_{train\ door}\text{, where TD = number of doors of a train} \quad (9)$$

Station Platform Door Failures

$$TTR = (1/PD)\ TTR_{platform\ door}\text{, where PD = number of platform doors on the route} \quad (10)$$

Tier C Approach – Service Mode, Fleet and Station Based

This approach is generally the same as in the case of Section 1 above, the most prevalent Measure of Service Availability Used in the Industry, except for the definition of a service mode downtime event. The Tier C Approach defines a service mode downtime event as train failures for unscheduled stoppages of trains, or incomplete train trips on a route as defined for Tier B. Such definition does not account for the fact that other trains may still be operating properly in scheduled service, resulting in a disproportionate penalty for a single train failure. This inadequacy might be rectified by the inclusion of a “fleet factor” that would factor against the failing train’s downtime as follows:

MTD_i is the total scheduled down time during Period i, defined as follows:

$$MTD_i = (1/nt) \Sigma_j\ TDT_j \quad (11)$$

where:

nt is the number of trains scheduled to be operated on a route during Period i and

TDT_j is the downtime of each failing train j of the fleet for Period i.

4. A SIMPLE BUT COMPREHENSIVE MEASURE OF BOTH THE AVAILABILITY OF SERVICE AND SYSTEM EQUIPMENT RELIABILITY

One measure that reflects both the availability of passenger service and system equipment reliability is most desirable. The availability measures of Section 2 and the Tier B and C approaches of Section 3 discussed above all account for the reliability of the two main subsystems with which passengers interface for service – trains and stations. It is believed that the desirable aspects of these three measures can be included a simplified measure that looks only at the availability of trains and stations, resulting in a measure of passenger service availability and system equipment reliability. The problem of giving undue weight to stations platform doors in the Tier B approach can rectified by the definition of station platform availability of Section 2 and the Tier C approach. The problem of failures of parts of trains can be rectified by defining cars for the fleet availability of Tiers B and C as is done in Section 2.

It is believed that the Service Mode Availability term used Section 2 and the Tier C approach is unnecessary, can be eliminated and this downtime can be easily and better accounted for by the definition of fleet availability. For example, the downtime for an unscheduled stop of a train, or an incomplete trip on a route, should be counted on a car basis rather than a train basis (i.e., factoring in the number of cars in the failing train). If the failure affects other following trains on the route the downtimes of all the affected cars of these trains would be accounted for as they begin their individual unscheduled stops and resumptions. Where all trains on a route stop at the same time due to a system wide failure the total downtime would be reflected in the summation of the downtimes for the individual trains on the route.

The following is a simple but comprehensive measure of both the availability of service and system equipment reliability that achieves these goals.

Passenger service and system equipment availability is defined as follows:

$$A(i) = A_f(i)\, A_s(i) \qquad (12)$$

where:

$A(i)$ is the system Service Availability for the Period i,

$A_f(i)$ is the Fleet Availability for the Period i, and

$A_s(i)$ is the Station Platform (or platform door) Availability for the Period i.

$$A_f(i) = (FTSi - FTDi) / FTSi \qquad (13)$$

where:

FTSi is the total car time scheduled for the total operating fleet of trains during Period i, where the car is the smallest passenger carrying unit,

FTDi is the total downtime of cars of the scheduled operating fleet during Period i, where cars are not available for passenger service due to failures an/or cars are taken out of service, and

$FTD_i = \sum_j CD_j$, where CD_j is the total downtime of cars of train j in Period i. (14)

$A_s(i) = (STSi - STDi) / STSi$; (15)

where:

STSi is the total time scheduled for passenger station platforms (or platform doors) during Period i and

STDi is the total downtime of passenger station platforms (or platform doors) where such are not available for use by passengers during Period i because of failure and/or have been taken out of service.

Compensation for degraded service modes that are used when the scheduled service mode is down can be accommodated by defining K-factors for each degraded service mode as discussed in Section 2 above. System Service Availability for defined periods of time (i.e., day, week, month, year) would then be calculated by equation (6).

5. CONCLUSION

The measure of service availability defined in Section 4 above is the simplest and most comprehensive measure that reflects fairly both the availability of passenger service and system equipment reliability. This measure is a refinement of that of Section 2 which has been proven effective by numerous applications over the past 25 years. This measure can allow credit for partial service during mode failures by the inclusion of degraded mode K-factors as defined in Section 2. The algorithms for this performance measure can be simplified by eliminating the service mode availability term, as failures of a service mode can be accounted for in the calculation of fleet availability, un-complicating the collection of data and application software.

REFERENCES

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ALTERNATIVE PROJECT DELIVERY STRATEGIES

Sanjeev N. Shah [(1)], P.E., J.D., M.ASCE (Primary Contact)
Larry Coleman [(2)]

(1) Principal, Lea+Elliott, Inc., 5200 Blue Lagoon Drive, Suite 250, Miami, FL 33126; PH 305 500 9390; Fax 305 500 9391; snshah@leaelliott.com
(2) Senior Associate, Lea+Elliott, Inc., 5200 Blue Lagoon Drive, Suite 250, Miami, FL 33126; PH 305 500 9390; Fax 305 500 9391; lcoleman@leaelliott.com

Abstract

Project delivery approaches span from the traditional design-bid-build (open architecture), design-build, design-build-operate-maintain and design-build-finance-operate-maintain. The project scope may include some or all components of the project i.e. infrastructure and the operating system.

A project delivery approach is not one-size fits all; instead it is a business decision based on multiple factors that include 1) scope of work; 2) risks in terms of schedule and costs; 3) legal requirements and finally, the owner's approach to financing the project i.e. pay as you go, or some form of public-private-partnership.

This paper examines key factors in a typical owner's decision making process when applied to structuring the procurement. Also examined are the implications for the bidders/tenderers and potential approaches that can alleviate risks to provide a cost effective and competitive project procurement.

Background

Transportation projects are often implemented by public agencies, they span multiple jurisdictions and unlike commercial projects, the benefits are spread out amongst the various stakeholders, who may not necessarily be involved in the funding of the project. The genesis of a transportation project is the given local/regional need to improve transportation such that it makes or keeps the region economically competitive; it is not simply a return on investment cash-flow type consideration on whether to make a particular investment. A particular region is economically attractive to businesses due to presence of a skilled workforce, lower costs, and an effective transportation system. Effective transportation systems are expensive to implement, span multiple jurisdictions and require a focused project delivery strategy for success; with limited funding capacities, the system must be implemented in segments such that they deliver the maximum benefit for the given investment while retaining the ability and opportunity, ideally, to utilize the derived benefits for the next incremental expansion/improvement. The various factors and criteria that influence the GO/NO GO decision on a transportation project are complex and driven by local, regional and business sensitivities; examining these is beyond the scope of this paper.

Assuming that a particular transportation project has gone through the initial techno-economic viability evaluation and found to be desirable, the project delivery strategy is one of the most important decisions that an Owner can make. This decision alone can make the project successful by helping assure a timely and on-budget completion. While the general strategies described herein can be applied to general transportation project the focus herein is on strategies for procuring Automated People Mover Systems.

1.0 PROJECT DELIVERY CONSIDERATIONS

APM systems are comprised of two major parts: the Operating System and the Fixed Facilities. The Operating System is made up of major subsystems (e.g., vehicles, tracks, switches, control systems, station equipment, etc.). These subsystems are generally developed as proprietary designs from individual suppliers. An Owner could issue a detailed design specification through a Design-Bid-Build approach to procure component parts (subsystems) for a complete system and accept the responsibility for their successful integration; this open architecture approach is typically applied in metro/transit systems where the Owner has sufficient in-house abilities to manage and mitigate the risk and where the subsystems from different suppliers are often times designed to be interchangeable.

However, where the Owner is not a transit agency, does not have the in-house expertise, and the Owner's primary purpose is other than the operations of the transit system, the Owner is not in a position or willing to accept the integration risks and the inherent cost and schedule implications. Such Owners are most likely to procure APM Systems to enhance their facilities/operations, such as an airport. Considering that APM systems are proprietary designs, such Owners typically procure the APM Systems as complete packages under a turnkey design, supply and installation contract via a Design-Build arrangement. This approach allows the Owner to issue a Request for Proposals (RFP) with a performance based specification that places the burden and risk on the supplier to design and integrate individual elements into a single system. The Design Build delivery approach also encourages suppliers to develop new, innovative and proven product designs that can be configured to satisfy site-specific requirements defined by the Owner. Further, to obtain best value in terms of life-cycle costs, the Owner often includes the Operations and Maintenance requirements into the Contractor's scope and requires fixed pricing for a set number of years; this incentivizes the Contractor to consider the overall life cycle of the delivered system in their capital design because it now must mitigate risks in the operations and maintenance services.

The Fixed Facilities include the guideway structure, stations, wayside equipment rooms, maintenance building and other facilities that "support" the operation of the Operating System. A sufficiently large pool of firms to provide the Fixed Facility design and construction services can be anticipated to be available and, as such, a traditional design-bid-build approach for the Fixed Facilities can be reasonably expected to provide for a competitive bid environment.

By contrast, due to the proprietary nature of the APM technologies, there are a limited number of potential suppliers/vendors who may be qualified and who may participate in the procurement process. Suppliers who own such technologies tend to be multinational corporations based in North America, Europe and Asia. Also, some suppliers own multiple different technologies that could potentially be proposed on a project.

While multiple APM technologies within the large Automated Guideway Transit (AGT) class can adequately meet most project requirements, it is critical to establish a competitive environment in the procurement of the APM systems to meet budget and funding constraints. Our experience in recent procurements indicates that competition in the procurement process generally leads to proposals within the established project budget. However, it must be noted that the actual proposal prices are also dependent on the contract terms and conditions and other market conditions, such as the number of other APM system procurements that may be underway and currency and market fluctuations.

A Project Owner's interest in different technologies and to an open and fair procurement environment, as perceived by the industry, is an important factor in generating interest and competition for the procurement. Meetings with and site visits to potential APM suppliers' facilities have generated substantial competitive interest on past APM procurements, and these must be integrated into an established procurement methodology to ensure that the procurement process is perceived as being fair and open by the industry.

2.0 GOALS OF PROCUREMENT METHODOLOGY

The procurement methodology (including permissible teaming arrangements) and evaluation methodology must facilitate the following critical goals that can directly impact the quality, cost and delivery schedule of the project:

- Permit maximum number of possible applicable technologies (including from the same supplier) to be proposed. This will allow the Owner the opportunity to consider the benefits of a full range of available technologies that may result in a more optimized project, possibly providing schedule and budget benefits.

- Foster interest and competition within the limited pool of potential suppliers/vendors, thus likely resulting in more competitive pricing.

- Balance the requirements of any applicable public records laws, with the ability to maintain confidentiality on certain aspects of the proposals through the evaluation process until selection is completed. The APM project scope is unique and different from traditional design-build projects and will require detailed technical and management proposals. If aspects of a proposer's proposal are known to their competitors, then an Owner's ability to seek clarification of the contents of the proposals and identify potential savings and technical enhancements would be compromised as would the competitive nature of the procurement itself.

- Minimize risk of protest.

- Structure the procurement in a manner to maximize flexibility to the Owner to reduce project costs. For example, there will likely be cost benefits to Owner if proposals with varied technologies are received for consideration.

It is very important that the procurement methodology for a new APM System be carefully thought out, rigorously followed, and fairly applied to minimize the risk of legal complications that could delay the project resulting in substantial schedule and budget overruns. Past experience indicates that legal complications/protests typically occur when the proposal submittal requirements and/or the procurement process deviate from the procurement norms of the Owner and/or the process has not been clearly identified. To minimize this risk the following issues must be identified, evaluated and adhered to:

- Strictly conform to the applicable laws, regulations and guidelines. Where deviations from the Owner's procurement norms are necessary due to the specialized nature of the APM procurement, these must be identified and evaluated and appropriate action should be taken by the applicable governing body authorizing the deviation.

- Treat suppliers both professionally and fairly. The procurement process must be clearly identified together with a strict communication protocol between the potential supplier and the Owner. This is necessary to maintain the "integrity of the procurement." In this matter, it is crucial that not only the process be fair and impartial, but it also be perceived as being fair and impartial by the industry.

- The procurement documents must clearly identify the following:
    - Scope of Work.
    - Submittal Requirements.
    - Responsiveness and Responsibility Criteria.
    - General Evaluation Process including selection criteria.
    - Process to allow for a fair hearing and resolution of any protests and any conditions associated with using the process.

Due to the proprietary nature of APM Operating System technologies, there can be a wide variation in the specific approach of each supplier to the project specific requirements. To provide for a fair competitive environment, the technical requirements for the project should be established as performance based requirements together with site-specific constraints that must be adhered to. This permits each supplier to evaluate their specific proprietary technology for the project and identify the adaptations that must be made to meet the project specific performance based requirements. This will maximize the competitive environment while assuring that the best technology can be proposed and selected for the project to meet its needs in an optimal manner.

3.0 SCOPE OF OPERATING SYSTEM PROCUREMENT

The implementation of APM Systems typically occurs in two distinct phases:

Phase 1:

Phase 1 of the Contract will involve the design, analysis, construction, manufacture, supply, fabrication, assembly, factory testing, shipping, installation, integration, testing and demonstration of the following Operating System elements and any other elements that are required for the operation of the system:

- Automatic Train Control (ATC)
- Vehicles
- Communication Systems
- Supervisory Control and Data Acquisition (SCADA) System
- Traction Power Distribution System
- Guideway equipment

APM Operating System technologies are proprietary in nature. Typically, the design process includes the adaptation of "off the shelf" proprietary designs to site specific constraints. The system equipment is manufactured off-site and installed at the site by the contractor.

The design and construction of all fixed facilities required for the APM System can be designed and by the same team as the Operating system or procured separately. For this illustration, the fixed facilities are separately procured.

Phase 2:

Phase 2 of the Operating System Contract will include the Operations and Maintenance (O&M) of the APM System (Operating System) by the same Phase I Contractor. The O&M requirements include operations to meet the passenger demands at desired levels of reliability. Also, maintenance of the system (vehicle maintenance, guidance equipment maintenance, etc.) is performed.

Typically, the O&M aspect of the contract can begin with a five year (or shorter) term with an Owner option to extend services in multiple year increments up to maximum number years. Recent experience indicates that Industry is willing to provide pricing for upto 15 years of O&M services. It is "service oriented" type of work wherein, usually, the Operating System supplier would provide the scope of services. This provides the supplier with the incentive to consider life-cycle costing in their Phase I designs. Options to terminate some or all of the Phase II services can be established by the Owner giving the ability/flexibility to either re-bid at some point or to take over the O&M services if it so desires. By establishing two separate phases, the Contractor team can be released from the Performance and Payment Bonds that are related to Phase 1 of the contract. This minimizes potential risks, reduces the duration of the Performance and Payment Bonds and likely increases the field of firms who will be interested in participating on the project; thus increasing competition and likely reducing bid prices.

To facilitate this two phased approach APM Operating Systems it is recommended that systems be procured under a Design-Build-Operate and Maintain or DBOM arrangement whereby the APM system contractor will initiate the O+M phase upon the successful completion of the Phase I supply and installation of the respective APM system.

4.0 AVAILABLE PROCUREMENT PROCESSES

Having established that DBOM is the preferred project delivery method, there are different procurement processes that have been used successfully for public DBOM procurements for APM Operating Systems. Although they are referred to by numerous other terms, they can be all reduced to the following four basic methods:

1. Non-Competitive – Sole Source Option

2. Competitive One-Step Option, including the one-step low price and one-step best value

3. Competitive Two-Step Option, including the two-step low price and two-step best value

4. Competitive Negotiated Procurement, also referred to as the Best and Final Offer (BAFO).

Each method is briefly described below:

4.1 Non-Competitive Sole Source Option

In this option, the Owner has determined that only one supplier is capable and/or preferred for the public procurement. Many state and local statutes/ordinances permit agencies to make this determination if they can demonstrate that this is in the best interests of the project (due to existing conditions, budget, schedule, etc.) and that a competitive procurement process would not yield any benefits. In such a case, the

Owner enters into negotiations with the single supplier for scope of work and price(s) leading to a negotiated contract that is awarded.

In most cases, however, most public entities are required to pursue and/or seek the benefits realized through a competitive bid process. As such, this Option is generally not suitable for most public procurements.

4.2 Competitive One-Step Option

The competitive one-step procurement approach is the most commonly used approach in public procurements. It is characterized by a single action (one-step) advertisement/solicitation by the Owner for the procurement of the specified product(s) and/or services. The vendor(s) submit their technical and bid proposals in response the solicitation at one time; the Owner evaluates the responses and makes a determination on responsibility and responsiveness of the proposal(s) and then makes final determination for bid award. There are two basic variations to this procurement approach – the One-Step Low Bid approach and the One-Step Best Value approach.

4.2.1 One-Step Low Bid Approach

Typically, if the product and/or services to be procured are very well defined (such as with a solicitation for construction of facilities based on design drawings and specifications prepared by a professional A/E firm on behalf of the Owner) and therefore all proposals are considered equal, then the award determination is based on a low-bid preference among bids/proposals that are found responsive and responsible. This approach is typically referred to as the One-Step Low Bid approach.

Under this method the proposals offered by all responsive bids from responsible bidders are considered to be equal except for price. The evaluation consists of determining if the proposal is responsive to the requirements of the plans and specifications and contract terms and conditions and if the bidder is qualified (responsible) to successfully perform the contract. Therefore, all responsive bids by responsible bidders are considered to be equal, except for price, and the award is made on the basis of lowest bid.

4.2.2 One-Step Best Value Approach

This approach is more suitable for procurement of products/services wherein all proposals (responses to the solicitation) are not or may not be considered equal – in terms of technical merit/quality and price. In this process, the respondents to the solicitation are required to submit a technical proposal and a separate price proposal at the same time. To avoid possible bias due to knowledge of pricing information, the technical proposals are evaluated first for responsibility and responsiveness and then scored based on a pre-determined criteria for technical merit (only if found responsible and responsiveness). Technical proposals are evaluated against a set of minimum technical requirements however; proposers can also propose alternates, in addition to the base proposal, that may generate costs savings. If alternate approaches are considered to be acceptable or feasible with some minor modifications then they are included for further consideration.

The corresponding price proposals are then opened and evaluated for responsibility and responsiveness; the price and technical merit scores are combined in a pre-established manner to identify the best value responsive and responsible proposal. The best value may be based on a pre-determined weighted combination of the price and technical merit score or based on ranking determined by dividing the technical merit score into the price (the lower the number, the higher the value of the proposal).

Variations to the basic process described above include the ability for the Owner to seek clarifications from each of the vendors/respondents on the technical proposal prior to final technical merit scoring. The exact procedure is developed in coordination with the Owner's normal contracting/procurement procedures in conjunction with the applicable laws/regulations governing the procurement to assure that the risk of protest is mitigated.

4.3 Competitive Two-Step Option

The competitive two-step procurement approach is often used when the product and/or services which are being solicited are not or may not be considered equal – in terms of technical merit/quality and price. This approach is characterized by a double action (two-step) advertisement/solicitation by the Owner for the procurement of the specified product(s) and/or services. It is similar to the One-Step Best Value approach except that the pricing proposal is obtained as a second-step and only from those vendors who are found qualified after evaluation of their technical proposals obtained in step-one.

In step-one, the Owner solicits only technical proposals in response to the specified products and/or services to the procured. The vendors submit their technical proposals. These are reviewed for responsibility and responsiveness prior to determination of the vendors' qualifications and or capabilities to provide the products and/or services in a satisfactory manner. Responsive and responsible vendors found capable and qualified through this first step evaluation are then requested to submit a price proposal; this being the second step of the process.

Maintaining the confidentiality of the contents of the technical proposals (and their evaluations for technical merit and/or ranking) is crucial; if competitors are aware of the contents (and/or evaluation) of each other's technical proposals, it is likely to influence their pricing strategy when they are asked to submit their pricing proposals in step-two. There is also a risk that, after evaluation of the technical proposals, the number of vendors found qualified to participate in step-two may be too small and this could have an impact on the degree of competitiveness for the pricing proposals.

Variations to the process include the ability of the Owner to request and obtain clarifications from the vendors on their technical proposal(s) prior to determining their qualification to participate in their second step and/or scoring of the technical proposals for technical merit.

4.3.1 Two-Step Low Bid approach

In this approach, during the first-step the vendor's qualifications and or capabilities to participate in the second step (submitting price proposals) are determined as described in Section 4.3 above. During the second step, the "prequalified" vendors are requested to submit price proposals. These are evaluated for responsiveness and responsibility. The contract award recommendation is based on the lowest responsive and responsible price. The implicit assumption in this approach is that after the first step, when the vendor qualifications are determined, that all technical proposals are equal in technical merit and quality and that the only difference is in price.

4.3.2 Two-Step Best Value Approach

In this approach, during the first-step the vendor's qualifications and or capabilities to participate in the second step (submitting price proposals) are determined as described in Section 4.3 above and then scored for technical merit based on pre-established criteria. Technical proposals are evaluated against a set of minimum technical requirements however; proposers can propose alternates, in addition to the base proposal, that may generate costs savings. If alternate approaches are considered to be acceptable or feasible with some minor modifications then they are included for further consideration.

Again, maintaining the confidentiality of the contents of the technical proposals (and their evaluations for technical merit and/or ranking) is crucial; if competitors are aware of the contents (and/or evaluation) of each other's technical proposals, it is likely to influence their pricing strategy when they are asked to submit their pricing proposals in step-two.

The corresponding price proposals, obtained during the second-step, are then opened and evaluated for responsibility and responsiveness; the price and technical merit scores are combined in a pre-established manner to identify the best value responsive and responsible proposal. The best value may be based on a pre-determined weighted combination of the price and technical merit score or based on ranking determined by dividing the technical merit score into the price (the lower the number, the higher the value of the proposal).

The exact procedure is developed in coordination with the Owner's normal contracting/procurement procedures in conjunction with the applicable laws/regulations governing the procurement to assure that the risk of protest is mitigated.

4.4 Competitive Negotiated Procurement

In the Competitive Negotiated Procurement method an award is made on the basis of price and other evaluation factors that are considered to be in the best interest of the Owner. This approach is a variation of the Best Value approaches except the Owner has the ability to negotiate with multiple vendors at the same time in strict confidence on all matters including technical and price issues.

The term "bid" is not to be used in this method. The Competitive Negotiated Procurement method has been successfully applied for many federal government procurements and other public procurements where it was determined that the goods and/or services that would result could not be determined to be equal, as in the case of the Competitive Bid – Low Price methods.

The acceptability and quality of a proposal may be assessed in terms of a minimum set of requirements and evaluation criteria. For complex systems and products, where the success or failure of a project is highly sensitive to the system or product being procured, the qualifications of the proposer may be considered very important. Therefore, most Competitive Negotiated Procurements score the qualifications of proposers as part of the basis for the award. Finally the price must be considered because it is the determinant of affordability and value of the proposal.

The approach is the same as for the best value approach. However, the Owner opens the Technical and Price proposals at the same time and then determines a negotiation strategy with each proposer. Negotiations, on technical and price matters, are conducted with the multiple suppliers/vendors concurrently.

Maintaining the confidentiality of the contents of the proposals (and their evaluations) is crucial; if competitors are aware of the contents (and/or evaluation) of each other's technical proposals, it is likely to influence their negotiating strategy with the Owner. Often times, even the number of proposals received (and names of vendors) is maintained in confidence to assure maximum leverage to the Owner during any subsequent negotiations.

Upon completion of negotiations, the Owner may amend the Request for Proposals and request Best and Final Offers (BAFO). The BAFO will take the same format as the initial proposals and may be in the form of amendments to the initial proposal documents. BAFOs are evaluated in accordance with the same criteria and procedures as the initial proposals, essentially as updates to the original evaluations. The award is made on the basis of price and other evaluation factors that are considered to be in the best interest of the Owner. At any point in the process, the Owner may decide to award the contract without further consideration (or request for BAFOs) or may decide to re-advertise.

While this approach maximizes an Owner's flexibility during the procurement process it is viable only if applicable laws and statutes permit a public procuring agency to negotiate with multiple vendors/suppliers in confidence on technical and price matters.

5.0 EVALUATION AND CONCLUSIONS

A first screening of the available procurement approaches, described above, can be based on an evaluation of the product/services to be procured. However, further evaluation relative to the applicable legal and contractual processes/requirements will be necessary in order to narrow the choices and then develop the appropriate procurement strategy. The following key factors should be considered by the Owner during this first screening:

1. APM Operating Systems are proprietary designs that must be procured as complete packages. The major subsystems (e.g., vehicles, tracks, switches, control systems, station equipment, etc.) from different suppliers cannot be mixed to form a system. The Operating System of an APM application is specially configured using "off the shelf" equipment designs that are applied to satisfy site-specific requirements.

2. Due to the proprietary nature of the APM technologies, there are a limited number of potential suppliers/vendors who may be qualified and who may participate in the procurement process. Suppliers who own such technologies tend to be multinational corporations - based in North America, Europe and Asia. Some suppliers own multiple different technologies that could potentially be proposed on the project.

3. Early and immediate need to identify the range of potential technologies and their specific interface requirements to a) provide early input to the Fixed Facility programming in support of timely designs and construction to meet the project completion dates; and b) avoid "generic technology" designs that would then have to be updated to the selected technology – thus minimizing schedule and cost impacts if the range of technologies is closely defined.

4. Requirements of applicable public records act (varies) as they relate to handling of proposals received by a public agency and conduct of meetings whether or not the Owner has ability to maintain the confidentiality of any proposals, negotiations, or information.

5. The minimum technical requirements that may be required as part of the procurement.

Based on these criteria, an evaluation of options could proceed as follows.

If public records and open public meeting requirements apply, then the Non-Competitive Sole Source Option and the Competitive Negotiated Procurement Option would not be viable leaving either the Competitive One Step or Two Step Options.

Next, consider if the Request for Proposals (RFP) establishes the desired minimum technical criteria that must be complied with (these may include minimum service-proven criteria, etc.). If a minimum requirement stipulation is made in the solicitation, it is likely (but not guaranteed) that after the technical evaluations (after appropriate negotiations/clarifications from the proposers) one may find that all the proposals are equal on the basis of technical merit. In such a case, the only difference would be price and, by default, the lowest responsive, responsible bid would be the best value and thus the award determinant – thus making it a Two-Step Low Bid approach. However, if multiple technologies are feasible and can be proposed, it is possible that all proposals will be not found equal on the basis of technical merit in which case the One-Step or Two-Step Low Bid approaches would not be appropriate and then the Competitive One or Two Step Best Value Approach would be preferred.

6.0 OTHER PROCUREMENT PROCESS CONSIDERATIONS

While not the subject of this paper there are additional considerations in formulating the procurement process for such a project. These include the contract terms, conditions, and procedures of the Owner, statutory legal requirements regarding such things as the formation of joint ventures and licensing requirements of primes and subcontractors and project funding and finance. In the latter case, depending on the nature of the subject APM system and the facilities it would connect between, there may be opportunities for the Owner to secure financing from the Contractor through a Design Build Finance Operate and Maintain (DBFOM) and/or a Public Private Partnership (P3). Opportunities and structures for DBFOMs and P3s will be explored by the authors in future papers.

BART OAC PROJECT: APPLICATION OF BUY AMERICA TO A CABLE-PROPELLED SYSTEM

Thomas Dunscombe, P.E., Group Manager - Oakland Airport Connector, Transit System Development, BART, LKS-21 300 Lakeside Drive, Suite 2100 Oakland, CA 94612 (510) 287-4822; (510) 287-4860 (fax); tdunsco@bart.gov

Scott Van Dussen, Project Manager - Oakland Airport Connector, Transit System Development, BART, LKS-21 300 Lakeside Drive, Suite 2100 Oakland, CA 94612 (510) 287-4792; (510) 287-4860 (fax); svandus@bart.gov

G. John Kennedy, P.E., Principal, Lea+Elliott, Inc., 101 Montgomery St., Suite 1750, San Francisco, CA 94104, (415) 908-6450; (415) 908-6451 (fax); jkennedy@leaelliott.com

Jackie C. Yang, AICP, Manager of Planning Projects, Lea+Elliott, Inc., 101 Montgomery St., Suite 1750, San Francisco, CA 94104, (415) 908-6450; (415) 908-6451 (fax); jyang@leaelliott.com

ABSTRACT

The Bay Area Rapid Transit District's (BART) Oakland Airport Connector (OAC) project, a 3.2-mile (5 km) APM to link the BART regional rail system to the Oakland International Airport, is now under construction with opening day scheduled for fall 2014.

This project is subject to Buy America provisions due to receipt of funding and oversight from the Federal Transit Administration (FTA). The FTA Buy America provisions include:
1.) Rolling stock, including vehicles, train control, communications, and traction power equipment: The cost of components produced domestically must be more than 60% of the total cost of the components and all final assembly must take place in the U.S.
2.) Manufactured products, including guideway and guideway equipment, stations and station equipment, and maintenance facilities and maintenance equipment: 100% must be produced in the U.S.
Seven separate certificates for each end product were required as part of the proposal.

While Buy America provisions are used for many transit projects throughout the country, this was groundbreaking as one of the first examples for an APM project. In addition, the systems supplier Doppelmayr Cable Car (DCC), part of the Flatiron / Parsons Joint Venture (FPJV) that was eventually awarded the contract, provides a cable-propelled system, adding complexity to the definition of the rolling stock components. This paper discusses the preparations leading up to the FTA required

pre-award review and current status of compliance with the Buy America requirements.

The FTA required pre-award review for vehicles, which was performed in fall 2009. There was ongoing discussion between FTA and BART regarding the definition of vehicles. With DCC cable system technology, the vehicle is actually just the shell, with the propulsion motors located at the maintenance facility. For the audit, BART's position was that the vehicle definition could include the wayside propulsion system and braking equipment. FTA was not in agreement with BART's position, and the audit was revisited. DCC showed 98.2% in their pre-award review, far exceeding the Buy America requirements.

As the project progresses, DCC is providing quarterly updates with actual cost information. The latest update shows compliance with Buy America requirements for all seven end products.

FTA also requires a post delivery review to be performed. This is scheduled for late fall 2014.

Project Overview

The OAC connects the BART Coliseum Station to the Oakland Airport terminals with a potential future station located at the Doolittle Maintenance Facility site. Because of the complexity and cost of extending BART's rapid rail technology from the existing Coliseum Station to the Airport, lower cost Automated Guideway Transit (AGT) technologies were selected as the connection method.

The form of the AGT to be provided was not restricted to self-propelled types. Technologies that could meet the passenger demand, headways, round trip times and other criteria - including histories of successful operations at other sites - were also considered. Thus, cable-propelled systems that could meet the required criteria were allowed to propose as well as self-propelled technologies. After receipt and evaluation of proposals for the OAC, the Flatiron / Parsons Joint Venture (FPJV), along with Doppelmayr Cable Car (DCC) GmbH, was awarded the Design-Build Contract. In addition DCC was awarded the 20 year follow on contract for operations and maintenance (O&M) of the system.

As shown in Figure 1 below, a significant portion of the alignment will operate along an elevated guideway with an at-grade portion along Airport Drive and a subway segment under Doolittle Drive to meet Federal Aviation Administration (FAA) flight path height requirements.

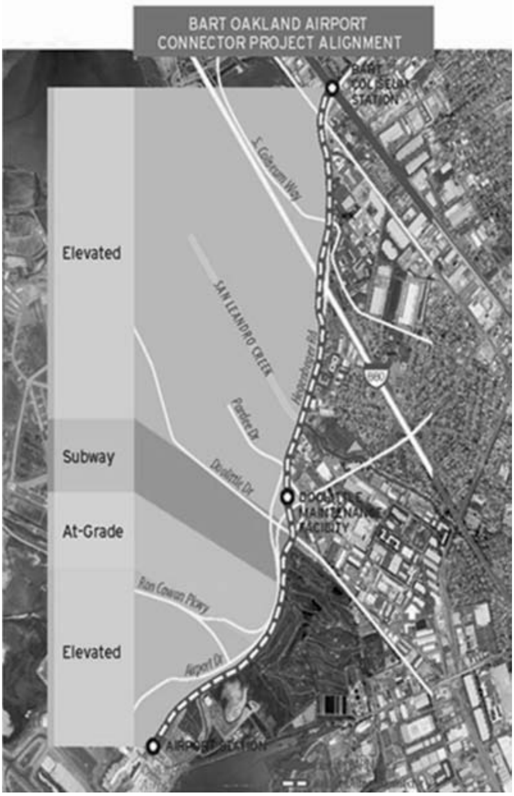


Figure 1. OAC Alignment (Courtesy of BART)

Unique System Design

Due to length limitations in which the DCC system is restricted to operate to one rope (or cable), the DCC system will operate with four different ropes. Four trains will be provided with each of the four trains restricted to operating on a different rope. Using detachable vehicle grips and rope exchange technology, trains change ropes at the Doolittle Maintenance Facility and the end stations.

The guideway will be of an open truss design typical of the DCC systems (Figure 2). This open design provides minimal shadowing along the alignment, particularly along Hegenberger Road. With this lightweight truss system the FPJV capitalized on a lighter foundation to carry the load, which provided cost savings on the fixed facilities costs as compared to other APM concrete guideways. The steel truss will be prefabricated off-site, trucked to the site, and erected on top of cast-in-place concrete columns. At the time of this writing (December 2012), about one hundred twenty truss elements have been erected.

Figure 2. DCC Open Truss Guideway along Hegenberger Road (Courtesy of BART / FPJV)

Four, three-car trains will operate on 4.5 minute headways. In-vehicle travel time will be about 8 minutes, so the average trip time will be just under 11 minutes. The system will provide a capacity of about 1500 passengers per hour per direction (pphpd) to meet the initial 1400 pphpd capacity requirement. The ultimate capacity of 1900 pphpd will be met by adding a car to each train.

FTA Requirements / Discussions

Due to FTA funding, the OAC must meet Buy America requirements. Systems that are identified as “rolling stock” must meet a minimum of 60% domestic content in the make-up of components and must be manufactured in the United States. The systems that are identified as rolling stock include vehicles, train control, communications and traction power. Other elements of the entire OAC, such as fixed facilities and guideway are considered “manufactured product” and must be entirely made (100%) of US product and must be manufactured in the US as well.

All proposers were required to certify compliance with the Buy America requirements for seven components, however, only the vehicle rolling stock would be subject to pre-award and post-award audit. The FPJV / DCC team committed to this as a prerequisite to being selected.

As a cable-propelled system had never been subject to Buy America requirements, in the fall of 2009 in preparation for the pre-award audit, BART and FTA had multiple discussions regarding the definition of the vehicle rolling stock. Per the Buy America requirements, 49 CFR Part 661.11, Appendix C (Typical Components of Rail Rolling Stock):

"The following is a list of items that typically would be considered components of rail rolling stock. This list is not all inclusive.

Car shells, main transformer, pantographs, traction motors, propulsion gear boxes, interior linings, acceleration and braking resistors, propulsion controls, low voltage auxiliary power supplies, air conditioning equipment, airbrake compressors, brake controls, foundation brake equipment, articulation assemblies, train control systems, window assemblies, communication equipment, lighting, seating, doors, door actuators, and controls, couplers and draft gear, trucks, journal bearings, axles, diagnostic equipment, and third rail pick-up equipment."

The Buy America provisions are geared toward self-propelled technologies. As this system would be cable-propelled, BART did not believe it was necessary to analyze a cable-propelled vehicle rolling stock any differently than a self-propelled vehicle. As such, the typical components of rolling stock as listed above were examined for their application on the DCC vehicle rolling stock. Where this became somewhat problematic was the fact that on a cable-propelled system, these components are not located on the vehicle carshell or structure themselves, but are mounted on the wayside. BART's interpretation was to include these wayside items as part of the rolling stock as the vehicle carshell or structure could not operate as a complete system without these wayside mounted elements. For clarification of the dilemma, Figure 3 shows a comparison between the cable-propelled and self-propelled technology components.

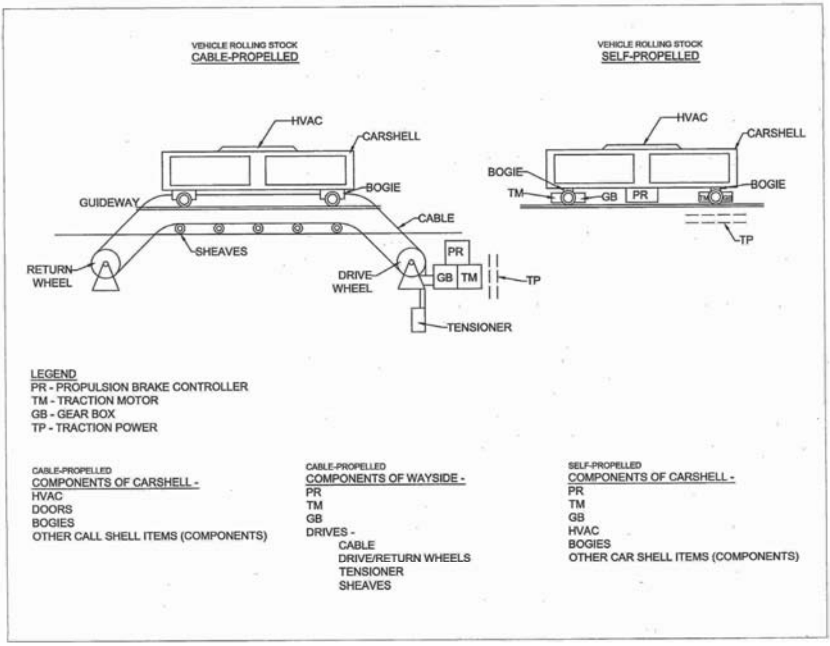


Figure 3. Comparison of Cable-Propelled and Self-Propelled Rolling Stock (Courtesy of L+E)

It is clear that the functionality of the wayside propulsion on the cable-propelled system when compared with the self-propelled propulsion systems is one-in-the-same. Thus, BART's initial pre-award audit performed in November 2009 using this interpretation resulted in a domestic content of the vehicle of approximately 81.9%.

DCC also noted their proposed final assembly location of Portland, Oregon at the facilities of SAPA, Industries. The activities to take place include final assembly of the vehicle shell and performing factory acceptance tests.

Well prior to the issuance of the proposal, BART met with FTA on several occasions to explain and obtain the FTA's confirmation of its interpretation of the FTA's Buy America requirements. While FTA staff then verbally agreed with BART's interpretation, after proposals were received and a cable-propelled system supplier was the on the team of the apparent winner, a self-propelled system supplier (also a bidder) wrote to the FTA protesting BART's interpretation of the Buy America statute. At that point the FTA responded with a position letter stating that the previously agreed interpretation was incorrect. BART was then obligated to revisit the audit with the bidders and to remove the wayside propulsion components from the vehicle subsystem component. Those components that were not attached directly to the car shell / vehicle structure were to be reclassified as either traction power or train control rolling stock.

After the reclassification, another pre-award audit was performed in December 2009 and resulted in a domestic content of 98.2%. DCC shifted manufacturing and / or assembly of some key components (bogies / trucks and assembly materials) to the US in order to meet the FTA requirements. The reclassification resulted also in a 60% domestic content for traction power, train control and communications.

The FTA accepted the revised pre-award audit in January 2010. Updates on the domestic content of each of the rolling stock items are provided on a periodic basis to the FTA. In addition, a post-award audit shall also show compliance with Buy America, or the project could lose FTA funding. Although the process was frustrating at times, the application of Buy America requirements to a cable-propelled system were finally established and met. Other transit authorities faced with a similar situation now have a precedent and guidance on the application of Buy America to cable-propelled systems.

Current Status

As of this writing (December 2012), BART and Contractor staff are finalizing fixed facility designs and continuing with system designs. Construction work is ongoing.

After DCC's bidding process for the vehicle supplier, United Streetcar, located in Portland, Oregon, was selected as the vehicle manufacturer. This was accepted by BART.

DCC has been providing quarterly updates on the Buy America status to BART and FTA based on actual cost data. The latest update as of November 2012 shows compliance with the Buy America requirements, as listed in Table 1 below.

Table 1. Compliance with Buy America as of November 2012

Rolling Stock	**Requirement**	**To Date**
Vehicle subsystem components	**60%**	**66%**
Train Control subsystem components	60%	88%
Communications subsystem components	60%	76%
Traction Power subsystem components	60%	66%
Manufactured Products	**Requirement**	**To Date**
Guideway and Guideway Equipment	100%	100%
Stations and Station Equipment	100%	100%
Maintenance Facilities and Maintenance Equipment	100%	100%

The Light at the End of the Guideway

Substantial Completion and the start of revenue service are anticipated to occur in fall 2014, with Final Acceptance in spring 2015. DCC has a 20 year O&M Contract and will provide 27 full-time staff to meet the required 99.5% availability to receive the full O&M payment.

Previous APM Conference Papers

This is the fifth paper on the OAC project to be given at International APM Conferences. For reference, the previous papers are:

- Cartwright, E., and Dunscombe, T. Orlando 2005: “Oakland Airport Connector, Pushing the Design-Build Envelope”.
- Cartwright, E., Dunscombe, T., and Moore, H.L. Vienna 2007: “DBOM to DBFO: the Long and Winding Road”.
- Cartwright, E., Dunscombe, T., Kennedy, G.J., Moore, H.L., and Yang, J. Atlanta 2009: “DBOM to DBFO: The Longer and More Winding Road”.
- Dunscombe, T., Kennedy, G.J., Moore, H.L., and Yang, J. Paris 2011: “BART OAC Project: Moving Forward at Last”.

MODSAFE – A Detailed Safety Model for Urban Guided Transport Systems

Joerg Schuette[1] & Sven Scholz[2]

[1]*University of Technology, Dresden, Germany, Faculty of Transportation Sciences "Friedrich List", Institute for Transportation Systems Engineering, D-01062 Dresden, joerg.schuette@tu-dresden.de, PH +49 351 463-36695, FAX +49 351 463-37825*

[2] *TelSys GmbH, Werdauer Str. 1-3, D01069 Dresden, sven.scholz@telsys-gmbh.de, PH+493514755110, FAX +493514755120*

Abstract

In 2012, the four years European Commission Project "MODSAFE" has presented its final results. 22 Urban Guided Transport Operators (London Underground, RATP Paris, Metro Madrid etc.), System Suppliers (Alstom, Bombardier, Ansaldo) and other Institutions (TU Dresden, Budapest University, TÜV Rheinland, UITP, UNIFE) had established a Safety and Security Model for Urban Guided Transport Systems including Metros, Lightrails, Tramways and APMs operated in four Grades of Automation, from Line of Sight driving to completely unmanned operations.

Basis of the Safety Model is a complex System Hazards and Risk Analysis, including over 1.000 entries and containing all train controls related potential hazards but also hazards related to environmental effects, operations and degraded modes situations.

In order to control and cover the hazards, a train control oriented MODSafe Functional Model had been agreed, including some 70 detailed functions in close coherence with the IEC62290 standard. Since the safety related functions are built up by physical entities, a MODSafe Object Model has been researched and agreed, containing a list of generic constituents of train control architectures. In order to derive adequate Safety Requirements, two different Safety Requirement Allocation Processes had been performed for every individual Function and the result checked for consistency. The Safety Requirements are ultimately linked to a THR (Tolerable Hazard Rate) and presented as a SIL (Safety Integrity Level) for every function. As a final result the Safety Requirements/Safety Attributes are allocated to a Spread Sheet between the safety related objects and the safety related function for every Grade of Automation GOA 0-4.

The paper presents the rationale of the project and its results as well as an outlook of the applicability and further possible works.

Introduction

In 2008, the European Commission has granted a research funding as part of the 7th Research Framework Programme to a larger consortium consisting of urban guided transport operators, railway supply companies and research institutions and consultants; leadership in the project was assumed by the TÜV Rheinland and the

UITP. The supported project MODSafe built on previous projects such as MODURBAN, MODTRAIN or UGTMS and had as major objectives to research and propose a commonly acceptable Safety Model as defined by the Cenelec Standard EN50126 [1], [2] in the highly diversified European field of urban guided transport systems such as tramways, lightrails, subways or automated people movers. The safety (and also security) project focused on questions such as:

- What elements of an urban guided transport system at a generic level are suitable to get Safety Requirements allocated to it?
- What may be a commonly acceptable mechanism to find and allocate the Safety Requirements?
- How can a complete set of Safety Requirements be found for all urban guided transport systems and for all grades of automation and what may be the adequate level of detail?
- Is there a commonly acceptable scheme across Europe for Acceptance and Safety Certification?
- What kind of security related aspects are transport operators facing today?
- What countermeasures are existing or may be recommendable?
- Are there common methods for Safety and Security Analyses?

Figure 1 shows an overview of the MODSAFE Working Packages, that had for representation purposes been arranged in a V-Model shape.

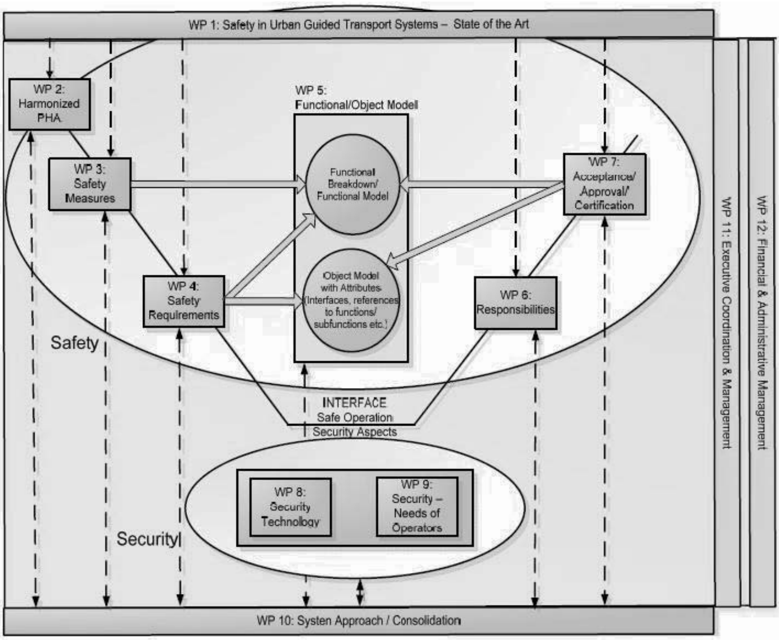


Figure 1 Overview of the MODSAFE working packages

This paper describes the safety related works and neglect the security work aspects.

The MODSAFE Approach

In order to achieve a consistent and reproducible logic for safety requirements allocations, the MODSAFE approach constrained itself to the Urban Guided Transport Passengers as Risk Group (neglecting staff, trespassers etc.) and takes a systematically conservative perspective. The idea was to start with a complete analysis of urban guided transport processes and reflect in every situation what could go wrong if the typically known safety functions would not be installed or would fail due to error, failures or faults (but maintaining the operational scenarios such as passenger densities, track layouts, headways etc.). In any of these situations, all possible hazards to the passenger where listed and further analyzed for causes at multiple levels of detail. Also the risk level associated with any hazard was analyzed in a conservative but still likely way.
In parallel to the hazards and risk analysis a generic functional model was developed, containing all safety related functions that are typically found today in urban guided transport or that may be developed one day. These functions, together with operational procedures or maintenance activities where then used to reach a complete coverage of all possible hazards of a system for each Grade of Automation. Once a function (or set of functions) where identified to cover a hazard (or hazard development into an accident), the severity level of possibly related accidents where used to identify a Tolerable Hazard Rate associated (THR) with the scenario. Since the THR must be suppressed by the Safety Function to an acceptable level as prescribed by the Cenelec standards EN 50126, 50129, a maximum wrong side behavior (or wrongside failure) rate may be derived. After conservative inclusion of potential risk reducing factors, a Safety Integrity Level is such derived in a straightforward manner. Figure 2 shows a graphical representation of the overall process.

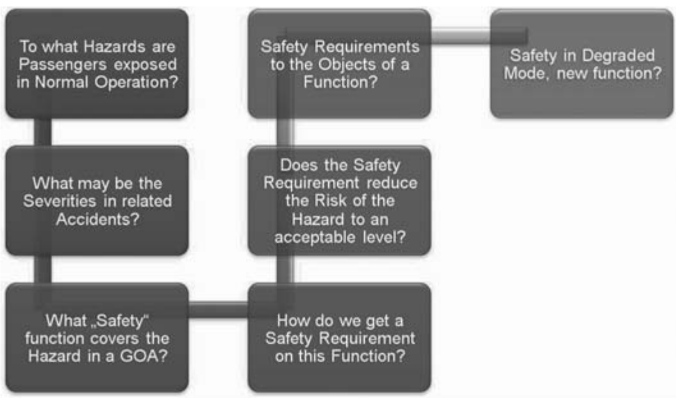


Figure 2: Overall Modsafe Process Steps

MODSAFE Hazards Analysis

One basis of the project safety works is the Hazards Analysis. A team of five partners (Responsible TU Dresden, contributing Budapest University, TÜV Rheinland, RATP Paris, London Underground) had first accumulated all available hazards and risk analyses in the domain (public transport) and established an ordering system to organize the hazards. Concerning the shape and representation the team agreed on a straightforward list and used MS-Excel to set it up. The hazards analysis organizes all entries into one of nine groups:

1	Train movement
2	Train interior
3	Train-Station Interface (with train in station)
4	Train-Station Interface (without train in station)
5	Depot
6	Operation Control Centre (OCC)
7	Maintenance
8	Emergency – Evacuation
9	Environment (force of nature)

Within any group, potential hazards where often refined at multiple levels of detail (up to seven) by reflecting on root causes of prime hazards, leading ultimately to an analysis of approximately 1.200 lines (of which approximately 50% are distinguished hazards). Figure 3 shows an example of the hazards analysis layout and organization into levels of detail.

Hazard Identification						Estimation of initial risk					Safety measures
Hazard Numbering (up to 10 level)	Hazard	Hazard Cause	Type of Accident (primary)	Possible consequential accidents	Remarks	Severity of Conse-quences	Assumed Probability	Risk reduction	Risk	Remarks	generic safety measure X = responsibility of operations staff (may be realised by techn. system) S = realised by the control/command and supervision of train movement system
1.1.1.2.2.1.3	**Wrong position registered**	Odometer failure	Derail-ment	Collision		Catastrophic	Frequent	1	Intolerable	Cf. D4.2	Determine Train Location
											Respond to Train Location Failure
1.1.1.2.2.1.4	**Wrong route**										
1.1.1.2.2.1.4.1	**Wrong route selection / authorization**	ATP failure	Derail-ment	Collision		Catastrophic	Frequent	1	Intolerable	Cf. D4.2	Ensure safe route as combination of route elements - This function is intended to allow ATP to define and implement a route as a combination of route elements according to the needs of the operator and to release routes as part of it either
		Wrong route selection by OCC staff in	Derail-ment	Collision							Safe display - HMI OCC

Figure 3 Hazard Analysis Table Layout

The hazards analysis table was also used for the subsequent Risk Analysis and provided already specific columns for later coverage analysis by the safety measures (or safety functions). It shall be noted that the Hazards Analysis was also verified for completeness in so-called “degraded modes”. A number of scenarios had been performed, where the regularly operating system left the nominal state due to failure and entered into a failure management or degraded operating mode state (eg. train stranded in the tunnel, subsequent evacuation of passengers and commencement of run-around mode). Although it is a priori not clear, that the hazards emerging in these states were already all found in regular operations analysis, it turned out that only very few new hazards showed up during the degraded modes analysis and entered the Hazards Analysis.

For the Risk Analysis, every hazard was considered in its context and briefly analyzed in the two risk dimensions, namely what possible (but still likely) consequence the hazard may yield if it further develops into an accident and how often this may arrive if the safety function does not exist or has failed. In order to define accepted and comprehensive categories of risk, the metrics of the Cenelec standard EN50126 was adopted for the project as shown in figure 4. While the Severity Analysis turned out relatively straightforward, the estimation of likelihoods or frequencies of the (uncovered) hazards turned out relatively complicated. One source of difficulty origins from the fact that the risk matrix of EN50126 (see Figure 4 below) names the frequency categories by verbal descriptions of frequency such as “occasional” or “remote”, but does not give numeric values for it. Here, the team agreed on a decadic logic where the highest frequency (“frequent”) is associated with a rate of 10^{0}-10^{-1}/h and the lowest is associated with a rate of 10^{-9}/h. Employing the numeric scheme, the estimation of most of the typical train control functions became more or less straightforward, but in particular the class of “Environmental” Hazards (such as strong winds, earthquakes etc.) remained almost impossible to be estimated for all European Countries through one number. The actual estimation should be considered therefore a very rough first estimate and the project recommends every future user (eg. operator) to re-estimate the likelhoods of these hazards for his specific property.

Frequency of occurrence of a hazardous event	Risk Level			
Frequent	Undesirable	Intolerable	Intolerable	Intolerable
Probable	Tolerable	Undesirable	Intolerable	Intolerable
Occasional	Tolerable	Undesirable	Undesirable	Intolerable
Remote	Negligible	Tolerable	Undesirable	Undesirable
Improbable	Negligible	Negligible	Tolerable	Tolerable
Incredible	Negligible	Negligible	Negligible	Negligible
	Insignificant	Marginal	Critical	Catastrophic
	Severity level of hazard consequences			

Figure 4 Risk Matrix according EN50126

Directly linked to the frequency of a risk occurrence due to a failed or not existing safety function is the THR, where the inverted scale applies, meaning that if a hazard is estimated to appear frequently due the failed safety function, then the target THR shall be 10^{-9}/h, if the hazard occurrence may be considered incredible even if the protecting function fails, the associated target rate is 10^{-1}/h.

MODSAFE Functions Model

According the MODSAFE approach, the Hazards Analysis needs to be covered by safety measures, which are for the project essentially Safety Functions (basically train control functions), Safety Procedures and other mitigations (like preventive maintenance actions). In order to find a generic set of functions that cover, or "control" respectively the hazards, previous train control architectures and projects (such as UGTMS, MODURBAN) had been analyzed as well as the draft standard IEC 62290. After several review loops amongst the transport operators, an IEC62290 oriented set of functions had been retained as the "MODSAFE Functions Model", where a few groups of top functions are broken down into up to five levels of detail ending with approximately 80 functions (see Fig. 5).

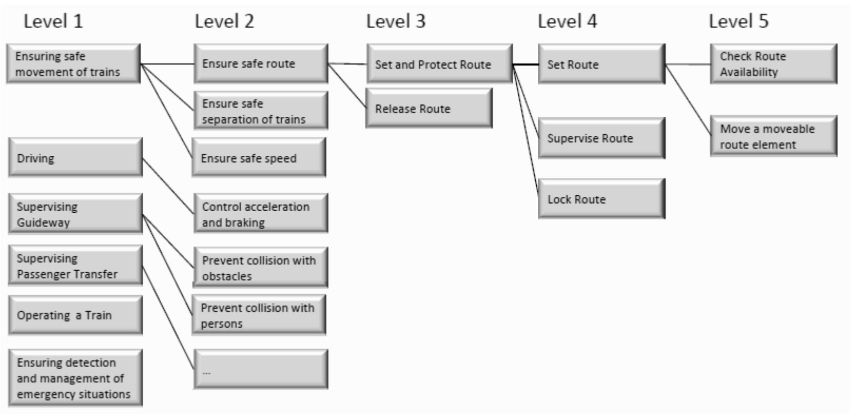


Fig. 5 The IEC 62290 oriented Functions Model contains about 80 functions in five levels of detail

It has been verified independently by a review team of the railway supply industry that the functions cover in fact the Hazards included in the Hazards analysis.

Safety Requirements Analysis for Continuous Mode Functions

Prior to further safety analyses it was decided to distinguish between those functions that are operated in Continuous Mode and those that are operated in Low Demand or Low Rate Mode. "Continuous Mode" simply means in this respect, that a function shall work more or less all the time, and if it ever fails wrong side the system enters immediately into a hazardous state. For the "On Demand" or "Low Demand" functions, a railway-adapted definition of the IEC60508 was adopted

since the CENELEC standards EN50126 ff. exclude explicitly these functions from their scope.
For the Safety Requirement Allocation several existing and exercised methods were checked and evaluated

- Risk Graph (IEC 61508)
- Risk Matrix (EN 50126)
- MODURBAN Method
- MODTRAIN Method
- Recommendations by ERA (European Railway Agency)
- Recommendations by the British Yellow Book
- Specific Methods of Urban Guided Transport Operators

In order to define a repeatable – yet compliant - method with most of the above practices, a particular MODSAFE process was developed.
In a first step the probable worst consequence (or "severity") of a possible resulting accident was determined in a risk estimation for the case where a safety related function fails "wrong side". Since the Risk Matrix advices a metric according to which a Tolerable Hazard Rate (THR) shall not exceed a certain value for any specific severity category, the THR can be directly associated with the estimated severity class. In the event that no further risk reducing factor may be conservatively assumed, the THR numerical value can be directly transferred into a numerical Safety Integrity Value. These equivalences simply mean, that if a safety function failure leads eg. to catastrophic events without any possible further barrier, it is not tolerable by a rate above a certain value (here 10^{-9}/h) and therefore also the function may not fail more frequently in this mode than by this rate, so the SIL is also characterized by 10^{-9}/h).

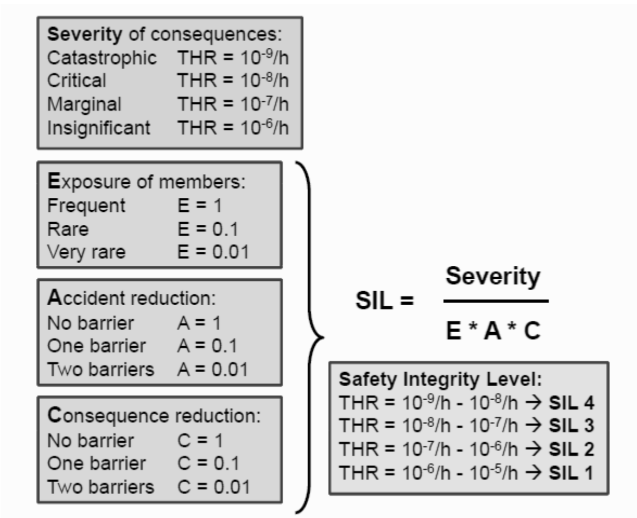


Figure 6 Basic elements for the Safety Requirement Allocation process

In real life operations there are, however, risk reducing factors often impacting the system safety. Therefore, the MODSAFE team first determined the classes of risk reducing factors, and then a metric of how to downscale Safety Requirements (SILs) from the raw THR. In order to stay consistent with other methods (eg. IEC 61508 risk graph [3], [4], [5]) the metric was developed by orders of magnitude in the decade system, and safety rates were up- or downscaled by one or more factors of ten if one or more reducing factors may be conservatively assumed. Figure 6 assembles the basic elements of the process. The risk reducing factors take into account whether any member of the risk group (here passengers) are really exposed to a possible accident (eg. mainline train operation vs. accident in the yard), if there are any other element that may still avoid the accident (eg. back up signaling equipment, train captain reactions) or if the consequences may be still reduced once the accident becomes unavoidable (eg. speed reduction by train captain).

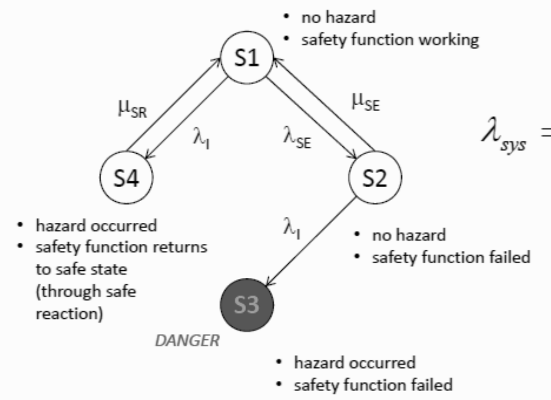
The above process had been applied for all (continuous mode) safety functions in all Grades of Automation, Figure 7 shows an example for the applied process (here for route lock).

Item		Description
Name of safety function		**Lock route**
Description		This function is intended to lock the route against route release by operator command if a train is approaching and the movement authority allows entry into route, or a train is within the route.
Reference of functions		IEC 62290-2 – 5.1.1.1.3
Reference for risk analysis		None
Possible wrong side failure		No inhibition of movement of moveable route elements
Hazardous situation		Train movement into unsecured route
Possible hazard consequences – accidents		Derailment due to overspeed or moving switch while train passing Collision with oncoming train or flank movement
Exposure probability to hazard		Passengers are permanently onboard of trains
Accident probability reduction		No barrier can be assumed
Consequence reduction probability		Passenger cannot escape from hazard consequences
Severity of consequences due to failure of safety function		Catastrophic
Initial THR per hour		10^{-9}
Risk reduction factors	E	1
	P	1
	C	1
Final THR		10^{-9}
Final SIL		**SIL 4**

Figure 7: Example for the MODSAFE Safety Requirement Allocation Process

Safety Requirement Analysis for Low Demand Rate Mode Safety Functions

Different to the continuous mode safety functions there are also safety related functions involved in urban transit that are demanded only with clearly lower rates, such as Fire Detectors or Derailment Detectors, where the undetected wrong side function failure does not automatically mean that also Fire or Derailment Hazards are present (see also [6]). In order to derive a Safety Requirement in the shape of an acceptable wrongside failure rate λ_{SE} for the safety System Element, the relatively low hazard or incident rate λ_I (eg. once or several times per year) and the failure detection or inspection rate μ_{SE} must be involved to determine the total rate λ_{sys} in which the system may be in an unsafe state. In the MODSAFE project, the relation between these safety relevant parameters was found by following IEC61508 advices and integrating the differential equations coming from the Markov Process shown in Figure 8.



$$\lambda_{sys} = \frac{\lambda_{SE}\lambda_I}{\mu_{SE}}$$

Figure 8: Markov Process for Low Demand Rate Safety Functions in MODURBAN and the solution

From the state transition chart in Fig. 8 it can be clearly seen, that an arriving hazard with working safety device as well as the failure of the device with absent hazard are not considered dangerous. Only the coincidence, a failed device with a hazard arriving in the time interval until the failure would have been detected/inspected, is considered the safety critical event. The algebraic result also shows that it is rather the relation or quotient of how often the safety device fails and how long it takes to detect the same which governs the safety of the device (than a pure wrong side failure rate alone).

Figure 9 gives a numerical example of this process. The example clearly shows, that for Low Demand Rate Safety Functions it is not possible anymore to define one generally applicable safety requirement as was the case for the Continuous Mode functions, but that the results depend on operating artifacts such as inspections, self diagnostics, maintenance or other checks; the process is therefore recommended to be performed for these specific functions by every individual operator for his specific operations.

Item	Description
Name of safety function	**Supervise platform tracks**
Description	This function is intended to supervise the actions of an external platform track detection device to stop the train in case of intrusion of person.
Reference of functions	IEC62290-2
Reference for risk analysis	None
Possible wrong side failure	Device does not detect person on platform tracks
Hazardous situation	Person on platform tracks while train is approaching the station.
Possible hazard consequences	Collision of train with person on track. Maximum one fatality, Critical Severity THR = 10^{-8}/h

Assumed rate for person on track: $\lambda_I = 10^{-4}/h \Rightarrow \frac{THR}{\lambda_I} = \frac{10^{-8}/h}{10^{-4}/h} = 10^{-4} = \frac{\lambda_{SE}}{\mu_{SE}}$

With system self inspection rate 10^1/h: $\lambda_{SE} = \mu_{SE} \cdot 10^{-4} = 10^1/h \cdot 10^{-4} = 10^{-3}/h$

Figure 9: MODSAFE-Example for Low Demand Rate Safety Function

Conclusions and Outlook

The MODSAFE project defined and applied for the first time a complete and consistent safety analyses and safety requirements allocation for an Urban Guided Transport System Functions Set. It includes for the first time a process that may yield equivalent safety requirements also for Low Rate Demand Mode Functions. As a base analysis for the safety requirements allocations, a complete Hazards Analysis for Urban Guided Transport Systems was performed and includes degraded operating modes considerations.

Future work may concentrate on some particular functions that were found to depend on the passenger density (eg. on platforms), where architectural artifacts start to have an impact on passenger safety. Also, the low rate demand mode functions examples may be further analyzed by individual operators.

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Improving Airport People Mover Performance with an Intelligent Onboard CCTV system

S. Scholz[1], J. Schuette[2] & C. L. Crawford[3]

[1,2] University of Technology, Dresden, Germany, Faculty of Transportation Sciences "Friedrich List", Institute for Transportation Systems Engineering, D-01062 Dresden, PH +49 (351) 46336695, FAX +49 (351) 46337825, e-mail: sven.scholz@tu-dresden.de; joerg.schuette@tu-dresden.de

[3] Bombardier Transportation Germany, Director, Network Solutions, Schoeneberger Ufer 1, 10785 Berlin, PH +49 (30)986071493, e-mail: chris.crawford@de.transport.bombardier.com

Abstract

Operational performance and security of Automated People Mover (APM) systems especially at airports are becoming more and more important. Many APM installations serve large parts of an airport, such as terminals or parking lots but also run from security to non-security areas. Today, mostly manual visual inspection either on-site or remote from the operation control center is used to check the status onboard the vehicles. This relates to the emptiness from passengers, e.g., before entering the depot area, up to an estimation of the passenger load onboard. With the presented Empty Vehicle Detection video analytics module, the security of the APM system as well as the airport can be increased. Vehicles can only travel to restricted areas if they are confirmed empty. The estimation of the number of passengers onboard can help optimize operational benefits. In case vehicles are too crowded or hardly occupied at all, additional trains can be put into service or some trains be removed, respectively. This helps improve operational performance of such APMs by either providing additional capacity or reduce costs in case of saved trips. This paper presents the two video-based approaches to automatically detect the number of people onboard the train and report this status to a control center.

Introduction

Today, Automated People Mover systems form integral parts of many airports with extensive terminal facilities. Many APM installations serve terminal areas and nearby parking lots. Since most APM systems are equipped with onboard CCTV technology the status onboard the vehicle can then be determined automatically by using video analytics modules. Even existing systems can easily be retrofitted with onboard CCTV to provide this functionality. Small cameras combined with powerful yet compact embedded PC technology require only limited space for supplementary installation.

The University of Technology Dresden has therefore developed together with Bombardier Transportation an enhanced solution to check the status onboard the trains automatically (cf. Figure 1). The system shall help improve operational processes and enhance security at airports by detecting people and baggage left behind or automatically estimate the occupancy rate onboard.

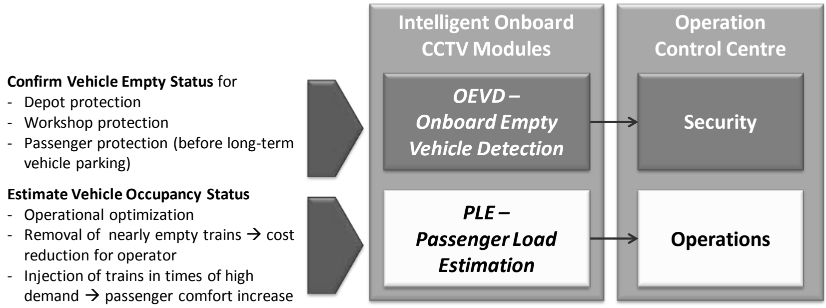


Figure 1: Operational Context of Intelligent CCTV Modules

APM vehicles may travel between security and non-security areas or to and from depots or workshop facilities. Since vehicles run without any attendance staff, emptiness from passengers shall be checked before the vehicle enters a turn back facility, a workshop, the depot or even travel to restricted areas. In all cases, people shall be prevented from unauthorized access. However, manual inspection of the vehicles requires considerable personnel effort and is even prone to failure, in case the staff is distracted and does not check carefully enough. With the Onboard Empty Vehicle Detection (OEVD) module, manual inspection of the vehicle is not required anymore. Instead, automatic image processing will analyze the vehicle status and inform central control security staff. Local personnel may then intervene on site only in exceptional cases.

Additionally to this yes/no estimation regarding people or luggage onboard, a more sophisticated detection module has been developed which can help improve operational performance of the APM. With the Passenger Load Estimation (PLE) module, the detection algorithm can indicate up to five different levels – from ‘empty’ (identical with nominal OEVD module status) to ‘overcrowded’ – for the number of passengers. In both cases, *empty* and *overcrowded*, operational measures shall be taken by central control staff to optimize the train service. This can contribute to substantial operational savings on the one hand and increase comfort for passengers on the other hand. Since APM systems run without any driver staff, there is the big advantage to inject or withdraw vehicles into/from service just according to operational needs. If the vehicle is indicated to be more the less empty, substantial capacity can be saved if the operating train fleet is reduced. Major reduction in quality for the passengers may not be expected as long as vehicles still maintain a minimum acceptable headway, e.g., 5-7 minutes. However, savings would be possible in terms of electricity or reduced vehicle tear and wear for the operator. Similarly, it is operationally beneficial if additional trains are injected into service, once trains are detected *overcrowded*. Passengers will appreciate an increased comfort level due to more seating capacity and less overcrowded trains. Even from an operational point of view, a smoother traffic can be expected due to faster passenger exchange and thus a more stable train service.

Hence, both Intelligent CCTV modules can help offer a more attractive train service with increased security and optimized operations for passengers as well as for the train service operator.

Existing methods to detect people onboard of vehicles are presented in the next section. The principles of the detection algorithm are then illustrated and the hardware concept used for development, lab and field tests is described at the end of the paper. Eventually, the paper closes with some final remarks on future development efforts.

Onboard vehicle status detection approaches

Passenger counting has been a very active field for both industrial applications as well as scientific research and development activities so far. Most applications rely on light barriers, turnstiles or weight measurement to either explicitly count individuals when entering and/or leaving vehicles or at least correlate the vehicle's mass with an estimated number of people (Kovács, 2009). Another method uses so-called "gate counting" cameras, which require separate cameras at the zenithal position above each train door. Since any remaining passenger or baggage onboard the train shall be detected with high confidence, these approaches have been found inadequate for empty vehicle detection due to limited accuracy.

Detecting passengers or objects inside vehicles using cameras has found widespread use especially in the automotive sector (Pavlidis, 1999). Near-infrared images taken from outside the car are automatically evaluated to count the number of people. The exact position of the passengers in the front and back seats helps reinforce certain parts of the image to enhance visibility. Similar approaches based on stereo-image evaluation are proposed by Yao (2011) and Devy (2000). Again, single seats inside a car are supervised for the presence of people, e.g., adult, child or baby seat. However, stereo camera imaging requires a higher number of cameras compared to single image processing and more complex algorithms to merge the images of two cameras. A security-oriented approach to detect and monitor passengers in busses is presented by Chee (2007). It is based on a dedicated recognition of the human's head and tracking the identified head inside the vehicle. The recorded movement profile may be used to indicate suspicious behavior of the person. Detection and counting of people inside a crowd is explained by Choudri (2009). Like most approaches, the focus is on dedicated people counting making use of human specific features. Regardless of the field of application, detection systems for people inside vehicles usually focus on counting individuals to get an estimation of the occupancy of the vehicle. Many approaches assume a specific location of people inside the vehicle. However, this is not the case for empty vehicle detection or passenger load estimation inside an APM vehicle.

Little research has been done in the field of public transport so far to use video image processing to detect people onboard of trains. Related approaches deal with crowd detection or crowd density estimation in confined areas, such as shopping malls or train stations. For example, Yahiaoui (2008) and Crespi (2007) use stereoscopic vision from an overhead position to observe large areas in public spaces.

Regarding the detection of people onboard of trains, two different methods can be distinguished in principle. On the one hand, every individual is counted separately. As a consequence, every person must be recognized as human being inside an image. Dedicated detection algorithms have been developed to detect humans due to typical body features, such as heigt/width-relation, head shape or face-recognition (Chee, 2007; Mukherjee, 2011). These methods work quite reliably, with a limited number of people (no occlusion) per image and special camera alignments. However, the algorithms are comparably complex, computationally intensive and hence result in long processing times and higher performance requirements for the hardware. Some more pragmatic approaches try to estimate the number of people (Hou, 2008; Ye, 2008). Typically, these methods make use of image features such as the number of moving pixels, edge density (Nuske, 2008; John, 2009), background-foreground difference (Davies, 1995; Ye, 2010; Choudri, 2009; Tang, 2007) or texture (Lo, 2001; Boland 1999) and compare those feature with some pre-defined reference background information representing an empty scene. Although these methods are comparably simple, the big challenge is to make them robust against typical changes which can alter the background reference obsolete, e.g., lighting conditions or shadows.

In conclusion, none of these algorithms had been found immediately applicable to the onboard passenger detection / empty vehicle detection issue. Dedicated passenger counting approaches had been discarded in favor of less computationally extensive methods. A new approach based on edge detection and foreground-background subtraction has been developed in order to conclude the presence of people or objects onboard an APM vehicle.

Video-image based state detection

Background comparison

As described in the previous section of this paper, the simple approach of foreground-background comparison seemed most promising for the estimation of the occupancy rate inside the train. Thus, the definition of an adequate reference background image and its maintenance in course of time was concentrated on. The algorithm itself consists of the definition of an image background model, the computation of a background subtraction image and the regular update of the background reference image. The regular background update is required to adapt to changing environmental conditions. For the PLE module the background model is based on a classical Running Gaussian algorithm (Jaehne, 2005) to describe the mean $\mu_{i,j}(t)$ and variance $\sigma^2_{i,j}(t)$ of the background pixel at the coordinates *i,j* of the image frame *F*:

$$\mu_{i,j}(t+1) = F_{i,j}(t+1)\cdot\alpha\cdot B + (1-\alpha)\cdot\mu_{i,j}(t)\cdot B$$

$$\sigma^2_{i,j}(t+1) = \left[F_{i,j}(t+1) - \mu_{i,j}(t)\right]^2\cdot\alpha\cdot B + (1-\alpha)\cdot\sigma^2_{i,j}(t)\cdot B$$

An update of the background model is only performed in case the pixel is classified as background (B = {1,0}). Due to the learning parameter α the mean and variance values are updated frame by frame.

Next, a threshold value is applied to check a significant deviation of the background pixel value from the current frame value. If so, the pixel is marked as foreground and the vehicle interior is considered occupied at this location inside the image. In principle, a clear dependency between the number of people onboard and the covered image background can be seen (cf. Figure 2).

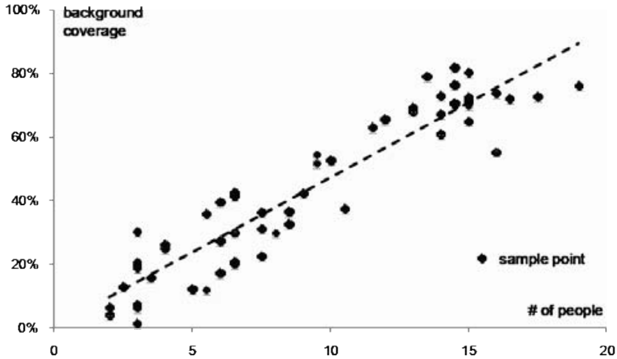


Figure 2: Number of people on board vs. the subtracted background coverage level

However, this linear model needs further improvement especially regarding high levels of train occupancy. An asymptotic curvature is expected for high occupancy levels. Additional people onboard will hardly cover further parts of the background, if coverage is already close to 100 % saturation. In this respect, the current model shall be improved in the future and it can then provide a more accurate detection of overcrowded situations.

Edge detection

The background reference image approach had been found inadequate for the Onboard Empty Vehicle Detection. Due to the fluctuation in background coverage of about 15 to 20% (cf. Figure 2) it was considered not suitable for the OEVD application, which requires a highly reliable state decision, whether the vehicle is empty of not. Hence, complementary to this background subtraction technique an edge detection method is used for the OEVD application (cf. Figure 3). Due to the robustness against environmental impacts, such as light changes, edge detection is prominent for this kind of task. Characteristic image features from an empty vehicle are compared with each image, which is to be analyzed. Significant differences indicate in Figure 3 those elements which do not correspond to an empty vehicle reference image.

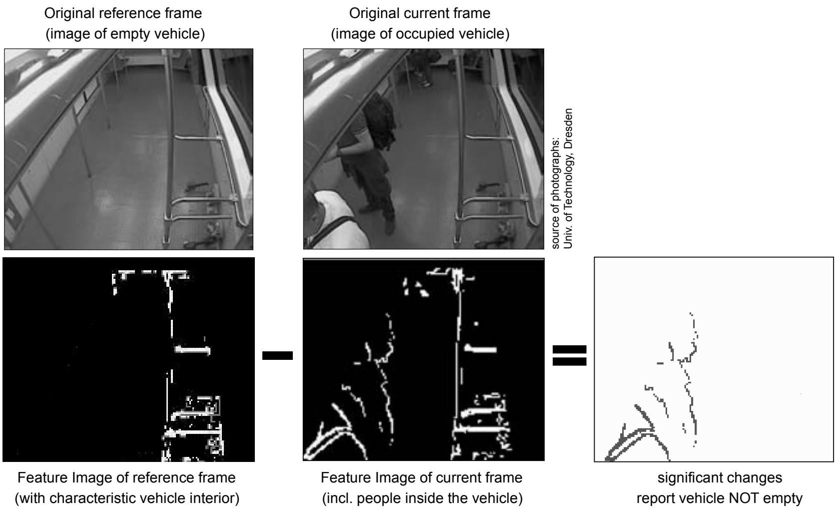


Figure 3: OEVD detection example based on prominent image edges

In order to provide the in-vehicle status with high level of certainty regarding emptiness in case of the OEVD application all images and the system itself is checked regularly for its correctness. A health signal indicating proper functioning of the software and hardware is output permanently, e.g., to indicate the acquisition of valid image data (no frozen image, no moved camera position, minimum and maximum brightness of image).

Prototype architecture concept

The system comprises two cameras per train car and an embedded industrial PC, which can also provide Network Video Recorder (NVR) functionality (cf. Figure 4). The two cameras are IP-based digital network cameras and are connected to the embedded PC via Ethernet-LAN including power supply through PoE (Power over Ethernet). The embedded PC is interfaced to the onboard Automatic Train Control (ATC) system via relay contacts. It receives status information, such as the train door open/close signal and a scan trigger pulse from the ATC. In the same way, the ATC receives the scan result of the vehicle's interior and self-diagnostics data from the detection system. Complementary to this simple binary status interface, more comprehensive interface functionality is provided through a software interface based on Windows Web Service. The in-vehicle and system status are transmitted as event-based message data and can be sent directly to OCC or any desired terminal, e.g., via WiFi network. Even more sophisticated event messages can be generated, e.g., containing the ID of a faulty camera, a service code or the location of a detected object inside the train.

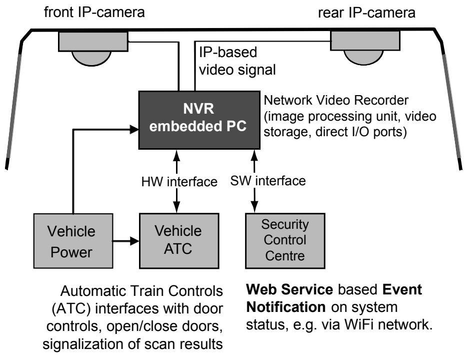
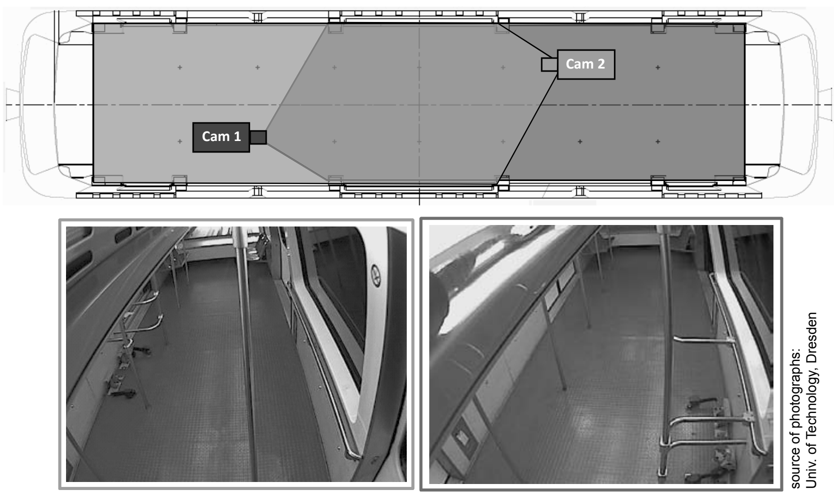


Figure 4: Hardware / Software architecture for prototype tests

The video analytics shall operate upon external request only. Therefore, a command (2-wire 24VDC or Web Service based trigger event) is sent to the system to activate the video analytics. In parallel, the door status is transmitted and the system will only start in case the doors are reported closed. It is essential to maintain train doors closed during scan to increase detection accuracy and reliability and to limit the interference from, e.g., strong and fast changing sunlight.

Typically, each train car is equipped with one pair of cameras each of which faces in opposite direction to allow complete supervision of the car's interior (cf. Figure 5). The cameras are mounted and aligned in such a way as to provide a most suitable field of view for the video analytics software. For example, they are placed strictly in line with the passengers' handrails and therefore even more distant parts of the vehicle are visible well.



hand rail centered (top, camera 1) hand rail centered (top, camera 2)

Figure 5: Camera position and field of view for Intelligent Onboard CCTV services (©Bombardier)

System verification and tests

Both detection modules were tested in different laboratory installations and using real world video sequences from an international airport before going into a field installation. Extensive data had been collected from an on-site field installation at the Rome International Airport in Italy. Various test scenarios with people and baggage were performed to check reliable detection of ‘Empty’ or ‘Not Empty’ status of the vehicle. Figure 6 shows an example. An empty car is shown in the left image, while there are people sitting near the rear window in the right image. The person only produces minimum changes to the background reference image but is detected properly. No detection failure had been recorded and the system identified each occupied vehicle correctly as ‘Not Empty’ proving the high level of confidence of this detection module for security applications.

source of photographs: Univ. of Technology, Dresden

Figure 6: Detection example of the OEVD module (left: empty vehicle; right: person at the rear)

The Passenger Load Estimation module was tested with additional video data of occupied vehicles. In a first step, the ground truth of the images had been gathered, i.e., different people were asked to classify the test images as either low, moderate, medium of highly occupied. Then the detection module was used to classify the images automatically applying the found mathematical relationship from Figure 2. On average approx. 85% of the images had been classified correctly into one of the four categories.

Summary

The developed onboard video-based detection system for APM Systems can automatically check the interior status of a vehicle. It provides two different detection modules to increase security and improve operational performance of the APM system. The Onboard Empty Vehicle Detection (OEVD) module can detect whether the vehicle is empty or not. Hence, people and baggage may be prevented from being taken into restricted areas of the network. It may therefore contribute to higher system security. A more sophisticated detection module is made to estimate the vehicle occupancy in order to indicate the occupancy level of the vehicle. If found nearly empty or overcrowded operational measures can be taken to remove trains from or inject trains into service. Thus, an optimized train service may be provided with less number of trips in low demand times and additional trips in peak hours. The system comprises of the onboard CCTV cameras and an embedded industrial PC to accommodate the image processing, video storage and event notification through dedicated interfaces to ATC and central control.

Further developments include an improved mathematical model to describe the dependency between image background coverage level and passenger load to increase the accuracy of the detection system. Another important step is to adapt the system to work with different vehicle types, e.g., metro cars and to check usability for urban applications.

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50 Years of Powering APMs: A Historical Perspective of Variables and Constants in Power Rail Design

Keith Forman[1]

[1]General Manager, Harlan Center of Excellence, Conductix, Inc.

Purpose: To provide a brief historical perspective on powering APMs and a practical guide for owners, operators, contractors, and consultants for the selection and life-cycle management of power rail systems for APMs.

Over the course of history, numerous methods of propulsion have been applied to people movers – automated and non-automated. Some technologies have stood the test of time providing safety, reliability and cost-effective operation, while others have gone by the wayside for a variety of reasons. This paper will start with a brief look at the pros and cons of three early people movers (only one truly automated.) The author offers these examples to convey the necessity of a systems approach to the application of modern power rail systems for APMs.

Rope Pull: Perhaps the earliest known PM is Der Reiszug (the Trip), believed to have been constructed in either 1495 or 1504. This 620' system on a 67% grade provided private access of people and goods to the Hohensalzburg Castle in Salzburg, Austria (Image 1.) In 1910, the system was converted from animal power to electric motors to pull the cables. [1]

While the cost to operate an animal powered system was certainly quite low, capacity was limited by the power supplied by the animal. As living standards of the castle residents and guests increased, so increased the demand on the system. Electric motors were a logical upgrade to increase the system's capacity.

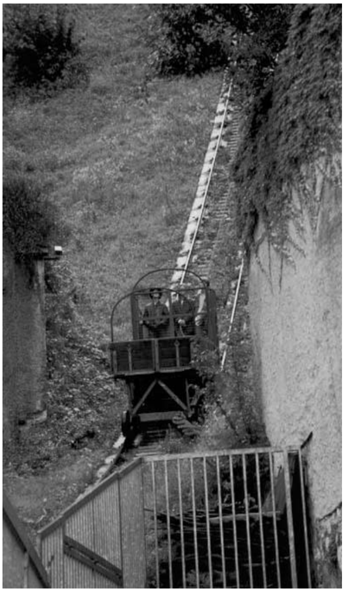


Image 1: Der Resizug at Hohensalzburg fortress, Salzburg [2]

Hydraulic: At the same site as Der Reiszug is the Festungbahn, a water-weighted funicular commissioned in 1892 providing public access to Hohensalzburg castle (Image 2.) Tanks in the cars were filled with water at the top of the track and emptied at the bottom. Limitations due to freezing rendered the system inoperable during the winter months. Growing ski tourism in the 1950s provided a supply of winter visitors to the fortress. In 1960, this system was converted to electric motor power to provide year-round access. [3]

Image 2: The Festungbahn at Hohensalzburg fortress, Salzburg [4]

Mechanical: One of the most interesting and innovative systems was the "Never-Stop Railway" built in Wembly, London for the British Empire Exhibition in 1925 (Images 3 & 4.) This ingenious system of 88 carriages was powered by a continuously revolving electrically driven screw located between the rails. The pitch of this screw was varied along its length to change the speed of the vehicles, from less than 1mph at stations for easy boarding without stopping to a brisk 24mph between stations. This system whisked up to 20,000 pphd, traveling along its 3 mile route in just 10 minutes.

Initially, there were failures of the bearings between the screw sections. The supplier replaced these after which the system operated trouble-free for two years. The Never-Stop Railway was removed shortly after the exhibition closed in 1926. [5]

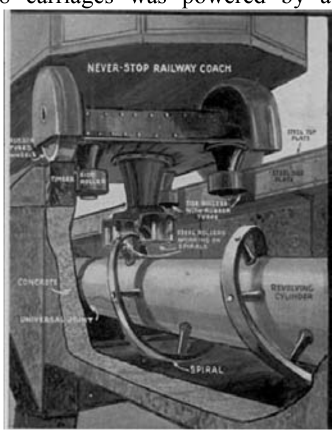


Image 3: The drive mechanism of the Never-Stop Railway [6]

Image 4: Never-Stop Railway at the British Empire Exhibition, 1925 [7]

Pneumatic or "Atmospheric Railway": The atmospheric railway uses air pressure for propulsion. Depending on the model, it either runs on a tube between the rails connected to the train via a suspended piston, or the car itself acts as the piston with the tunnel acting as the tube. Engines set up along the train's route left a partial vacuum just ahead of the car while pumping air behind the car, causing atmospheric pressure to boost the train. As the name suggests, atmospheric railways eliminated friction and jerkiness, and were nearly silent

Since the mid-1800's, several pneumatic systems have been designed and developed, with varying results. In 1846 the 20-mile (32 km) section from Exeter to Newton of the South Devon railway (now Newton Abbot) employed vacuum through a pneumatic tube laid between the rails, which propelled a piston running in it (Image 5). It had stationary engines at around 3 mi (5 km) intervals. Trains ran at speeds of up to 70 miles per hour (113 km/h), but service speeds were usually around 40 mph (64 km/h). The slots were sealed with leather strips kept supple by the regular application of beef tallow. Unfortunately, the tallow covered leather strips were appealing to rats, making the system difficult to maintain. To further complicate operations, the engines had to be run longer than expected, as they were not initially connected to the telegraph. Pumps were operated according to the railway timetable until the train passed. Consistently late train arrivals (a frequent occurence) increased pumping costs. The pneumatic system was abandoned in 1847 and replaced with steam powered engines at a significantly lower operating cost per mile. [8][9]

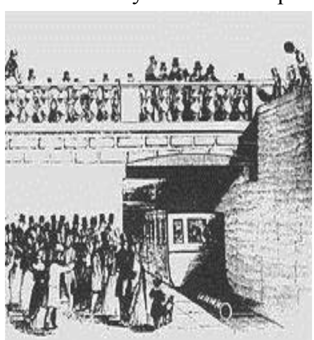


Image 5: South Devon Atmospheric Railway end of line, 1844 [10]

Image 6: Brunel’s Atmospheric Railway [11]

Through the work of companies such as Aeromovel and Flight Rail Corporation, pneumatic systems have been staging a comeback, facilitated greatly through the use of modern materials and control technologies. Time will tell if these advancements will make pneumatically powered systems commercially viable.

The three propulsion systems identified above, despite benefits, had limited viability for a variety of reasons. Table 1 identifies the pros and cons of each method.

Table 1: Pros and Cons of Early People Movers

Name	Vehicle Type	Propulsion Method	Pros	Cons
Der Resizug	Funicular	human or animal	low cost	low power, low capacity, low speed
Festungbahn	Funicular	water weight	simplicity, low cost	seasonal operation
Never Stop Railway	rail mounted tram	variable pitch screw	smooth, quiet	initial cost, safety

People Movers since these early beginnings have largely been powered with a system of electrified bars made of various materials later dubbed “Power Rails”. While the concept is fairly straight forward, there are technical issues involved with making these systems efficient and reliable. Let’s take a closer look at power rail design.

Composition of a Power Rail System

Power rail systems consist of 8 primary components:

- Conductor Rail: The conductors may be covered or bare and must satisfy the electrical and mechanical requirements of the application.
- Collector Assembly: Attached to the vehicle, the collector must maintain contact with and draw power from the conductor rail. The collector shoe part of the assembly can be made of various materials, but are usually a copper and graphite composite. Shoes need to have good wear properties as well as the right electrical properties.
- Splice Assembly: The splice is a mechanical and electrical connection which matches the conductor in strength and conductivity.
- Hanger: These both support and insulate the conductors from earth and other conductors while allowing thermal expansion of the conductors over the operating temperature range.
- Power Feed: This provides a connection point from the source of power supply to the conductor rails.
- Expansion Assembly: This takes up thermal expansion of the conductors while maintaining conductivity and a continuous contact surface for the collectors.
- Anchor Clamps: Anchors secure the conductor to hangers at specified intervals to direct thermal movement toward the expansion assemblies.
- Transfer Caps or Ramps: These manage the collector shoes across switch gaps or other discontinuities in the power rail.

Historical Background of Power Rails for APM's

In 1958 Conductix (formerly Insul-8) modified one of their existing crane electrification conductor systems to power a non-automated people mover, a children's ride. Since those early beginnings, power rails have evolved to satisfy a wide range of requirements through a multitude of profiles, configurations and features. Here's look at a few early applications of power rail to people movers.

Santa's Village, Big Bear, CA – 1962

This system used a 300A 8-Bar power rail developed and patented by Insul-8 Corporation in the early 1950's. The vehicles traveled at 8 mph around the 6000' route. Still produced today in profiles ranging from 100A to 350A, the conductor consists of strips of steel or copper roll-formed into a figure-8 and covered with an extruded PVC cover. As shown in Image 8 below, an opening in the PVC cover provides access for the collector shoe. While a simple design and quite adequate for straight-running overhead cranes, guiding the collector shoe with the PVC cover requires periodic replacement of the cover in high duty cycle applications such as amusement rides and people movers.

Image 7: Santa's Village Bumble Bee monorail [12]

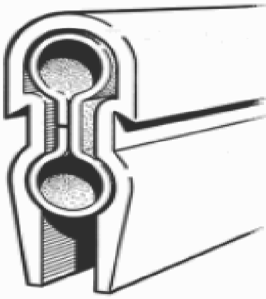


Image 8: 8 Bar conductor**,** Conductix Inc.

Texas Hemisfair – San Antonio, TX – 1968

This 11,000' long top-running monorail, with a design speed of 12mph used Insul-8's 300A 8-Bar power rail. One person was killed and 47 were injured when two trains collided. Driver error was suspected as the cause of this accident.

Image 9: Texas Hemisfair **'68** monorail [13]

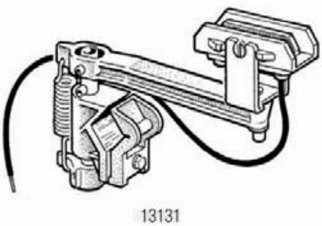


Image 10: 8 Bar collector, Conductix, Inc.

Rohr Aerotrain Tracked Air-Cushioned Vehicle (TACV), Pueblo, CO 1974

This DOT test vehicle traveled at 147 mph on a 29,400' track and was the fastest wayside powered vehicle at the time. Power was delivered by 1600A, three-phase conductors at 4160V designed and manufactured by Conductix (previously Insul-8 Corp.) The test project proved the viability of aluminum/stainless steel v-contact power rails in high speed applications.

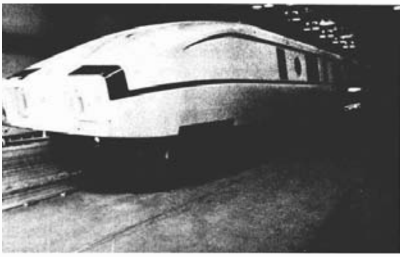


Image 11: Rohr TACV vehicle 1974, Conductix, Inc.

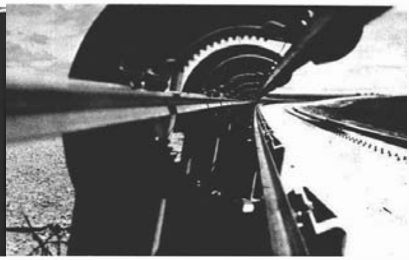


Image 12: 3-phase, al/ss v-contact power rails for TACV, Conductix Inc.

Bay Area Rapid Transit (Bart) – 1978

In 1978, BART installed 3000A aluminum/stainless steel conductors for mainline operation. This 2mm capped conductor design has been used in hundreds of miles of transit systems throughout the world since the late 1970s.

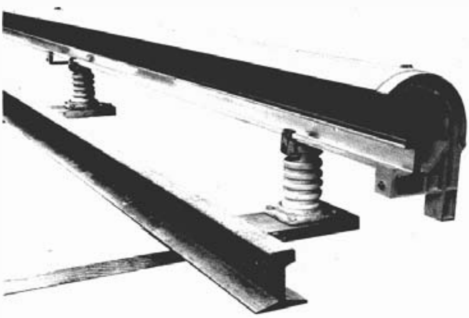
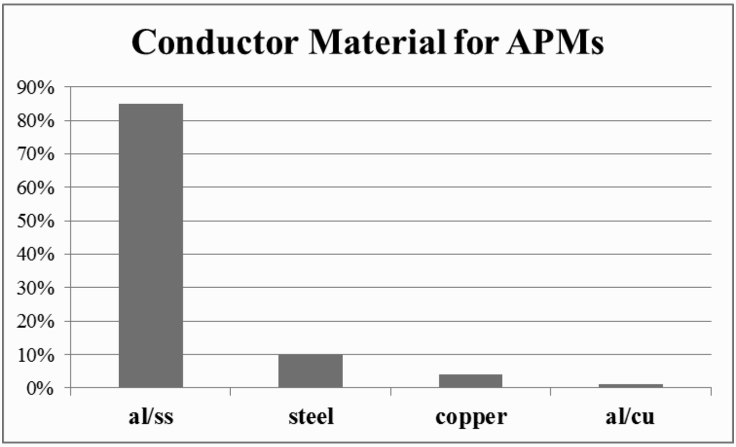


Image 13: BART 3rd rail system with conductor close-up, Conductix, Inc.

Aluminum/Stainless Steel: The state of the art in Power Rail Systems

There are approximately 140 operating APM's worldwide, with the oldest dating back to the mid-1960s. Over 95% of these employ power rail technology. Power rail types currently in use include steel, 10% (such as Chicago O'Hare, Paris Meteor), Copper, 4% (e.g. Circus-Circus in Reno & Las Vegas and Hersheypark, PA,) aluminum-stainless steel, 85% (like Morgantown PRT, Kuala Lumpur LRT) and aluminum-copper 1% (Palm Jumeirah, Dubai). (See Graph 1, below)



Graph 1. Distribution of conductor materials for APMs by type

The most prevalent and cost-effective among these is aluminum conductors with stainless steel contact surface (al/ss). The aluminum provides sufficiently low resistance (55% of copper by volume), excellent strength and stiffness, light weight, and good corrosion resistance. The stainless steel contact surface protects the aluminum from mechanical wear of the collector shoe and provides improved resistance to electrical arcing. This combination of materials provides a durable, cost-effective & electrically efficient conductor that is rigid enough to minimize the distance between supports. The relatively low cost of aluminum extrusion dies makes this an easily adaptable material to a wide variety of conductor profiles and configurations **Table 2** shows the cost advantage of aluminum over copper to be nearly a factor of 7. **Image 14** illustrates that AL/SS power rails can be made is a wide variety of shapes and sizes to suit the application.

Table 2. Cost Comparison of Aluminum and Copper as conductors

	Density (lb/ft^3)	IACS (1)	Cost ($/lb) (2)	Comparison
Copper	559	100%	$ 3.70	$ 2,068.30
Aluminum (55% IACS)	169	55%	$ 1.00	$ 307.27
				6.7

(1) IACS = percent volume conductivity compared to copper

(2) based on Dec 2012 material prices, does not include manufacturing processes

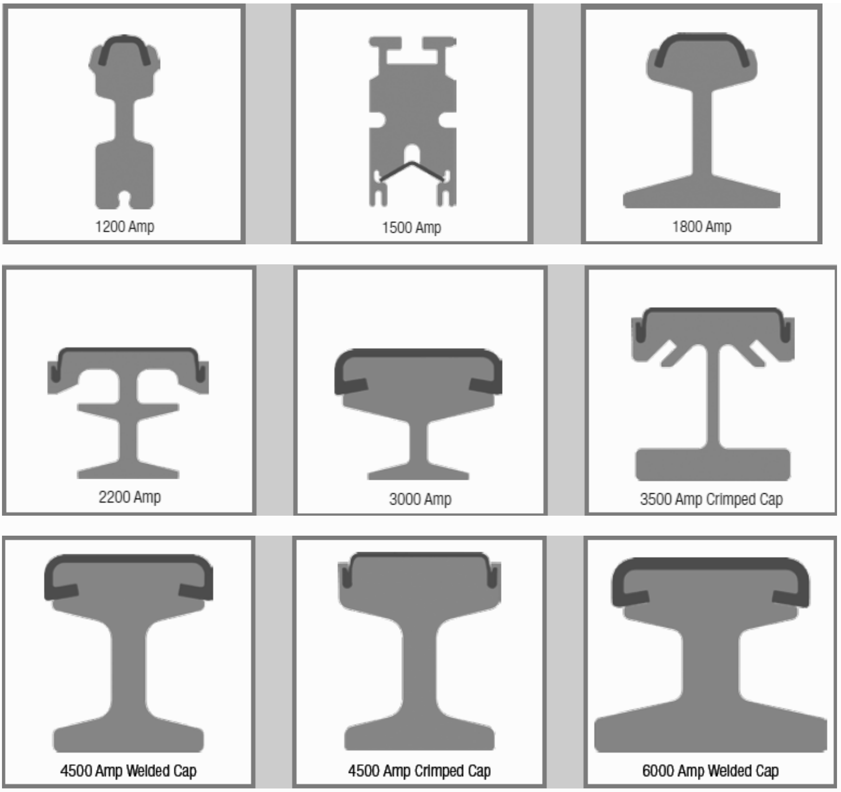


Image 14: Aluminum/Stainless Steel conductors can be produced in a range of shapes and sizes, Conductix Inc.

Extensive wear testing of al/ss power rails indicates exceptionally long life: from .21mm of wear over 93 million shoe passes with a cast iron shoe (Insul-8 Corp, 1977) to 1.43 mm of wear over 73 million shoe passes with a carbon shoe. (Conductix Corp, 2012) While performance varies among the several grades of stainless steel most commonly used, al/ss conductors provide significantly better life than copper or steel conductors. Image 15 shows a conductor wear test device developed by Conductix to evaluate conductor wear under speed and current load.

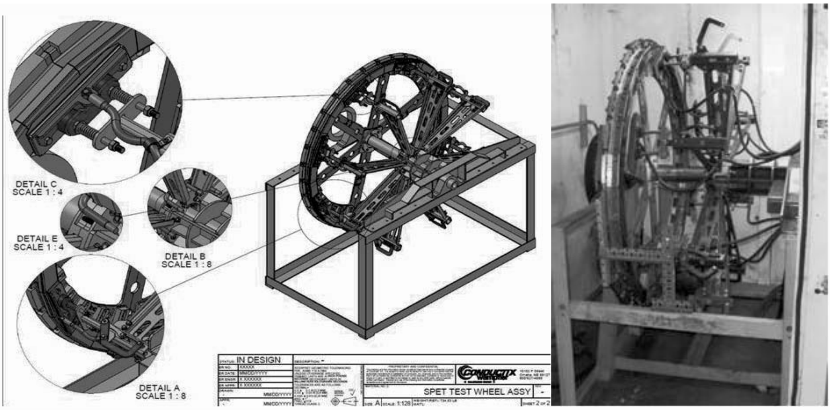
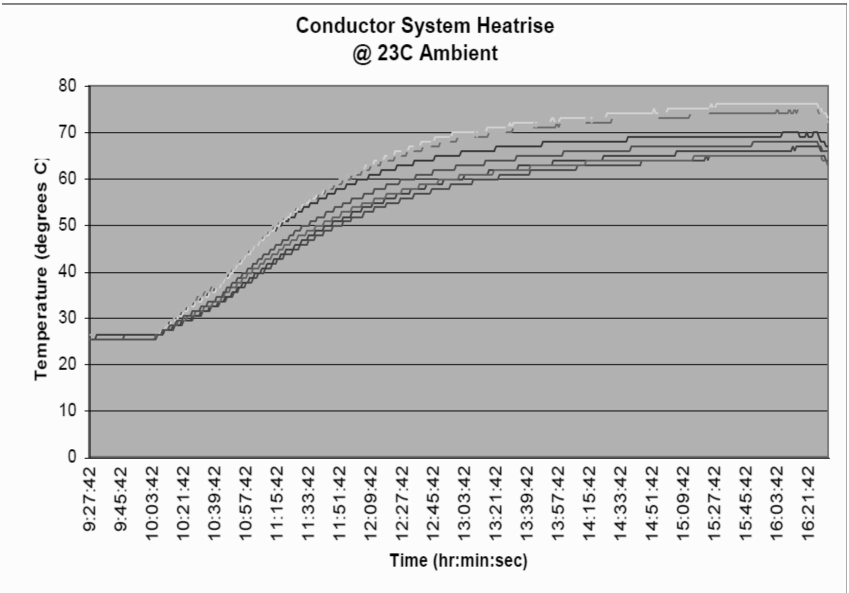


Image 15: Conductor wear test device, Conductix, Inc.

Design Variables to Power Rail Selection

Let's look at the design variables to be considered for power rail applications in APM systems. These variables are the characteristics which may vary from system to system and which may need to be accounted for through differences in design, materials and configuration.

Electrical: Understanding and meeting electrical current requirements is critical to proper power rail selection. Resistance (ohms per unit length) and vehicle current demand are the two most essential specifications for determining voltage drop and available power along the system. Although power rails are typically described in terms of their maximum steady-state current in amps, e.g. 1200A conductor, 99% of APM systems are limited by conductor resistance, rather than current rating. Therefore, the most helpful specification to the conductor rail supplier is resistance per unit length. To illustrate the arbitrary specification of current rating, the following graph shows that conductor rail temperature only stabilizes after more than 5 hours at rated current (Graph 2). This is typical of most conductor rail systems.



Graph 2. Conductor temperature vs. time at rated current, Conductix, Inc.

Where power requirements may vary widely along a given system, it is possible to use different conductors sized for specific current needs along the guideway. For example, the Jacksonville Automated Skyway Express uses a 700A power rail throughout except along the Acosta Bridge where it crosses the St John's River. Here a 1050A conductor was installed to provide sufficient power to the vehicles to climb the relatively steep grade. The different profiles can be spliced one to another and are interchangeable. This provides economy by using the same insulating cover, hangers and splice covers for both profiles (Image 16.) A similar approach was applied for the Kuala Lumpur LRT2 system where 4500A conductors were used for mainline power with 3500A conductors in the depot areas (Image 17.) By keeping the bottom flanges of the two conductors identical, only one insulator design was needed for the system.

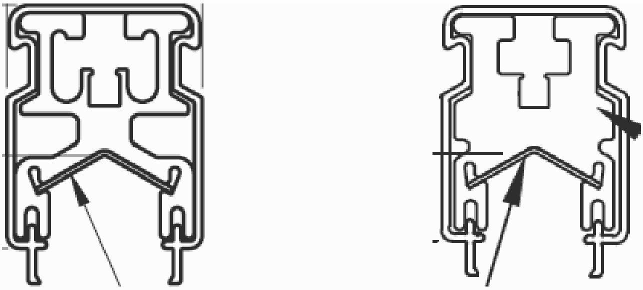


Image 16: 700A and 1050A profiles from the Jacksonville Automated Skyway Express are interchangeable, Conductix, Inc.

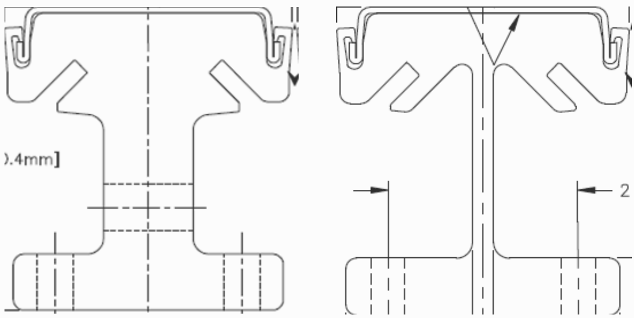


Image 17: 4500A and 3500A profiles from Kuala Lumpur LRT2, Conductix Inc.

Voltage, typically 600 or 750VDC or 480VAC, is the primary driver of insulating levels and creep distances for insulating materials. Environmental conditions (e.g. UV exposure, moisture, pollution levels, etc.) have a significant impact on the effectiveness of insulating materials and should be included in the system specification. Insulators must be designed with the necessary geometry and materials to meet system requirements. Image 18 shows a 750VDC insulator.

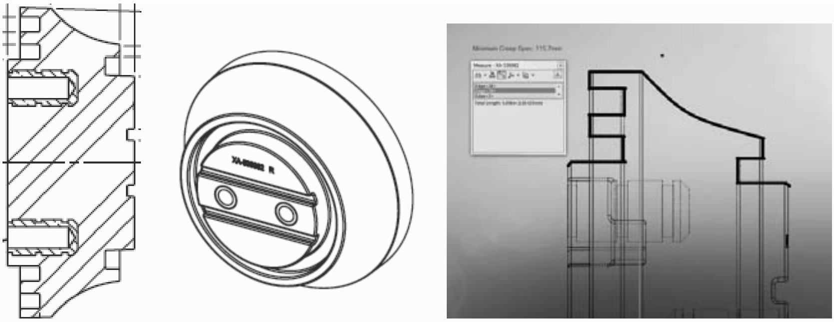


Image 18: Section & Iso views of 750VDC insulator (left) and outline of the electrical creep distance (right), Conductix, Inc.

Proper positioning of power rail feed points (cable attachment points) is another important and often overlooked electrical criterion. Ideally, feed cables should be fine-stranded, extra-flex or DLO type to allow for thermal movement of the conductors. Stiff cables act as anchors, preventing proper conductor movement, resulting in damage to conductors, insulators, hanger brackets or all three. When flexible cables cannot be used, power rail anchors must be located near the power rail feed points.

Mechanical: Mechanical considerations are every bit as critical as electrical requirements in proper power rail selection. Thermal movement, attachment to the guideway, deflection between supports, and flexing under a variety of load conditions must be addressed early in the system design.

Thermal management of conductors is of critical importance – both in absolute terms due to ambient temperatures and current heating of conductors as well as relative movement of the conductors to the guideway. Poor expansion management can lead to conductor snaking, sometimes so severe that the collectors are unable to maintain contact with the power rail (Image 19.) It is essential that guideway expansion joint movement is considered along with conductor thermal movement when designing and locating conductor expansion assemblies (Image 20.) Frequently, guideway expansion details (quantity, stroke and location) are not available at the time of power rail system quotation. This can lead to bill of material and system price changes later in the project.

Secure and precise attachment of the power rail to the guideway is essential for APM system reliability as well as power rail longevity. Maintaining proper position of the power rails relative to the collectors ensures contact force, contact area, and electrical transfer efficiency remain within acceptable ranges through the life of the system.

Adequate electrical clearances must be provided between live power rails and vehicle and guideway elements (Image 21.)

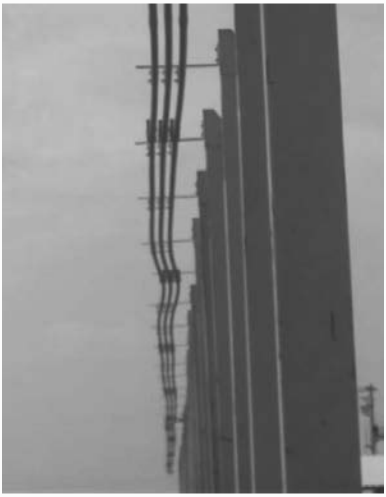


Image 19: Poor expansion management can cause conductor snaking and loss of collector contact, Conductix Inc.

Image 20: Curved Guideway section with an expansion (long overlap cover) between two splice assemblies, Conductix Inc.

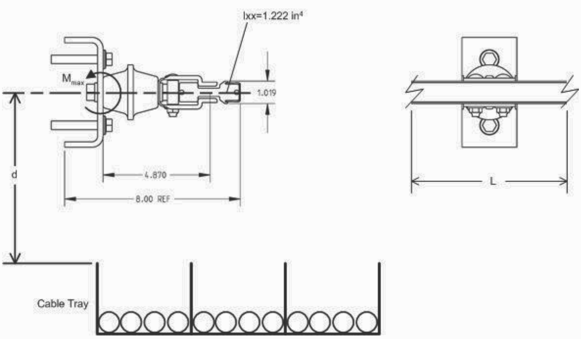


Image 21: Typical elevation view of power rail and clearance to a guideway element, Conductix, Inc.

Any condition which creates loss of or intermittent contact of the collector shoe with the power rail can result in excessive electrical arcing and damage to the conductor contact surface. When electrical erosion occurs repeatedly along a section of power rail, it often creates a "cheese grater" effect. This hard, sharp contact surface can severely shorten shoe life. If not detected in time, the combination of severely worn shoes and conductor surface pitting leads to a rapidly downwardly spiraling condition, often requiring the replacement of the damaged conductors.

Power rail system strength is also of critical importance not just for normal conditions such as management of thermal movement, but also for abnormal conditions such as fault current forces and damaged collector conditions.

Environmental: Environmental conditions vary widely, from the controlled environment inside an airport to tropical, desert, or temperate climates. Each poses unique considerations to ensure the highest reliability at the lowest possible life-cycle cost.

In regions of high solar radiation, insulating covers, insulators, cables and accessories must be selected for UV resistance (Image 21). Typically, these regions also have high temperatures, so thermal resistance must also be considered. With regard to temperatures, plastics are typically the most sensitive of the power rail materials to high temperatures; therefore it is strongly recommended that material certifications be provided for all plastic components.

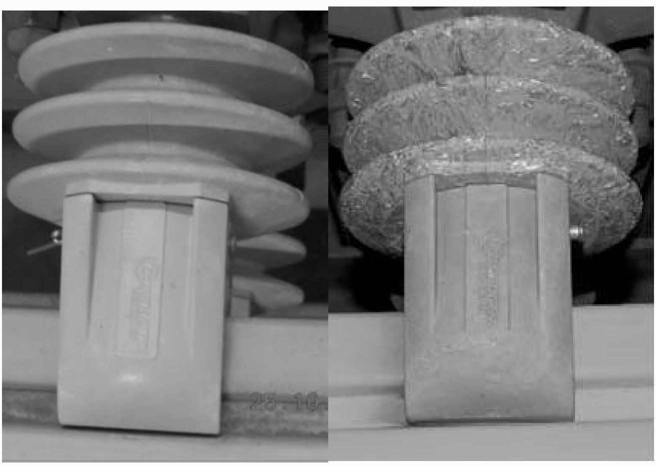


Image 22: UV degradation (right) typically only reduces the aesthetics of power insulators without decreasing dielectric or mechanical strength, Conductix, Inc.

Precipitation can also be problematic. One APM in a tropical environment with lateral conductor contact exposure suffers exceptionally high shoe wear after each heavy rain. This is due to the removal of the graphite deposits on the conductor contact surface. The rate of shoe wear stabilizes to acceptable levels after sufficient vehicle passes deposit a fresh coating of graphite. Orienting the conductors with the contact surface facing down (i.e. “bottom running”) prevents this problem.

In cold climates, heater wire systems can be effective in preventing the formation of insulating frost on the conductor contact surface. They are not intended to act as thawing systems for the removal of existing snow and ice. Heater wire systems must be programmed to go on before freezing temperatures are reached and should be a part of a comprehensive cold-weather management approach.

In hurricane and typhoon regions, conductor system must survive extremely high winds. Insulating covers are most vulnerable to this extreme condition. The insulating covers can be designed to stay in place but there remains no practical way to keep cars, trees and buildings from affecting the survival of the power rail system!

The flexibility of al/ss conductors renders them highly resistant to seismic loading. In fact, al/ss conductors have been installed through switches joints where they are flexed thousands of times through 15^{o} or more. Image 22 shows conductors permanently installed in a multi-position switch. Switch movement greater than 20^{o} will require a discontinuous solution such as shown in Image 23.

Image 23: 400A conductors installed at the point of a multi-position switch, Conductix, Inc.

Image 24: Transfer caps are commonly used to manage collector shoes across switch gaps, Conductix, Inc.

Aesthetic: Ideally, the power rail system should be as unobtrusive as possible and in harmony with the other guideway elements. For covered systems, this can be accomplished by color-matching of the insulating cover and accessories to the guideway. Even in the worst case, power rail systems cause less aesthetic concerns than overhead catenary wire systems.

Design Constants to Power Rail Selection

Experience indicates that, equally important as design **variables**, there are also **constants** which must be diligently addressed. These constants address the high degree of design coordination required between the APM system supplier and the power rail for project success.

Give adequate consideration to power rail early in the APM design process. If the power rail fails, the APM fails.

- Although the power rail is less than 5% of an APM system's total cost, it bears an inordinate amount of consideration due to its role in system reliability and life-cycle costs.
- The more detailed and complete the power rail specification prior to the request for quotation, the greater the likelihood of a firm price with on-time delivery.
- The further along the system design, the more disruptive (to schedule and budget) will be any changes.

Some general design rules for power rail include:

- **Consider that moving switch elements have components that may wear with time.** If such wear changes the alignment of the power rail across the switch gaps, collectors and or power rail elements at the switch may be damaged. One should either design the conductor supports at the switch ends to be adjusted with switch wear or design switches such that the fixed and free ends will maintain alignment throughout their design life.
- **Decelerate vehicles across power segmentation gaps.** It is best to coast or decelerate across power segmentation gaps (isolations) rather than accelerate. Hard vehicle acceleration across isolations increases electrical arcing and electrical erosion of the conductor contact surface. This is where close coordination of the vehicles' performance profile, PDS design, and power rail component positioning pays dividends.
- **Ensure adequate collector shoe redundancy.** Second only to electrical erosion from arcing across gaps is the deleterious effect of excessively high current densities at the collector shoe/conductor interface. This can pit and

destroy the conductor contact surface, regardless of the thickness of the material.

Installation:

- Be certain that the power rail is installed to the manufacturer's specifications. By including installation training and inspection in the power rail supply scope of work, you can make the power rail supplier a partner in your success. Use their expertise to help manage project risk.

Maintenance:

- Perform proper and routine maintenance. This sounds almost too obvious to mention. But too often, the O&M Manuals are not read and followed. Include training for the maintenance staff in the project scope of work.

Partner with the Power Rail supplier:

- Keep the manufacturer informed of system performance throughout the service life. Feedback is invaluable to power rail suppliers for the continuous improvement of their products and services. When the OEM to whom the power rail system was sold is not also the operator, the power rail supplier is often left in the dark about the system performance. In some instances, extended warranties may be available where the power rail supplier provides free 6 and or 12 month system inspections.

Conclusion: Power rail is not the only method for power APM's, it is however, the most common. It affords the APM system designed considerable flexibility to meet a wide range of operational, economic and safety requirements. APM system designers are encouraged to work closely with the power rail supplier to manage the **variables** to power rail design by developing complete and accurate specifications. Careful attention to project **constants** such as close design coordination early in the design process is necessary to overall project success.

Acknowledgement

A special thanks to Mr. Richard Prell for sharing his wealth of experience and knowledge of power rail systems.

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Energy optimization for public transportation applications

Nicolas Urien[1]

[1]Siemens SAS, Infrastructure and Cities sector, Rail Systems division, Urban Transport
Product Manager : Automatic People Mover systems
BP101, 92323 Châtillon cedex France; nicolas.urien@siemens.com

Abstract

Siemens offers infrastructures and intelligent power-management solutions that allow towns and cities to reduce their environmental footprint and to improve quality of life for their residents.

Among the broad Siemens' transportation portfolio, our APM solutions – first implemented in France in 1983 and now in operation on 12 different airport or urban mass transit lines worldwide – bring significant contribution to energy savings.

Thanks to our Val, Cityval and Airval systems we provide mass transit operators and authorities as well as airport infrastructure managers with efficient, proven and eco-friendly transportation solutions.

The purpose of this paper is:

- First to explain the energy consumption chain for an APM. It includes a presentation of the solutions we have integrated in our product lines Airval and Cityval (Siemens' state-of-art APM solutions resulting of the Neoval R&D program): system operation, vehicle performance and components.
- Second we will present solutions successfully implemented by Siemens to optimize energy consumption on existing metro lines:
  - Coasting mode, as for instance designed for Paris metro line 14 with Siemens' CBTC and which results in an average energy saving of 16%
  - Regulation of train dwell-time, which has been implemented on the 1st metro line of Torino operated with a Val 208 APM system with a saving of 3 300 MWh per year.

Urbanisation and environmental concern lead Siemens strategy

Siemens organisation and strategy is guided by the observation of the overall evolution of the world economy.

Key facts were analysed in four global trends:

Demographic change

- Tremendous increase in world population to 9 billion in 2050 vs. 7 billion in 2010
- Aging of societies: Generation 65+ almost triples until 2050

Urbanization

- Urban population expected to increase to ~70% in 2050 vs. ~50% in 2010
- Numerous megacities arise, especially driven by growth in emerging markets

Climate change

- Climate change is a fact, threatening humans and biosphere
- Costs of inaction will exceed costs of taking early action by far

Globalization

- Increasing interdependence of economies, politics, culture & other areas of life
- BRIC countries with strongest growth: China outruns U.S. in GDP before 2040

Siemens answers to urbanization trend

The **Infrastructure & Cities Sector** offers sustainable technologies for metropolitan centers and urban infrastructures. The portfolio encompasses integrated mobility solutions, building and security systems, power distribution equipment, smart grid applications, and low- and medium-voltage products.

The Sector consists of the following Divisions:

- Rail Systems
- Mobility and Logistics
- Low and Medium Voltage
- Smart Grid
- Building Technologies

Val, Cityval and Airval APM systems constitute the mid capacity rubber-tyred metro offered in the Rail Systems portfolio.

In airport applications, as feeder line in metropolitan areas or as backbone in midsize cities, Siemens APM systems provide a real opportunity to develop attractive public transport.

Energy for transport

Railway accounts for only two percent of green-house gas emissions related to transport– whereas the transport of people and goods is responsible for a total of 25 to 30 percent of the world's overall energy consumption.

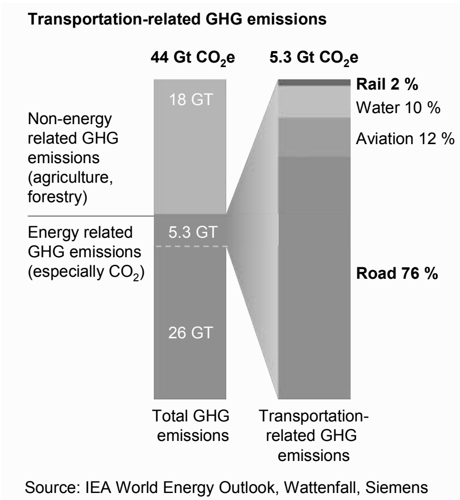

Figure 1 : Green House Gas emission Figure

Reduction of energy consumption in megacities requires a combination of solutions. The coordination of numerous measures to increase the energy efficiency of buildings, a greater emphasis on public transport and electric mobility, and the use of low-carbon energy sources actively contribute to cleaner cities.

Though public transport accounts for a relatively small share of the global energy demand (and the global electrical power demand), its quick growth combined with the pressure that energy consumption is generating on fare prices make it a fully relevant concern that Siemens wants to address globally and meticulously.

Energy consumption in an urban transport system

Consumption in a metro system consolidates parts for which a global optimum has to be found. Many of the different parameters are bound, sometimes indirectly, which makes the global optimisation more powerful than an action on individual parts.

Some contributors do not directly depend on the transport demand -for example wayside auxiliaries (stations equipment, HVAC[1] and lightning) – others are directly and not linearly linked to the way the line is operated.

Mechanical losses increase at a quadratic rate with speed and electrical losses with current intensity: a trivial solution would be to reduce speed and acceleration. This cannot be considered because performance of the transport system (passenger throughput; commercial speed) remains a top-tier criteria. For this reason we do not consider solutions that have a significant negative impact on line performance.

Traction related energy is the most significant (approx 75%) part of the required energy. We will analyse it at first.

[1] Heating Ventilation & Air conditioning

Speed and current profile for a single run

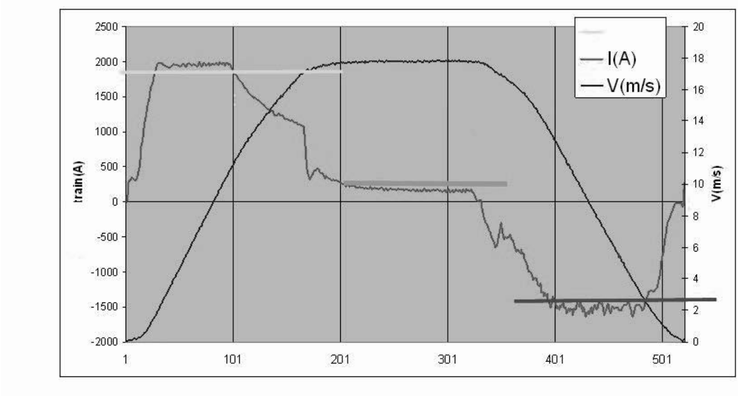

Figure 2 : Graph, Intensity/Voltage for one section between stations (Siemens)

When a vehicle goes from one station to the next, at first it accelerates with high power consumption until it reaches its target speed (phase shown in yellow on Figure 2). In a second period a steady speed is maintained and the required power is limited to the compensation of losses (plateau speed in phase shown in green on Figure 2). When approaching the next station the braking process begins. Electric brake process recovers kinetic energy (phase shown in blue on Figure 2).

Almost every electric urban transportation system follows these typical speed and current profiles.

On a metro line, a full set of vehicles is running in carrousel. The total required energy for the line sums the individual train consumption profiles and losses in power-supply in a consolidated energy demand.

The following graph gives a global overview of the power transfer from the grid to its final use:

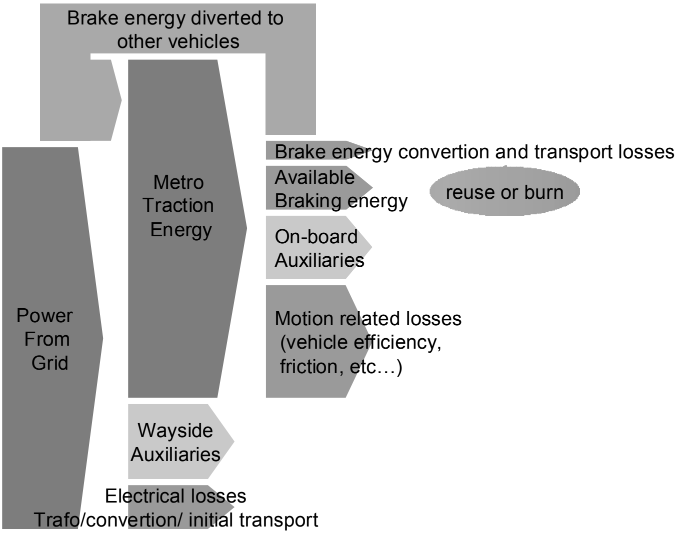

Figure 3 : Drawing, power transfer in a metro system (Siemens).

The relative importance of the different power consumption is depending on the application. RATP[2] (Operator and transport authority of Paris-France) considers that 75% of power is used for traction. Brake energy recovery may vary from 0 to 40% of the traction energy.

In order to maximize energy saving, Siemens has investigated each and every of the reduction potentials:

- Maximizing reuse of brake energy,
- Maximizing efficiency in conversion into motion,
- Limiting auxiliary consumption.
- Minimizing electrical losses

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[2] Régie Autonome des Transports Parisiens

Energy efficiency of Siemens APM

Cityval and Airval APM systems are the continuation of our proven Val systems. The new generation was developed within the Neoval R&D program framework, with environmental focus and energy soberness principles.

Figure 4 : Photo and 3D views of Val 208, Cityval and Airval (Siemens)

The Neoval R&D program has systematically considered energy efficiency during design and development phases.

We are presenting the main results hereafter

High vehicle efficiency:

- Minimise in train losses
- Economy running modes

High system efficiency:

- Maximise brake energy recovery
- Lower energy conversion
- Limit auxiliary consumption

Additional solutions for off-peak hours

- Storage and redirect solutions

All of the above methods contribute to energy savings. But there is also a positive side effect in reduction of network current peaks which gives an additional benefit on Joule effect losses

Cityval vehicle design for high motion efficiency

Choosing the most efficient components for the traction chain was a permanent objective of our design engineers. Electrical and mechanical parts of the traction chain were designed in order to maximize electrical energy transformation efficiency, to generate train motion but also to optimize energy recovery during the braking process.

Cityval and Airval are equipped with high efficiency permanent magnet synchronous motors allowing powerful pure electric braking from high speed to complete stop of the train. Friction braking is therefore only used in exceptional cases for emergency braking.

Economy running modes

Cityval and Airval use, Siemens Trainguard MT CBTC[3]. This automatic train control system includes moving blocks and integrated interlocking. It gives the freedom to

[3] MT : Mass Transit; CBTC : Communications-Based Train Control

define economy mode that locally minimize the required energy for one run in a given time.

A typical example of economy running mode is coasting.

Coasting (which basically consists in stopping traction halfway between stations, and let the train forward momentum carried ahead until it brakes for the next station, see Figure 5) appears in many cases to produce a significant reduction of energy spending but may hinder performance.

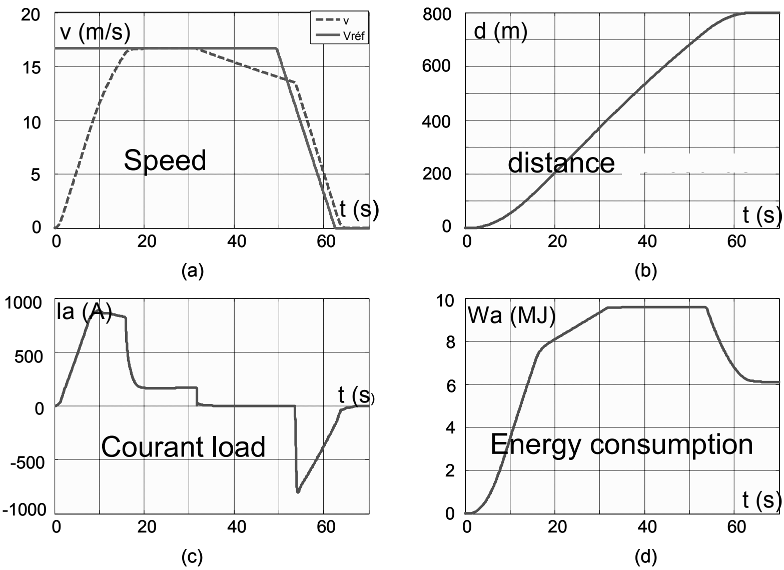

Figure 5 : Graphs, coasting mode on one section between stations (Siemens)

Coasting mode has a tendency to reduce commercial speed. This can be compensated by a higher maximal speed so that final reduction of energy is a balance between conversion efficiency and mechanical losses which is depending from the configuration (Paris line 14 later in this paper gives an example of positive result).

It is important to keep in mind that at system level, for a given passenger demand, a lower commercial speed is not only reducing transportation attractiveness but the running fleet has to be extended which in the end balances the expected energy consumption reduction.

Coasting mode is only worth during peak hours when fully compensated (equivalent commercial speed).

During off peak hours, there are fewer constraints on the system. This enables more opportunities to reduce the required energy. It remains a non trivial balance between running mode, train regulation and running fleet.

Siemens is developing dynamic evaluation methods and tools to determine the most interesting combination of local savings and global balance of brake energy recovery as developed in the next chapter.

Maximise regenerative braking at line level

Electric braking allows kinetic energy to be transformed back into electricity which the braking train injects back into the feeder network. Cityval and Airval vehicles are able to operate with electric-only braking (with no resort to friction brake outside of degraded modes) and to deliver this recovered energy back to the continuous current network.

This Thigh power energy has to be diverted to an appropriate consumption element being another train in traction phase using the same power range. Proximity between trains is a key efficiency factor, because of Joule-effect losses that must be considered at this level of current in the power rail.

As trains are running in carrousels, making sure a train in traction is close enough to the braking train in order to have a receptive network is a very efficient solution.

Thanks to Val concept of short & frequent vehicles, the relative position of vehicles can be more easily regulated so that the brake energy is transferred to a neighbouring tractioning train (most of the time on the opposite track). Tuning this synchronisation frequently represents a variation of 35% in consumption.

The regulation associated to Siemens CBTC train control system integrates solutions for optimisation of timetable in order to define optimal regenerative programs (taking into account rush hours, off peak hours and transition phases).

Operational variations from the scheduled plan may disrupt the optimum balance of the programmed timetable. In order to maintain energy efficiency during perturbed periods Siemens is leading a research program to determine the optimal system reaction to service disturbance that also maximises the energy efficiency.

During off-peak hours the higher distance between trains makes this energy recovery more difficult to achieve so that electricity might remain in excess for some seconds: so called "available braking energy" on Figure 3 above. .This remaining energy might be recovered for short term storage, or converted and sent back to the grid. Both methods are developed later in the text.

Lower energy conversion

Less electrical to mechanical conversion via less mass per passenger

Lower tare per passenger with lighter trains or with higher filling rates is an efficient leverage on energy consumption by passenger. Adaptation of the offered capacity to the effective demand is the key lever for filling rate. Fully automatic train operation especially with relatively small units enables rapid adaptation of the transport offer.

In the Cityval and Airval systems, unattended operation of short vehicles allows a quickly variable transport offer to permanently fit to passenger demand.

Keep Mechanical Energy:

Mechanical energy can be converted and stored as potential energy or as kinetic energy. Potential energy is transformed into kinetic energy by a descending slope and backward by an ascending slope. Were it is possible the profile (and the associated speed control) can be defined to take advantage of this effect.

Airval and Cityval track with low constraints in vertical radius for inflections does not only help for insertion but also for realising such a track profile.

Limit auxiliary consumption

In parallel with service performance, passenger comfort is another key factor for transportation system attractiveness. Reducing comfort is not an alternative. On the contrary thermal comfort on quay and dynamic information of passengers as well as security and accessibility equipments are now requested by almost every customer.

Val, Airval and Cityval systems, with shorter vehicles and shorter intervals offer high passenger throughput with shorter stations. Shorter stations reduce the energy diverted in the civil-works realisation and in its energy consumption. In addition it increases the feeling of security for passengers.

Store or redirect brake energy

Energy recovered from electric braking has to be transferred from the generating train to another consumer. For certain tracks or during off-peak hours the transfer to another train in the area is not sufficient; Storage and reconversion solutions were investigated and integrated in the portfolio.

On-board storage :

On-board storage provides to a single train the opportunity to re-use energy locally (no energy transport losses). This storage changes radically the train's current profile demand by cutting current peaks in braking phases as well as traction phases; which reduces current peaks on the continuous current network and allows to reduce the dimensioning demand for substations. Siemens has developed Onboard Energy Storage devices.

Figure 6 : Photo, Super-capacitor module Siemens SITRAS MES/SES

Sideway storage :

The 750V CC power supply line can be complemented with wayside storage units.

Siemens SITRAS Stationary Energy Storage (Figure 6) is based on Ultracap technology. Available brake energy is stored and returned as soon as demand appears in the vicinity.

Siemens system engineering process includes analytical methods to determine, the appropriate positioning and dimensioning of stationary storage units.

Redirect energy to the public grid Network:

When the public grid allows it, DC/AC conversion can be added to the substations in order to redeliver available brake current back to the grid.

Siemens Smart Grid-Rail Electrification department has developed a complete set of bidirectional substations.

Energy consumption reduction on existing line

Energy efficiency and consumption reduction is not only a topic applied to new APM projects but also part of Siemens offering to existing urban lines. Several Mass Transit lines, already benefit from the implementation of Siemens know how in energy conscious operation planning.

We develop hereafter two examples that illustrate how full automation (with unattended train operation) played a major role in the implementation of energy saving. In these projects, energy cost reduction implementation demonstrates its efficiency and attractiveness.

Paris Line 14 (Meteor) : Optimize operation efficiency

The 14th line of Paris Metro, operated by RATP, is running in commercial operation since 1998 and was the first heavy metro system to run fully automatic GoA4 (Grade of Automation 4) unattended operation. This line is now 9.1 km long and total journey time is less than 15 minutes.

Siemens realised the man-less automation with its Trainguard MT CBTC system.

The system is running with a commercial speed of 40 km/h and with train intervals of 85 s during rush hours.

RATP engaged a project for finding energy reduction and entrusted Siemens for upgrading on-board and regulation software.

After a 7-month test phase the system has been activated in 2010 on all trains in operation. The annual line consumption was reduced by approx 5500 MWh.

The implemented process is based on coasting mode, in a configuration that maintains the line performance during rush hours

The running profile during peak hours enables preservation of the travel time between stations next so that the average speed remains identical. Acceleration is maintained up to a higher speed than in normal (plateau speed) mode, until the train reaches the coasting point (point where the traction is completely shut down and the train continues on its forward momentum).

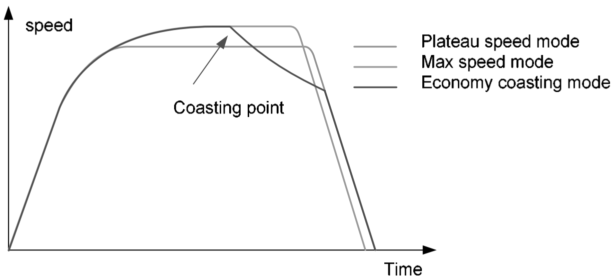

Figure 7 : Graph, speed profile on a give section between stations (Siemens)

On line 14 the balance between motor efficiency and running resistance force is positive, this running mode is consuming less than the normal plateau speed mode. It has been adopted for peak hours.

During off-peak hours, required energy is already lowered by the reduced number of running trains (some vehicles are stored in garage areas). We wanted to take benefit from the reduced pressure on average line speed to reduce it further. For a given transport offer, the system and the customer tolerates a little increase on travel time to reach the station (small degradation of the commercial speed).

A low energy profile (economy coasting mode on Figure 8) is defined with power limitation (lower acceleration rate) and coasting.

This profile is the resulting of a trade-off between travel time decrease and the number of required vehicles on the carrousel. Passenger transport capacity remains identical.

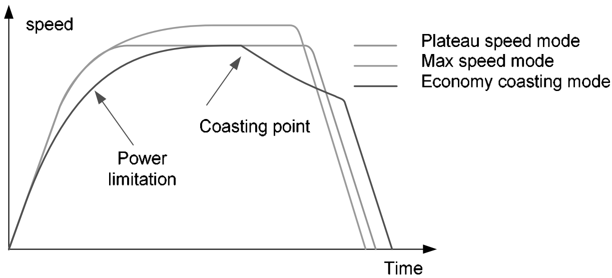

Figure 8 : Graph, Economy coasting mode with mean speed reduction

In addition to the benefit in normal operation, this more relaxed running profile makes it easier and less energy consuming for a slightly delayed train (i.e by operational variation, such as a door blocked by a passenger) to recover its schedule. This has a positive side effect on the required energy for regulation.

Coasting mode also reduces friction brake demand. This showed unexpected additional benefits to our customer in terms of wear and particle emission and then on air-quality in stations.

Val Torino : Optimised Timetable

Torino Line 1 is a fully automated APM system without on-board attendant on a 9.5 km track, transporting 23 000 pphpd. It is in commercial operation since 2006.

The system is running 52 m 4-car Val 208 trains, with a high level of availability and a very short (64 s) headway.

Energy efficiency project :

In order to improve energy consumption, Siemens helped the operator to tune its time tables and to choose the right parameters in terms of interval, turn-back delay and dwelling time. The implementation of the new preparation software allowed the customer to reduce its annual consumption of approximately 3300 MWh.

Conclusion

Energy optimisation is a tight combination of diverse factors and methods for which Siemens engineering team is prepared to help its customer to find the most accurate settings in each particular case. Those tools and methods have been successfully implemented with substantial results on existing fully automated lines.

Siemens Cityval and Airval rubber-tyred APM integrate energy sobriety by design. The APM turnkey integrated system conception allows Siemens to combine those means in order to reach a global optimum on the complete transportation system.

Energy Management Solutions for "Green" Transit Systems

Salwa Fouda[1], Ph.D., Todd Hollett[2] and David Gao[3]

[1]Product Manager, Bombardier Transportation, 5095 Taylor Kidd Blvd., Kingston, ON, K7K 2H6; Ph. (613) 384-3103 ext. 4738; email salwa.fouda@ca.transport.bombardier.com
[2]Power System Analyst, Bombardier Transportation, 5095 Taylor Kidd Blvd., Kingston, ON, K7K 2H6; Ph. (613) 384-3103 ext. 4432; email todd.hollett@ca.transport.bombardier.com
[3]Power System Analyst, Bombardier Transportation, 5095 Taylor Kidd Blvd., Kingston, ON, K7K 2H6; Ph. (613) 384-3103 ext. 4754; email david.gao@ca.transport.bombardier.com

ABSTRACT

Environmental and economic trends are driving transit system authorities to reduce system capital costs and identify opportunities for operating efficiency improvements. The factors driving these trends include rising energy costs and tightening public budgets. Operators face the challenge to select the appropriate technology and mode of operation that will provide peak performance, lowest operating cost and the smallest environmental footprint while minimizing energy consumption.

As a case study, Bombardier performed a detailed feasibility study for a very complex transit system. Using its *EnerGplan* simulation tool, the Energy Management Team conducted an annual energy-consumption baseline analysis, which agreed with actual field measurements. Then performed a detailed analysis to determine the optimal *EnerGstor* solution required for this system and quantify the potential annual energy savings and reduction of CO^2 emissions.

Introduction

Many technologies available in the market today claim to achieve significant energy reductions, but can be very expensive and largely ineffective if used inappropriately. In certain applications such devices may even lead to degradation of transit system performance. Bombardier Transportation's Energy Management Solution provides the means to design an optimized transit system and evaluate the impact of different energy saving technologies on the network through our proprietary simulation tool: *EnerGplan*.

This simulation tool can also provide an analysis of the optimal power system configuration such as location, rating and setting of energy storage devices to minimize energy consumption. A distinguishing feature of the simulation tool is the ability to model both the train and power system simultaneously and interactively to determine the effects of power system voltage drop on train performance.

Bombardier Transportation's Energy Management Solution also offers *EnerGstor* technology: Bombardier's new wayside energy storage system (WESS). In a typical transit system, trains are configured to provide energy via regenerative braking. If other trains are not available to use this energy, it is wasted through on-board resistors, wayside resistors or the train's mechanical brakes. As an energy saving device, the *EnerGstor* units captures this electrical energy for later use; as a voltage regulation device, *EnerGstor* technology evens out the demand placed upon the power supply system. *EnerGstor* units improve line voltage by charging when the power system is lightly loaded and releasing energy when the demand is high. As an emergency backup device, *EnerGstor* technology is able to provide traction power when the electric utilities normal power supply is interrupted to ensure trains do not become stranded in critical areas.

This paper is divided into three main sections. In the first section, *EnerGplan*: Bombardier's in-house simulation tool is presented. This is followed by a description of Bombardier's *EnerGstor* system. The final section summarizes the results of an energy storage feasibility study performed using Bombardier's Energy Management Solution. Although the study is based on a metro system, the energy management solution is not limited to any specific type of train or technology; it can be applied to everything from the largest metro systems down to the smallest people-mover applications.

EnerGplan: Bombardier's in-house Simulation Tool

The *EnerGplan* tool is an in-house designed operations and load-flow simulator comprised of user-friendly, graphical modeling and real-time simulation analytical interfaces as shown in Figure 1.

EnerGplan technology offers generic modeling capability. The alignment is constructed using drag-and-drop guideway elements such as tracks, stations, turnouts and chainage equalities. Alignment profiles can be modified manually or easily pasted into in the software from existing data.

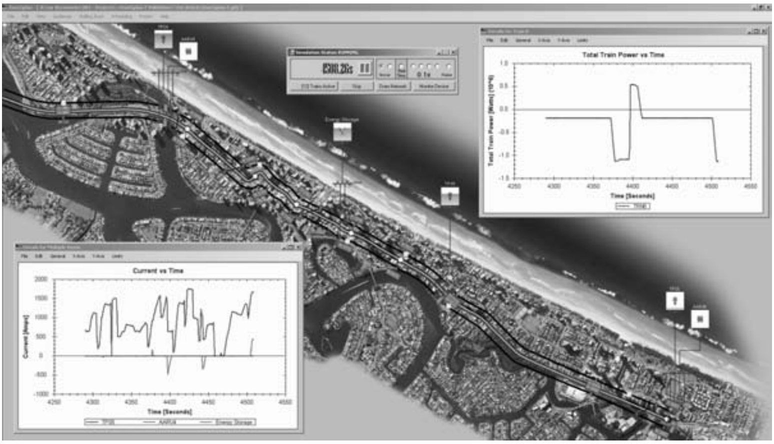

Figure 1. EnerGplan Tool Screenshot during a Load Flow Simulation

The simulator is capable of simultaneously simulating independently operated multiple train routes. The scheduling menu allows the user to assign unique properties such as color and dwell delay to each vehicle for easy identification of specific vehicles and to mimic realistic operational scenarios during simulation.

The *EnerGplan* tool's load-flow analysis capability allows analysts to optimize the power supply and distribution and energy storage systems. The energy storage system interface of the *EnerGplan* software is shown in Figure 2. It is very important to the customer to provide a turnkey system that is optimized to suit their requirements. Bombardier's experienced engineers use *EnerGplan* technology to design, analyze and optimize all types of systems. Due to the simulator's flexibility, various scenarios can be modeled easily and comparative analyses conducted in a very short time; therefore, several options can be provided to the customer based on a complete business case study.

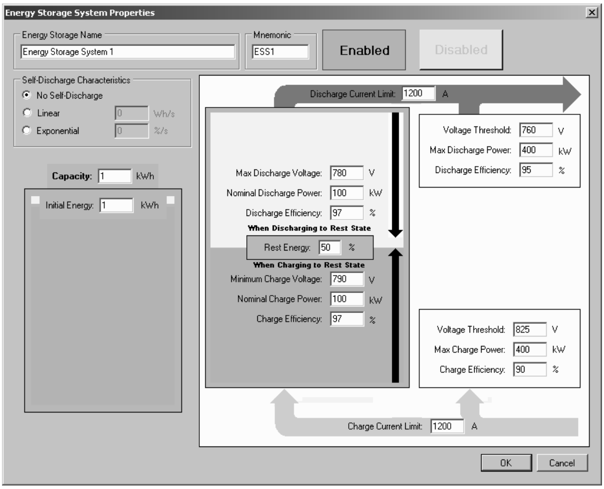

Figure 2. EnerGplan Technology's Energy Storage System Interface

EnerGstor: Bombardier's New Wayside Energy Storage System

The *EnerGstor* solution is Bombardier's new ultracapacitor-based wayside energy storage system (WESS) that captures and stores the otherwise unusable regenerated braking energy and recycles it back into the system. *EnerGstor* technology provides both economic and environmental benefits. The potential economic benefits include reducing the capital cost of a new transit system (or expansion of an existing system) and reducing the ongoing energy costs of transit system operation. Potential environmental benefits may include reduced energy losses (increased efficiency) of the electric power distribution system, reduced carbon emissions (depending on the source of electrical energy) and reduced waste heat generation.

Ultracapacitor technology – well known for its high performance, high duty cycle and low maintenance – is capable of holding a very high charge, which can be released in a controlled manner. *EnerGstor* technology is based on a modular design that allows individual units to be properly sized for any application. Each *EnerGstor* unit consists of one or more power cells and each power cell consists of a power converter controlling its own set of energy storage modules. These power cells are monitored by a common supervisory controller, which also provides optional wireless communication capability between the *EnerGstor* unit and the outside world. *EnerGstor* technology can be monitored and controlled locally or remotely through the internet or another network. Figure 3 demonstrates the *EnerGstor* system concept.

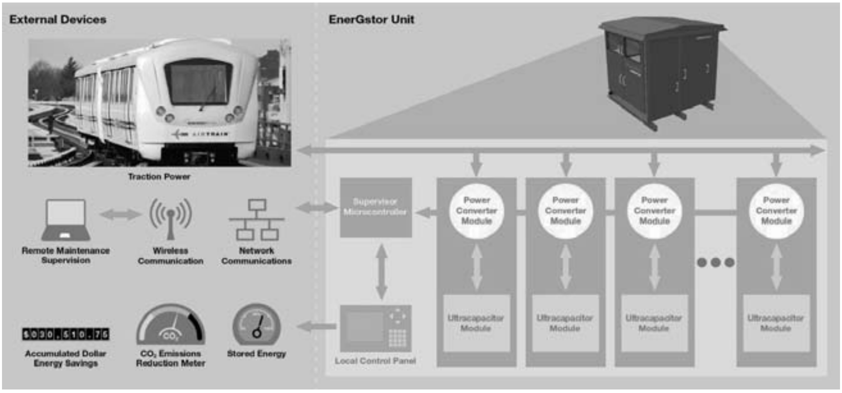

Figure 3. EnerGstor System Distributed Architecture

The energy savings achieved by the *EnerGstor* solution depends on the application. For example, if *EnerGstor* technology is installed for energy saving purposes, it can save as much as the entire regenerated energy of the transit system. The energy regeneration varies from one system to the other, ranging to as much as 30% of the total energy consumption. System receptivity must be taken into account when measuring or estimating the energy savings of *EnerGstor* technology. If installed to provide voltage regulation, energy consumption and maximum system demand will be reduced mainly during peak operating hours.

The *EnerGstor* system is currently in testing at our Kingston, Ontario test facility as shown in Figure 4. We conducted intensive lab testing successfully during 2011 and proceeded with field-testing in Q4 of 2011 when we installed the *EnerGstor* unit on our Kingston LIM metro test track (KTT). The KTT consists of a three-station continuous 1.88 km main loop, plus a spur track and maintenance facility. Completion of field testing and commencement of the production phase is planned for Q4 of 2012.

Figure 4. EnerGstor – Bombardier's Wayside Energy Storage System

Wayside Energy Storage System Feasibility Study

Bombardier recently performed a comprehensive feasibility study on a large metro system to propose an optimal wayside energy storage system solution. The analysis was mainly to optimize the quantity, location and rating of the WESS. An energy savings analysis was conducted to determine the kWh saving during the lifecycle of the WESS system. The metro system under study is a very complex system, consisting of 49 stations and 100 km of dual track guideway with five lines; each line containing multiple routes and schedule based variations in fleet operation. In addition to revenue service, non-revenue service, depot and yard activities were included in the study. The sectionalized dc traction power system is composed of both traction power and tie stations with current distributed throughout the network via a complex overhead catenary system and the running rails.

An annual energy consumption baseline analysis has been conducted and the simulated energy consumption (kWh) was compared with actual annual meter readings. Actual energy consumption will show some variation with fluctuations in operation and environmental variations; however, all-inclusive records of actual annual traction power energy consumption provided by the customer agreed to within 0.5% of the energy consumption simulated by the *EnerGplan* tool.

Bombardier employed a multi-step process to estimate the metro system energy savings and validate the results.

Saving energy by means of an energy storage system can only be achieved by recuperation and recycling of wasted energy. The *EnerGplan* tool's simultaneous train movement and network simulation approach is capable of determining this potential energy waste through accurately estimating braking resistor losses, distribution losses and line receptivity optimization through properly locating the energy storage units.

Table 1 summarizes the simulation results of the metro system that indicate the potential energy savings.

Table 1. Metro System Potential Energy Savings

	Potential Energy Savings (percentage of consumed energy)
Energy Lost to Braking Resistors	11.1%
Energy Lost to Friction Brakes	2.0%
TOTAL	13.1%

Next, location-based potential energy available to be recovered was used to determine the optimum locations and capacity of the *EnerGstor* unit. An *EnerGplan* system analysis of both the fleet and network's power and voltage profiles indicate optimal WESS locations. Twelve *EnerGstor* units have proposed at the locations depicted in Figure 5.

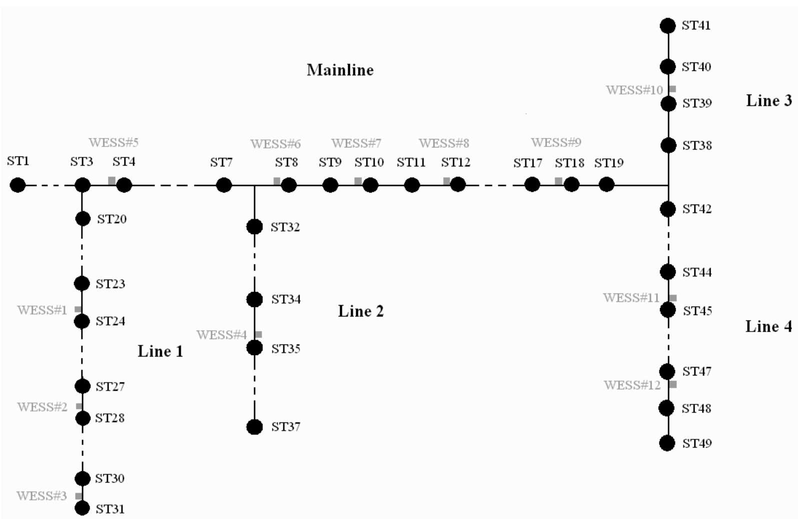

Figure 5. EnerGstor Unit Locations for the Metro System

Further detailed simulations were performed to optimize the ratings of the 12 optimal locations by attempting to recover the maximum amount of available braking energy as is practical. It was determined that *EnerGstor* technology ratings of 2 to 5 kWh per unit were best suited to this system.

Simulations show that through optimization of the *EnerGstor* unit performance settings, a savings of 10.4% can be realized. In addition, these savings do not represent the maximum capability of the energy storage system operating continuously at its full duty cycle, which would lead to an annual energy savings of 11.15 million kWh. Figure 6 illustrates the total potential energy savings and the savings per unit that are achievable based on the metro system's operating schedule.

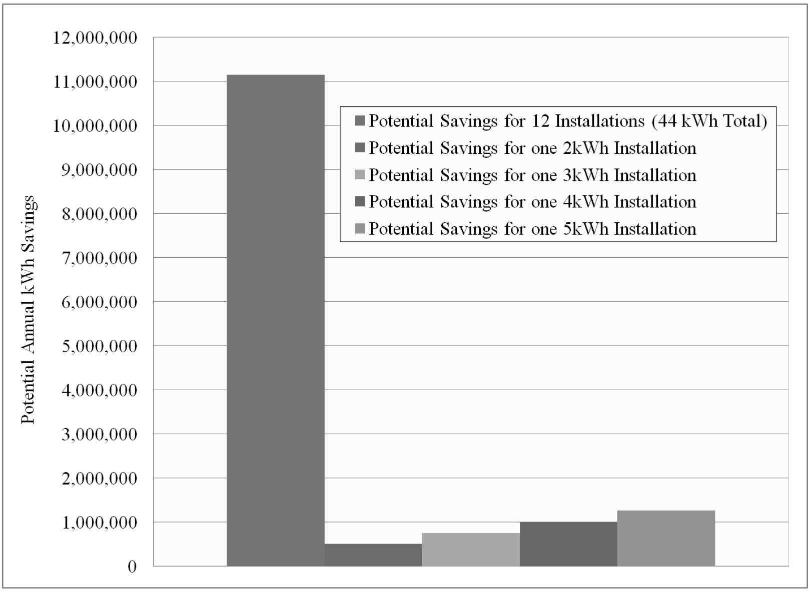

Figure 6. Potential EnerGstor Solution Savings for the Metro System

Based on the CO^2 production rate of the metro system's local power generation facilities, the energy savings estimated will have an environmental benefit of 204,000 tonnes of reduced greenhouse gas emissions over the energy storage system's 15-year optimum life span.

Conclusion

EnerGplan: Bombardier's in-house simulation tool offers an accurate means of assessing system performance and analyzing the benefits of optimized system operations and energy storage.

EnerGstor: Bombardier's ultracapacitor-based wayside energy storage system offers a high performance, high duty cycle and low maintenance energy storage solution. *EnerGstor* technology is a multi-functional system capable of energy savings, voltage regulation and emergency backup.

Bombardier Transportation has the knowledge and the tools to design and implement an energy management solution for any transit system. The energy management solution will capitalize on sources of energy waste to: save energy, alleviate demands on the power supply system and reduce negative environmental impacts. Combining the "know-how" for both system analysis and wayside energy storage hardware provides an optimized system from both a performance and economics point of view.

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Advances in Voice over IP and Passenger Information for APM Systems Utilizing Wireless Networks

Mark Kirschner[1]

[1]Manager Communications Systems, APM Center of Competence, Bombardier Transportation Systems, 1501 Lebanon Church Road. Pittsburgh, PA 15236;
PH (412) 655 – 5177; FAX (412) 655 – 5868;
email: Mark.D.Kirschner@us.transport.bombardier.com

Abstract

As network technology becomes increasingly prevalent in the marketplace, Bombardier has been adapting to capitalize on the benefits of integrating systems onto a common backbone. Each system individually has become more versatile in the process of this migration.

High bandwidth wireless systems are used to connect the wayside and vehicle networks together. This effectively extends the benefits of the wayside networks to the vehicles. Advanced data collection, monitoring, and functionality are now readily available.

Two-way passenger calls are digitized and transmitted over wireless networks. This is first demonstrated on the Phoenix Sky Train project. Likewise, high quality CCTV video streams can be sent through this same wireless network.

And finally, advertisements, Passenger Information, flight information, news tickers, etc can be sent over the same wireless network. It can then be displayed on bright LCD panels inside the vehicles as demonstrated on the Bombardier INNOVIA APM 300 platform and several other Bombardier projects.

This paper summarizes some of the challenges overcome with developing and integrating these systems together.

Converging Networks

As network technology becomes increasingly prevalent in the marketplace, Bombardier has been adapting to capitalize on the benefits of integrating systems onto a common backbone. Each system individually becomes more versatile as a result. The fixed network that interconnects stations is now capable of transparently transmitting data through the wireless network and then onto the vehicle network. In essence, the networks collapse into one encompassing network. With proper design, devices requiring high speed connections can be located on vehicles just as they can be located anywhere wired in the system.

Transmitted data can consist of many things including train location information, route map information, train operation analysis, live CCTV streams, advertisements, and digital voice conversations.

Wayside Network

The wayside network design consists of Layer 2 and Layer 3 switches distributed as appropriate through the system over a Single Mode fiber backbone. Full redundancy is employed to protect the system in case of failure. Layer 2 edge switches are placed in the guideway platform locations and along the guideway to connect with various edge devices like wireless transceivers (access points), emergency telephones, CCTV cameras, electronic signs, door intrusion control, etc.

Wayside network switches are housed in either 19” racks or in stainless steel cabinets rated for the environment.

Wireless Network

The limiting factor of the network continues to be the wireless segment. Although wireless systems can be expanded to potentially have the capacity for very large volumes of data, a practical balance needs to be made for each project. The more throughput requirements, the higher the cost. Regardless, there are technical boundaries which the market is continuously pushing forward.

As part of managing the throughput, it is vital as a Systems Integrator to manage the devices using the network. Limits have to be established for each of the systems utilizing the system. Otherwise the wireless network would be overtaxed and become unstable.

Examples of Wireless access points are shown in Figures 1- 3.

Figure 1: Photo[1] Access point on free standing pole.

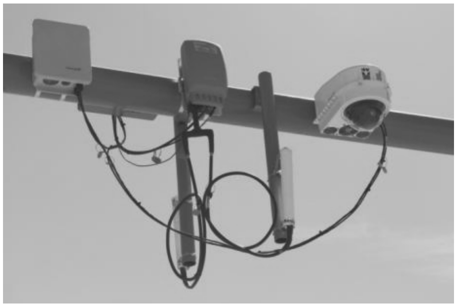

Figure 2: Photo[2] Access Point integrated with CCTV.

Figure 3: Photo[3] Access points in Maintenance Area.

Vehicle Edge Devices

Figure 4: Vehicle Edge Devices shows a number of possible connections to the network. While some devices can be connected over lower speed connectivity methods, use of Ethernet links allows for faster data transfer rates and a myriad of other advantages derived from using standard TCP/IP protocols.

For instance, the advertisement systems' signs can be accessed remotely and while the system is in full operation, the signs can be updated with new material. Software (developed by Bombardier) tracks the specific number of times the ad played completely and the number of times the advertisement was interrupted.

Route map signs and LED signs have similar remote access characteristics; they can be accessed remotely and therefore managed successfully from a remote location. If an Operator desires to install a special message to customer such as, "Thanks, for visiting our city?" they can do so with ease.

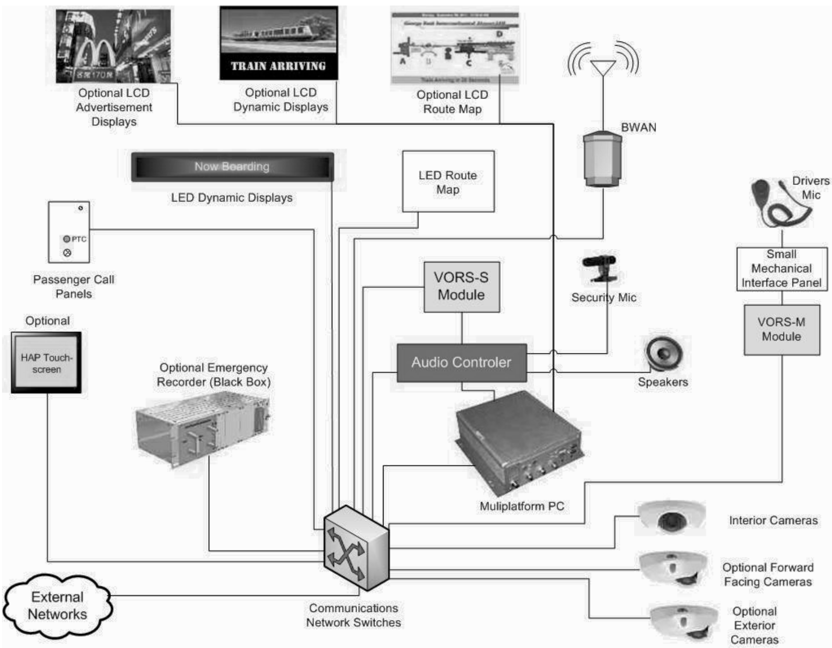

Figure 4: Vehicle Edge Devices

Audio Systems

One of the most recent challenges for Bombardier was implementing the VORS design on the Phoenix project. VORS is the VoIP (Voice over Internet Protocol) Operational Radio System. Other VoIP systems have been done on trains before, but to our knowledge, VORS is the first such type system implemented over wireless in a pure TCP/IP mobile platform. One of the advantages of developing and implementing this system over the traditional analog radio system is that the VORS system can share the infrastructure required for CCTV. Therefore, when both systems are required, a cost savings is realized.

Figure 5: Photo[4]VORS Equipment Assembly on in Compartment

VORS operates by digitizing analog audio to a VoIP protocol at each panel. These panels are for passengers. But the same technology is utilized in the drivers panels and for making public announcements. The management of calls is combination of configuration of devices and software that resides on a local computer. Bombardier calls this PC the VCCU (Vehicle Communications Control Unit). The PC is ruggedized for the harsh environment and meets EN50155 requirements.

A security microphone is hidden in the ceiling of the vehicle for eavesdropping purposes. This can be enabled or disabled per customer requirements. Likewise, the passenger panels can be called without visible or audible notification to the passengers.

VORS Functional Description

Public Announcement

Public Announcements (PA) are generated from either the Central Control Operator (CCO) or the Driver. When generated from the CCO, a VoIP phone call is first set up between the CCO phone and the vehicle VORS-S panel. This VORS-S panel has outputs to the vehicle amplifier. Now depending on the type of train, this audio signal can be either sent to the next car via trainline, or it will just be broadcast on that vehicle alone.
If the CCO wants to call multiple vehicles, the call is set up through the mulicast unit at his console. From there, the call is transmitted to all of the vehicles desired.
The other type of PA is generated on the vehicles and doesn't require use VOIP technology. It is purely an analog signal that is amplified and distributed down the trainline to the other vehicles. This pathway is kept like this in the event that the wireless system or VORS system is disabled, the driver can still make announcements to the train.

Two-Way Call

Two-Way Calls are initiated by the passenger from the Passenger call panel. The CCO is in control of the call at all times. See Figure 6.

Figure 6: Photo[5] Passenger Call Panel

The passenger presses the Request to Talk button on their panel. This button is registered as a digital input on the VoIP panel. The input is registered in the VCCU. The VCCU tells the panel to flash the LED around the button and it plays the message, "Your call is being processed" It communicates with the CCO PC to place call request on the screen. It is then the CCOs turn to decide what to do. Since the CCO can potentially receive many requests concurrently, he can pick and choose which call to answer/put on hold. Once call is selected, the VCCU communicates with the panel to indicate that the digital output should stay steady on. The VoIP call is now activated and the call can proceed.

The driver's microphone and panel provide the Driver with three options. Trainline PA, Local PA, CCO two-way call. Some of these may be disabled depending on customer request. The CCO two-way call works just like the Two-Way call from a passenger call panel. LED buttons and speaker/microphone are provided for the driver in a locked compartment.

Alarms

Large quantities of alarms are available. They range from dropped call to smoke alarm.

CCTV

A typical people mover system requires two fixed CCTV cameras on each car, but more can be provided. Up to 8 on a car have been requested by customers to date. The cameras used are IP (Internet Protocol) based. They are capable of multiple simulcast streams. Therefore, one video stream of one setting; say15fps (frame per second) at 4CIF (Common Intermodal Format) can go to the recorder and one video stream of 10fps and 4CIF can be transmitted to the wayside.

Due to the nature of wireless, it is possible for multiple users or a single user to try to pull too much data from the vehicles than the switches are capable of doing. This was described earlier. This is an issue that some vendors in the CCTV industry are now addressing.

Event Recorder

For the Sao Paolo project, the customer requested a “Black Box” to preserve certain data in event of a crash. This can be seen in Figure 4. This Black Boxes' purpose on Sao Paulo was only to record CCTV in a backup/ emergency fashion. The Black Box functionality can be expanded to record other data as deemed critical by the customer.

Touchscreen (HAP Screen)

The HAP Screen (Hostler Access Panel) is a touchscreen user interface designed for customers who want to have drivers (when present on train) to have direct interfaces to the communications systems while onboard the train. The HAP allows the driver to select a car, choose a call panel, place or retrieve a call. It also associates the call with a camera. So when the call request is made, the driver would immediately see the camera associated with that call panel.

Summary

Convergence of networks or collapsing of networks unto one unifying network provides many benefits and challenges for mobile communications. As the technology increases to allow for this, so do the demands of customers for functionality and performance.

References

[1] Photos Courtesy Erik Larsen, Bombardier Transportation Systems, Phoenix SkyHarbor APM Communications System.

Friction Stir Welding APM Vehicle Body Structures
Innovia APM 300 Case Study

Scott Moore[1]

[1]Senior Vehicle Design Engineer, APM Center of Competence, Bombardier Transportation Systems, 1501 Lebanon Church Road, Pittsburgh, PA 15236; PH (412) 655 – 5917; FAX (412) 655 – 5442; email: scott.a.moore@us.transport.bombardier.com

ABSTRACT

Bombardier's *INNOVIA* APM 300 body structure has been designed to meet the structural requirements of **ASCE 21 Automated People Mover Standards – Part 2**. The body structure consists of an aluminum roof, floor, and side wall panels. The roof and floor panels consist of aluminum extrusions continuously joined by the Friction Stir Welding (FSW). The FSW process has many benefits in joining aluminum; however, it was difficult to quantify these advantages using existing analysis methodology and design standards. This paper:

- Discusses the criteria applied to FSW joints based on existing design standards (ASCE 21, Aluminum Association Design Manual).
- Compares Innovia APM 300 floor and roof panels to previous APM designs.
- Discusses the benefits of the FSW process as applied to the Innovia APM 300 design using Bombardier's experience along with academic research and industry consensus.
- Explores how the maturation of FSW standards and design criteria could increase margins of safety for the Innovia APM 300 design and result in more efficient body structure designs in the future.

INTRODUCTION

The BOMBARDIER *INNOVIA* APM 300 automated people mover (APM) system is the culmination of four decades of Bombardier experience in building people movers for urban centers and the world's major airports.

The *INNOVIA* APM 300 vehicle design increases the capacity over both of its APM 100 and 200 predecessors. The overall size of the vehicle is comparable to the APM 100 vehicle while maintaining the wheel base of the 200 vehicle. The body also supports the addition of a second motor for performance level 2 (PL2) propulsion configuration for higher top speed and better grade traversing capabilities.

INNOVIA APM 300 structure utilizes aluminum extruded panels to better position the design for synergy with the other transit vehicle bodies. The use of aluminum also improves the sustainability of the *INNOVIA* APM 300 vehicle due to its recyclability when compared to materials used on past APM designs. Figure 1 shows the *INNOVIA* APM 300 structural assembly. The floor and roof panels consist or extruded shapes that are joined using the FSW process. The FSW process is a solid state joining process in which a rotary tool passes through the seam of the two panels being joined stirring the metal together. The process does not melt the material, resulting in less area in the panels being affected by heat. This reduction in heat improves tensile strength, fatigue strength, dimensional integrity of work piece, and reduces Heat Affected Zone (HAZ) around the joint.

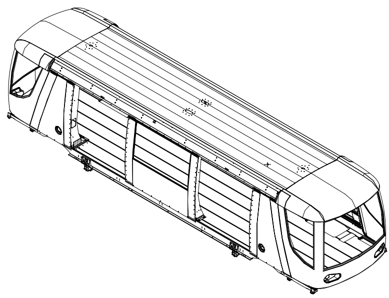

Figure 1: Innovia APM 300 Structural Assembly[6]

STRUCTURE DESIGN DESCRIPTION

The *INNOVIA* APM 300 structural design utilizes a "flat pack" approach for assembly. Figure 2 shows a complete carset of structural panels loaded on a trailer. Figure 3 shows a roof and floor panel loaded into the sub assembly area at the Bombardier assembly facility in Pittsburgh. The assembly consists of an aluminum floor panel, six aluminum side panels, aluminum roof panel, localized aluminum and steel structures, and two fiberglass end caps. The end caps are not factored into the structural analysis and can be customized to suit customer aesthetic preferences without affecting the integrity of the structural design.

Figure 2: Body Panel "Flat Pack" on Trailer[5]

Figure 3: Body Panel "Flat Pack" Staged for Assembly[5]

The aluminum floor is comprised of eight multi-chamber extruded panels welded together on the top and bottom using the FSW process. This panel is then machined for equipment interfaces, door and wheel well openings. The roof panel consists of eight extruded panels, six solid panels and two multi chamber panels, welded together using full penetration FSW joints.

The body panels are joined using structural rivets. Figure 4 shows an exploded view of the structural assembly. The assembly process utilizes components that remain with the structure as part of the fixtures in order to reduce the tooling required. The portability of the structural components coupled with the minimal manufacturing footprint allows for improved speed and flexibility in vehicle body production.

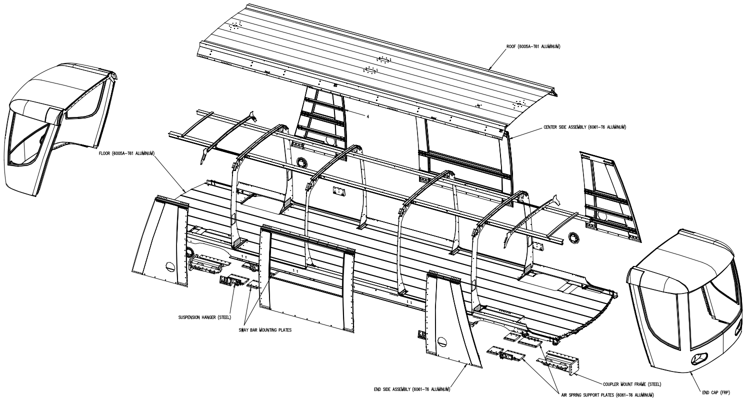

Figure 4: Structural Assembly Exploded View[6]

Figure 5: Structure on Assembly Fixture[5]

STRUCTURAL DESIGN CRITERIA

The *INNOVIA* APM 300 has been designed to operate under the static and dynamic design loads as defined in ASCE 21 Part 2 [1]. A Finite Element Analysis (FEA) and proof load testing were performed to verify that expected stresses fall under the maximum allowable stresses. The welded roof and floor are constructed with 6005A-T61 aluminum. Table 1 lists the properties for this material.

Table 1: 6005A-T61 Aluminum Properties

6005A-T61	SI
Elastic Modulus (E)	69,000 N/mm^2
Shear Modulus (G)	26,000 N/mm^2
Poison's Ratio (ν)	0.33
Density (ρ)	2.7E-9 t/mm^3
Tensile Strength (S_{tu})	260 N/mm^2
Tensile Strength (HAZ) (S_{tuw})	165 N/mm^2
Yield Strength (S_{ty})	240 N/mm^2
Yield Strength (HAZ) (S_{tyw})	90 N/mm^2
Elongation (min.)	8%

Allowable Stress

The allowable stress in these components has been reduced by the required design safety factor. Design safety factor for proof load is 1.5. Design safety factor for fatigue load is 1.33. These factors are required by ASCE 21 Part 2 [1] and are considered very conservative when compared to much lower factors applied in European standards.

Static Loading

Table 2: Static Loading Allowable Stresses

6005A-T61	MPa	Comments (1.5 Factor from ASCE 21 Part 2 [1])
Tensile	160	$S_{ty} \div 1.5$
Tensile (HAZ)	60	$S_{tyw} \div 1.5$

Tensile stress allowable (including reduced allowable in HAZ) is compared to von Mises stress in the FEA.

Fatigue Loading

Per Aluminum Association Design Manual (ADM) [2] allowable stress ranges for base metal and weld (infinite life) are shown in Table 3.

Table 3: Fatigue Loading Allowable Stress Ranges[2]

Category	MPa (range)	Comments (1.33 Factor from ASCE 21 Part 2[1])
A	52.6	70 ÷ 1.33
B	27.8	37 ÷ 1.33
C	21.0	28 ÷ 1.33
D	12.7	17 ÷ 1.33
E	9.77	13 ÷ 1.33

S-N Curve from ADM is shown in Figure 6. Endurance limit for infinite life is indicated by dashed line.

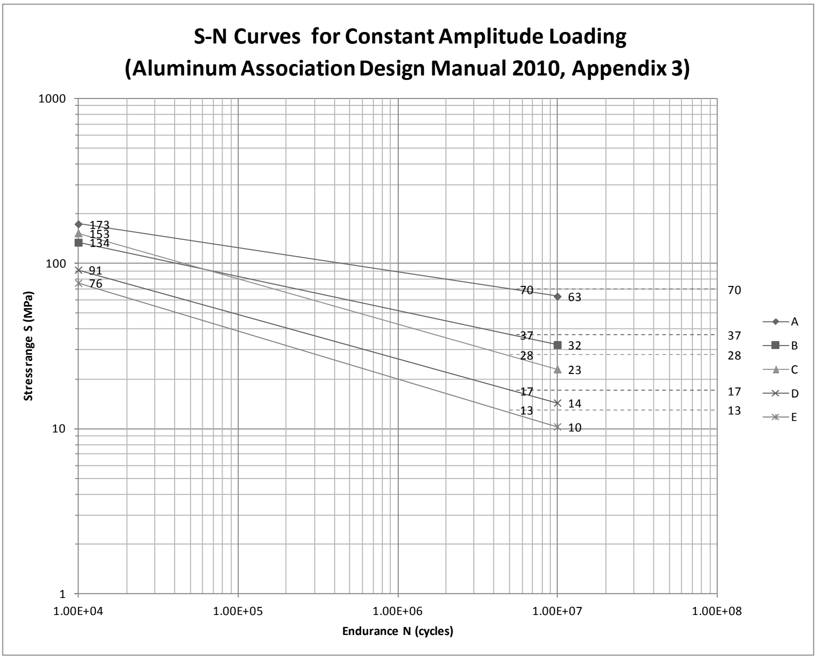

Figure 6: S-N Curve from Aluminum Association Design Manual [2]

The fatigue categories applied to the *INNOVIA* APM 300 are as follows:

- Category A is used for base material away from welding. A stress concentration factor (SCF) is applied to the calculated stress when appropriate. Principal stress is used to compare to the allowable.
- A reduced Category A is used for base material away from the weld but within the heat affected zone. The reduced value is calculated based on the ratio of welded affected ultimate strength to ultimate strength (S_{tuw}/S_{tu}). This is done to keep the analysis conservative. Principal stress is used to compare to the allowable.
- Category B is used on friction stir welds where the weld surface is substantially flush and there is no weld root present. Component stress normal to the weld line is used to compare to the allowable.
- Category E is used on friction stir welds where the weld root is present. Component stress normal to the weld line is used to compare to the allowable.

The *INNOVIA* APM 300 structural analysis shows that the stresses associated with the static and fatigue loading as specified in ASCE 21 Part 2 [1] fall below the allowables listed in Tables 2 and 3 and Figure 6. The welds in the floor and roof panels are treated as traditional Metal Inert Gas (MIG) welds in the development of allowable stresses. This is a conservative approach since the FSW process produces more robust welds than the MIG process. This decision was taken since in certain situations small MIG weld repairs may be required during the manufacturing process and the applicable standards and guides (Aluminum Design Manual, ASCE, etc...) do not give guidance on an agreed measurable improvement of the FSW process over the MIG process.

The selection of allowable stresses for the FSW joints of the *INNOVIA* APM 300 vehicle structural roof and floor as described is a very conservative approach. Even with the very low allowable stresses, the design meets this set of criteria. Bombardier believes that there is additional margin in this design that may be recognized in the future as design standards and guides better reflect the improved properties that are achieved with the FSW process.

Structural Fire Endurance Testing

ASCE 21 Part 2 [1] calls for the application of NFPA 130. NFPA 130 [3] calls for a fire endurance test (per ASTM E 119) to be conducted on the floor structure of an APM vehicle for 15 minutes with the maximum loading including body mounted equipment. There is also a requirement of 30 minute test duration for all other types of vehicles. The new loading requirement has resulted in nearly double the load as tested on previous vehicle designs.

The *INNOVIA* APM 300 was tested in two configurations early in 2012. The first configuration was the extruded aluminum floor with fire shielding and insulation. This configuration survived for 30 minutes at which time the test was terminated to preserve the test sample for the second test.

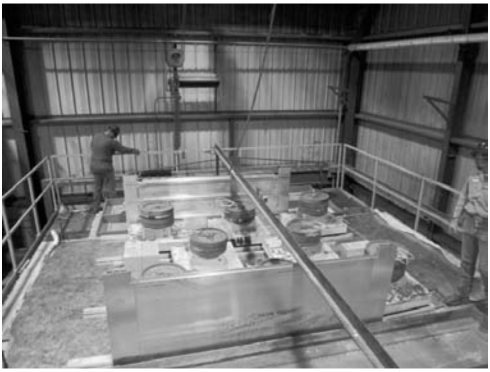

Figure 7: ASTM E 119 Test Loading[5]

The second configuration was the first test panel with the fire shielding and insulation removed. This configuration survived for 19 minutes at which time the test was terminated due to potential collapse of the rig into the furnace and not rise of temperature or ingress of fire. It is possible that the unshielded sample could survive longer had it not been partially compromised during the first test.

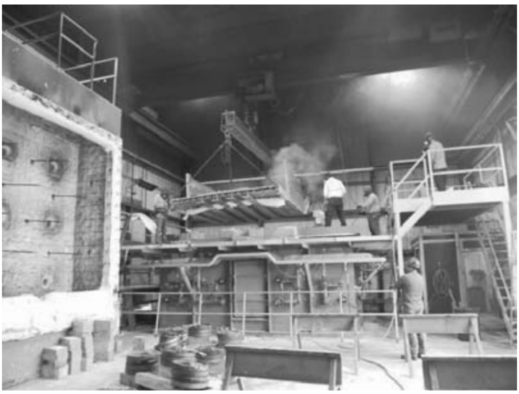

Figure 8: Unshielded Test at Termination[5]

Evaluation of the FSW joints after the test showed that they maintained their integrity under these very harsh temperature and loading conditions. The use of aluminum floor panels also helped to prevent differential thermal expansion issues that are often encountered during this test. The aluminum floor was also an effective heat sink, spreading the furnace heat throughout the structure.

FSW vs. MIG Process

Research comparing FSW and MIG joints in similar alloys as used on the *INNOVIA* APM 300 vehicle shows an improvement of 22 % in tensile strength, 23 % in fatigue strength, and as much as 96 % in dimensional stability [4]. Bombardier has conducted some testing related to the extent of the HAZ of a FSW joint and a joint repaired using the MIG process and found that the HAZ was nearly cut in half, see Figures 9 and 10. This anecdotal evidence is consistent with other research [4].

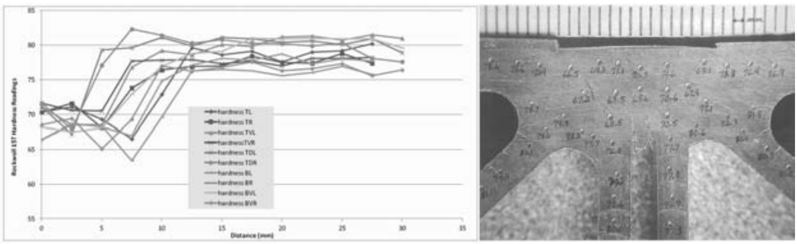

Figure 9: FSW Joint Hardness Test Data[5]

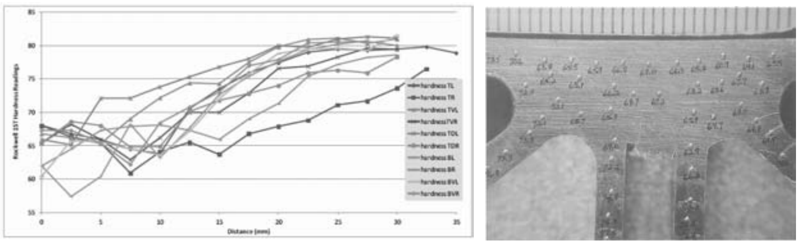

Figure 10: MIG Weld Repair Hardness Test Data[5]

The FSW process does not require the use of consumable gases and filler material.

FSW BENEFITS REALIZED

The reduced distortion in the floor and roof assemblies of the *INNOVIA* APM 300 vehicle have resulted in measurable improvements in carbody dimensional tolerances reducing them as much as 66 %. This improved accuracy results in better fit and finish of the vehicle interior. This accuracy is also expected to improve the reliability of the door system due to better fit of the operators and door panels. This better fit results in less wear on door guides and seals.

The use of continuously friction stir welded panels in the roof assembly has resulted in a water-tight roof assembly. Previous carbody designs with frameworks and skins attached by various methods result in roof assemblies that tend to have leak issues that have to be addressed during vehicle factory testing.

CONCLUSION

The *INNOVIA* APM 300 vehicle utilizes the FSW process in continuously joined extruded roof and floor panels. These panels meet the requirements of ASCE 21 Part 2 even though no credit is taken for the benefits of FSW over MIG process. The vehicle could therefore utilize either the FSW or MIG process; however, the current design uses the FSW process primarily for the improved dimension stability of the body structure. In the future as the design standards and guides take into account the improved material properties of the FSW process the *INNOVIA* APM 300 design will have additional margin and could potentially be refined to reduce cost and weight adding value to operators by reducing initial capital and energy consumption costs.

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[2] Aluminum Association Aluminum Design Manual (ADM) 2010.

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[4] Kulekci, Kaluc, Sik, Basturk, "Experimental Comparison of MIG and Friction Stir Welding for EN AW-6061-T6 (Al Mg Si Cu) Aluminum Alloy" , The Arabian Journal for Science and Engineering, Volume 35, Number 1B, (April 2010), p 324 – 325.

[5] Bombardier Transportation, Systems. (c. 2012) 'untitled', "various photographs", internal R&D project library.

[6] Bombardier Transportation, Systems. (c. 2011) 'untitled', "various 3D renderings", internal R&D project library.

Application of ASTM E 119 Testing Requirements to APM Vehicles

INNOVIA APM 300 CASE STUDY

Scott Moore[1] and Kevin Lewis [2]

[1]APM Center of Competence, Bombardier Transportation, Systems Division, 1501 Lebanon Church Road, Pittsburgh, PA 15236; PH: (412) 655-5917; FAX: (412) 655-5442; e-mail: scott.a.moore@us.transport.bombardier.com
[2]APM Center of Competence, Bombardier Transportation, Systems Division, 1501 Lebanon Church Road, Pittsburgh, PA 15236; PH: (412) 655-5351; FAX (412) 655-5442; e-mail: kevin.lewis@us.transport.bombardier.com

ABSTRACT

Bombardier's *INNOVIA* APM 300 vehicle has been designed to meet the fire test standards as outlined in **NFPA 130 Standard for Fixed Guideway Transit and Passenger Rail Systems, 2010 Edition**. Qualification of this design included a fire endurance test in accordance with ASTM E119 performed on a representative sample of the floor structure with a vertical test load including a passenger crush load. NFPA 130 2010 requires that Automated Guideway Transit (AGT) vehicles endure this test for at least 15 minutes while all other passenger carrying vehicle must last for 30 minutes. The Innovia APM 300 vehicle has been tested in two different configurations to meet both of these requirements. The 30 minute configuration included additional fire protection on the underside of the floor structure to endure the ASTM E 119 furnace temperature profile for the additional 15 minutes.

INTRODUCTION

For over 40 years, Bombardier has been at the forefront of developments in automated people mover (APM) technology. The *INNOVIA* APM 300 system is the latest in a long line of APMs for use at airports and in urban environments. In 2009, Bombardier began a project to update its APM technology to incorporate an all-aluminum carbody structure.

The new carbody structure consists of four basic modules - floor, roof, side center (2 per car), and side ends (2 left and 2 right per car). Each module is comprised of specially designed aluminum extrusions joined by using friction stir welding, fully fabricated and machined. The modules were assembled at Bombardier's Pittsburgh APM assembly facility.

TEST OBJECTIVE

Transit and passenger railcars are required to meet the NFPA 130, *Standard for Fixed Guideway Transit and Passenger Rail Systems*. The purpose of the Standard is to ensure passenger safety; the section relevant to this test requires the structural floor to maintain its integrity and contain and prevent thermal transmission to unexposed surfaces in a defined fire scenario. The test objective is to determine if the vehicle structure meets the predetermined fire exposure time.

Tests were conducted on the vehicle in two configurations. The first test was conducted with an underlying heat shield and insulation applied to the bottom of the structure. The second configuration was with the underside heat shield and insulation removed.

INITIAL THERMAL FEA ANALYSIS

A heat transfer FEA analysis was performed to predict the behavior of the structure in this extreme thermal test. For purposes of the FEA, a two dimensional analysis was made in an assumed steady state condition at the 15 minute point of the fire test. It should be noted that an initial assumption was made that the aluminum structure would need some type of heat shield and insulation to prevent premature structural weakening.

The thermal FEA floor section consisted of the extruded aluminum structural members, a stainless steel heat shield on the bottom with stone wool insulation

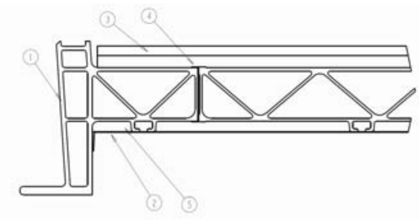

Figure 1: Floor Cross-Section

attached to the underside of the structure, and fiberglass insulation and plymetal on the top.

Item	Description	Material
1	Extrusion Structure	Aluminum
2	Fire Barrier	Stainless Steel
3	Flooring	Plymetal
4	Floor Padding	Silicone
5	Fire Barrier Insulation	Roxul (Stone Wool)

Thermal conductivity of the material varied with temperature, so the selected values were based on the estimated temperature of the material at the 15 minute point of the fire test, as follows:

Material	Thermal Conductivity
Aluminum	k = 167 W/m°C
Stainless Steel	k = 15 W/m°C
Plymetal	k = 0.15 W/m°C
Silicone	k = 0.06 W/m°C
Roxul (Stone Wool)	k = 0.045 W/m°C
Manniglas (Fiberglass)	k = 0.04 W/m°C

To validate the FEA, a manual, one-dimensional hand calculation was performed. From this manual cross check, it was concluded that the thermal FEA was adequate predictor of the thermal behavior of the vehicle structure.

The results of the thermal FEA (Figure 2) predicted that the floor section with the underside heat shield and insulation would meet the test requirements. It was interesting to note that the side wall acting as a heat sink greatly reduced the overall

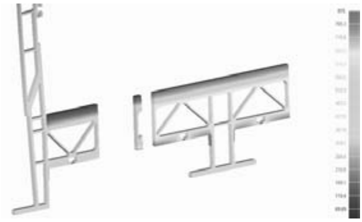

Figure 2: Thermal FEA, Floor with Heat Shield

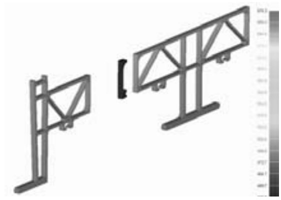

Figure 3: Thermal FEA, Floor without Heat Shield

temperature of the structure at the sides. It is a very good example of the superior advantages of aluminum has as a heat conductor.

Another thermal FEA (Figure 3) was conducted with the underside heat shield and insulation removed. The FEA predicted an undesirable result in that case. It was from this initial thermal FEA that the decision was made that the vehicle would be tested with the underside heat shield and insulation applied.

TEST ASSEMBLY

The test sample was the center portion of the Innovia 300 APM vehicle including the floor assembly and an approximately half height section of the center side walls.

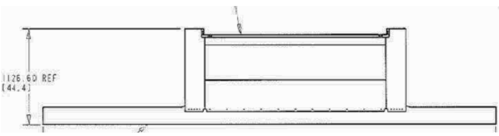

Figure 5: Test Sample, Elevation View

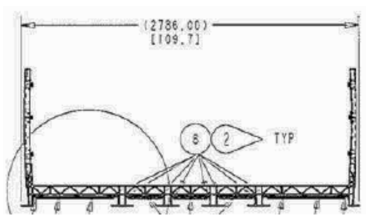

Figure 4: Test Sample Cross-Section

The main floor structure consisted of four main aluminum extruded floor beams, two aluminum extruded floor panels and two aluminum side rails. The floor extrusions were continuously welded using friction stir welding.

For the first test configuration (Configuration I), a fire mat was adhesively bonded on the underside of the floor structure between the equipment hangers. The fire mat was comprised of fire barrier fabric, silicone sealant and double-sided adhesive. Attached to the equipment hangers spanning the underside between the side sills and main floor beams were 0.6 mm thick stainless steel pans supporting 1 inch thick mineral wool insulation.

For the second test configuration (Configuration II) all the underlying thermal protection was removed from the underside of the structure.

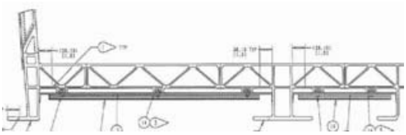

Figure 6: Thermal Protection Installation

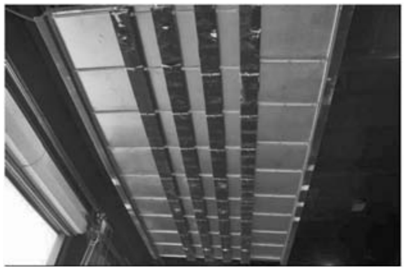

Figure 7: Floor with Thermal Protection

Photo:Bombardier/ Scott Moore, 2012

For both test configurations (Configurations I & II), the top (unexposed) surface was covered with a ½ inch thick Melamine foam sheets with 5/8 inch thick silicone foam spaced between the Melamine foam sheets. A composite plymetal floor comprised of two 1/4 inch plywood sheets sandwiching a damping layer in between and surfaced with 1.5 mm aluminum sheets outer layer was placed on top of the foam underlayment. The plymetal floor had four 5" x 12" cutouts along the outside edge near the simulated doorways. The cutouts exposed the bare aluminum floor.

TEST METHOD – CONFIGURATION I

NFPA 130, *Standard for Fixed Guideway Transit and Passenger*, Section 8.5 requires that the vehicles go through a fire test performed in accordance with ASTM E119, *Standard Test Methods for Fire Tests of Building Construction and Materials*. This Standard defines the fire to controlled laboratory conditions to achieve specified temperatures throughout a specified period.

For purposes of this test, the laboratory's large-horizontal furnace was used. The 17.3 ft. test sample was placed over their 8.5' x 12' opening resulting in an overhang of approximately 2' 8" on each end. A total weight was distributed uniformly over the exposed portion of the floor to approximate an AW3 floor load of 139.3 lbs/ft^2.

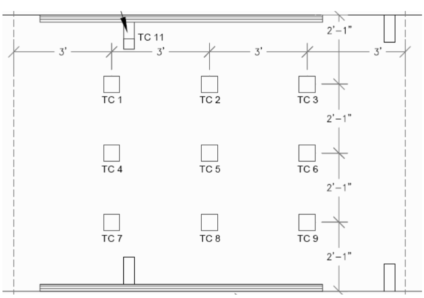

Figure 9: Thermocouple Locations

Figure 8: Floor Loaded to AW3

Photo:Bombardier/ Scott Moore, 2012

Nine thermocouples were mounted on the unexposed side of the test sample, one in the center of the sample, one each in the center of each quarter section and one each in between each quarter section.

Two additional thermocouples were installed. One thermocouple was embedded in the aluminum web underneath at the midpoint of the central equipment hanger. The other thermocouple was applied to the bare aluminum on the unexposed top surface where the plymetal had been cut out.

TEST RESULTS – CONFIGURATION I

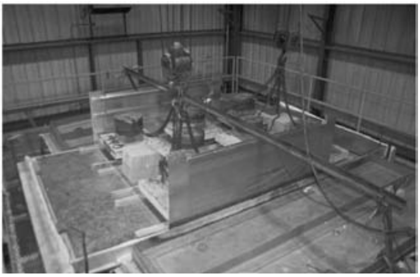

Figure 11: Floor Sample Over Furnace
Photo:Bombardier/ Scott Moore, 2012

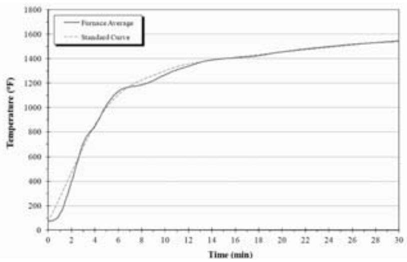

Figure 10: Average Furnace Temperature

The furnace was fired to the controlled temperature for a period of 30 minutes as defined by the Standard.

During the test, furnace temperatures, thermocouple readings and deflection were continuously monitored. Thermocouple readings were captured for all thermocouples. The average temperature for the nine thermocouples was 110.7ºF, which represented an average 36.5º F temperature rise. The maximum temperature of any one thermocouple was 117.0ºF recorded on at the TC 6 location.

It may be noted that the thermocouple located in the plymetal cutout area exceed the maximum allowable, but that was expected and does not constitute a failure. In the actual vehicle, the area of the cutouts has a fiberglass cover; there is no direct contact with the interior. In the opinion of the test laboratory, the materials in the vicinity of the plymetal floor cutouts would not experience temperatures to cause combustion. As a result, the elevated temperatures as measured at the bare floor in the area of the

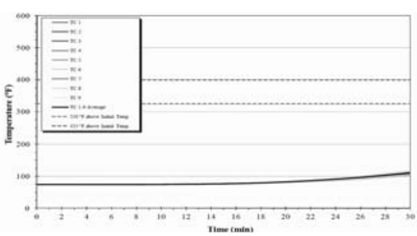

Figure 13: Unexposed Surface Temperatures

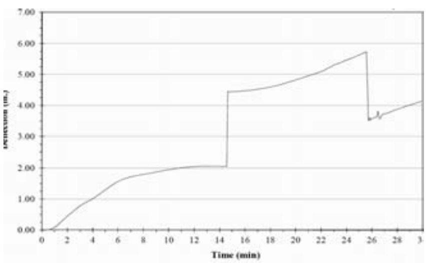

Figure 12: Floor Deflection

plymetal cutouts were not considered in the acceptance criteria.

At approximately 14 minutes 30 seconds into the test, the displacement transducer fell causing the large spike in the deflection measurement. At 25 minutes, the displacement transducer was repositioned and the deflection measurements were accurate after that time to the end of the test.

POST-TEST EVALUATION – CONFIGURATION I

At the conclusion of the test, an evaluation was made of the test structure and thermocouple readings. Based the test results, Bombardier's *INNOVIA* APM 300 insulated floor assembly successfully achieved a fire-resistance rating of 30 minutes, when tested in accordance with NFPA 130 and ASTM E 119.

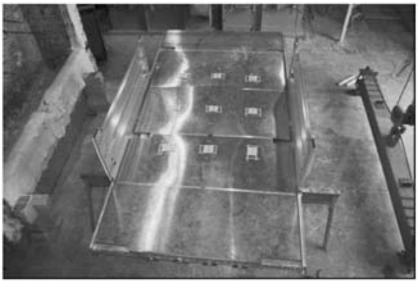

Figure 13: Top Surface After Test
Photo:Bombardier/ Scott Moore, 2012

Figure 12: Underfloor After Test
Photo:Bombardier/ Scott Moore, 2012

TEST METHOD – CONFIGURATION II

The second test configuration was performed using the floor assembly and test arrangement with **all** fire protection material removed from the underside (exposed) surface. The top floor insulation and plymetal flooring were renewed.

Nine thermocouples from the prior test were used to monitor the structure. Two additional thermocouples were applied on the top surface of bare aluminum floor in the location of one of the plymetal cutouts. Other thermocouples were embedded on the underside of the structure to monitor temperature of the structure. Loading was applied in the same weight and configuration used in the prior test.

TEST RESULTS – CONFIGURATION II

The furnace was fired to the controlled temperature for a period of as defined by the Standard. During the test, furnace temperatures, thermocouple readings and deflection was continuously monitored.

Thermocouple readings were captured for all thermocouples. The average temperature for the nine thermocouples was 93.3ºF at test termination (at 19 minutes), which represented an average 23.9º F temperature rise. The maximum temperature of any one thermocouple was 103.8ºF recorded on at the TC 2 location.

The thermocouples applied to the underside of the structure gives a dramatic picture of the direct effect of the removal of all the under floor insulation.

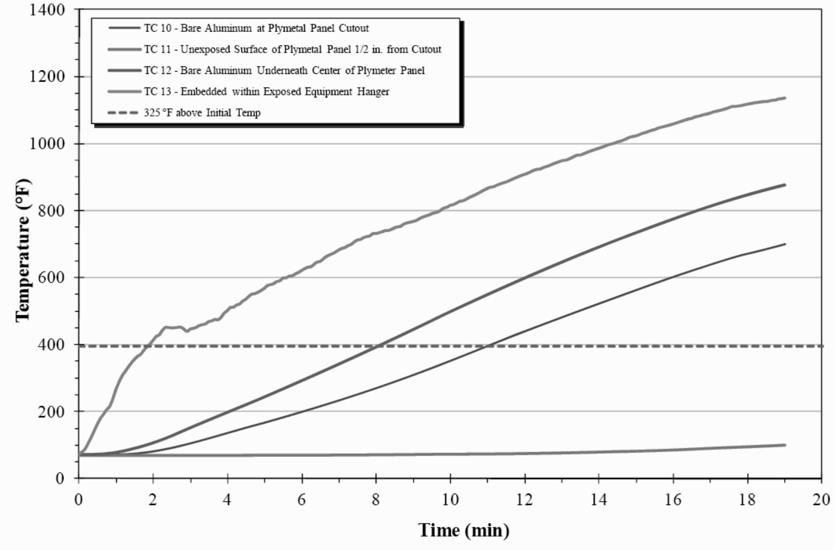

Figure 14: Unprotected Floor Temperatures, Representative Thermocouples

As previously noted, the test was terminated after 19 minutes due to the rate of deflection was at a rate that made the test no longer safe to continue.

POST TEST EVALUATION – CONFIGURATION II

At the conclusion of the test, an evaluation was made of the test structure and thermocouple readings. Based the test results, Bombardier's *INNOVIA* APM 300 un-insulated floor assembly successfully achieved a fire-resistance rating of 19 minutes, when tested in accordance with NFPA 130 and ASTM E 119, exceeding the 15 minute minimum requirement of NFPA 130. Bombardier also believes that, if tested with a new sample, the un-insulated floor would exceed the 19-minute duration achieved in this test, and could approach the 30-minute duration achieved by the insulated design.

SUMMARY AND POST TEST ANALYSIS

A comparison of the actual fire test results to the initial thermal FEA showed a very good correlation in the configuration with the underside heat shield and insulation (Configuration I). In the unshielded condition (Configuration II), the results of the thermal FEA were significantly worse than the actual results. The difference in the actual versus predicted results in the two configurations is a reflection on the difficulty in developing thermal FEA models for relatively complex structures in extreme conditions.

As a result of these two tests, Bombardier has successfully passed the ASTM E 119 test as required by NFPA 130 at 30 minutes with underframe heat shields (Configuration I) and at 19 minutes without underframe heat shields (Configuration II).

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Kevin Lewis
APM Product Manager, APM Center of Competence
Bombardier Transportation, Systems Division
1501 Lebanon Church Road
Pittsburgh, PA 15236
Telephone: (412) 655-5351
Fax (412) 655-5442
kevin.lewis@us.transport.bombardier.com

Scott Moore
Senior Vehicle Design Engineer, APM Center of Competence
Bombardier Transportation, Systems Division
1501 Lebanon Church Road
Pittsburgh, PA 15236
Telephone: (412) 655-5917
Fax (412) 655-5442
scott.a.moore@us.transport.bombardier.com

New "AC/AC" Propulsion System for the *INNOVIA* APM 300

Lance Schnur[1] and Raymond Castle[2]

[1]Senior Director, APM Center of Competence, Bombardier Transportation Systems, 1501 Lebanon Church Road, Pittsburgh, PA 15236; PH (412) 655 – 5106; FAX (412) 655 – 5442; email: lance.schnur@us.transport.bombardier.com
[2]Expert, Vehicle Electrical, APM Center of Competence, Bombardier Transportation Systems, 1501 Lebanon Church Road, Pittsburgh, PA 15236; PH (412) 655 – 6919; FAX (412) 655 – 5442; email: ray.castle@us.transport.bombardier.com

Abstract

Bombardier Transportation Divisions, Systems, and Propulsion and Controls, as part of the *INNOVIA* APM 300 vehicle development, are developing a new propulsion system to drive two AC traction motors from 600VAC, 3 phase track power rather than two DC traction motors as is the applied technology on our legacy APM 100 products (formerly CX-100). The new propulsion technology, consisting of two independent line converter/motor converter pairs, is referred to as the "AC/AC" propulsion system.

The resultant *INNOVIA* APM 300 AC/AC car, offers many improvements to our customers, such as, propulsion redundancy for improved availability, improved performance from better power factor correction methodology, reduced energy consumption from regenerating braking energy back into the mains power source, and a top speed boost to 50mph (80kph) from the 34mph (55kph) maximum previously ever deployed with the APM 100 system.

This paper summarizes the key development efforts of the new AC/AC propulsion system, and provides a comparison of features against those of the legacy APM 100.

Existing AC-DC System (APM 100)

Please refer to Figure 1. Power is collected from the 600VAC, 3 phase power rails and input to a thyristor-based phase control rectifier. The rectifier then presents DC power to the two DC traction motors where the armatures are connected in series with the field windings during motoring. The phase angle (or ON time) of the main thyristors is controlled to achieve smooth acceleration performance. During braking, the propulsion system is disconnected from the line and the motor fields are separately excited. The Dynamic Brake Transformer is used to draw a small amount of power from the line, where separate thyristors control energy to the traction motor fields and ensure build up of motor braking torque. The braking energy is dissipated via on-board braking resistors, as there is no means for regenerative braking energy to be placed back into the line.

Over the last 40 years, the system has evolved from a "3-pulse" to a "6-pulse" rectifier, or in other words, from a half wave to a full wave phase control rectifier (Figure 1 shows the full wave implementation). The full wave rectifier is implemented for improved power quality performance with respect to harmonic generation. In general, the system has proven to be extremely reliable due to its simplicity, and continues to operate successfully at many of our APM sites. Yet in today's world, there is growing demand for improved energy efficiency and power quality that the tried-and-true APM 100 propulsion system is not capable of meeting.

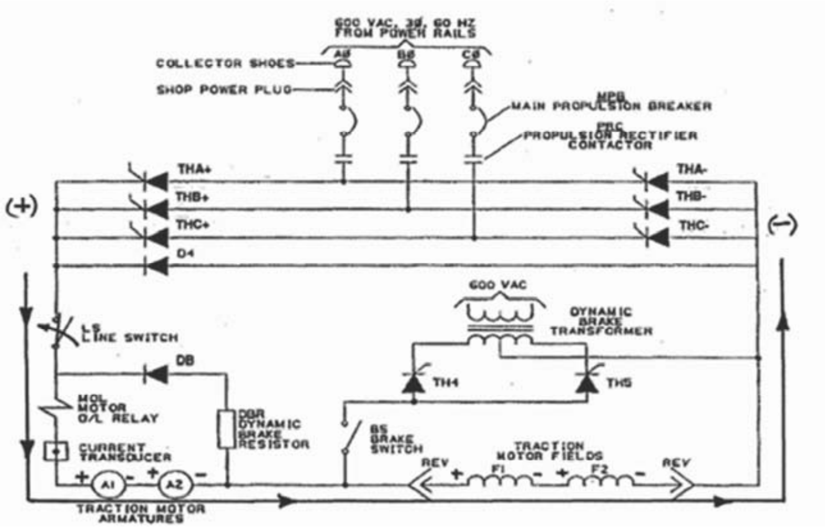

Figure 1 APM 100 Full-wave Converter

AC/AC Propulsion System Design Concept

The idea of converting the APM 100 propulsion system to an AC drive system is realized, in part, as the result of a new converter development by our Propulsion and Controls Group, namely the CM-Duo Converter Module. The CM-Duo module contains two independent 3 phase converters mounted on a common heatsink. This module is used on the *INNOVIA* APM 300 "DC/AC" vehicle, where each converter is used as a motor converter to power that vehicle's two AC traction motors. After a conceptual design process, it was decided to configure the new AC/AC propulsion system using two CM-Duo modules, with each module having its own line converter and motor converter within the module, to maximize availability. Each CM-Duo module is to power a single AC traction motor. The line converter half is responsible to interface to the 3 phase AC line voltage, and is an extension of Bombardier's existing-design, single phase line converter technology presently in use on various commuter rail cars.

Similar to the APM 100 auxiliary power scheme, auxiliary power is directly taken from the line through a transformer then distributed to the 3 phase loads.

Further design objectives are set for the propulsion system as follows:

- Operate at unity power factor (1 +/- 0.05) in both motoring and braking modes
- During braking, provide regeneration of electrical energy back into the 3 phase line
- Minimize harmonic content in both motoring and braking modes, in compliance with IEEE Std 519-1992, IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems

Performance Objective

The AC traction motor performance capabilities of our DC voltage energized *INNOVIA* APM 300 are maintained as equal performance objectives for the AC/AC propulsion system. The goal for the product family is to essentially maintain an identical vehicle, whether the source energy is be DC power or 3 phase AC power. Key aspects to preserve are:

- Vehicle weight (AW1) 23,000 kg (50,750 lb)
- Acceleration Rate 1.0 m/s/s (2.24 MPH/s)
- Braking Rate 1.0 m/s/s (2.24 MPH/s)
- Speed 80 kph (50 MPH)
- Towing 10% grade, AW1, 7.5% grade AW2

Figure 2 shows a plot of Speed vs. Time for the AC/AC propulsion system propelling the APM 300 vehicle.

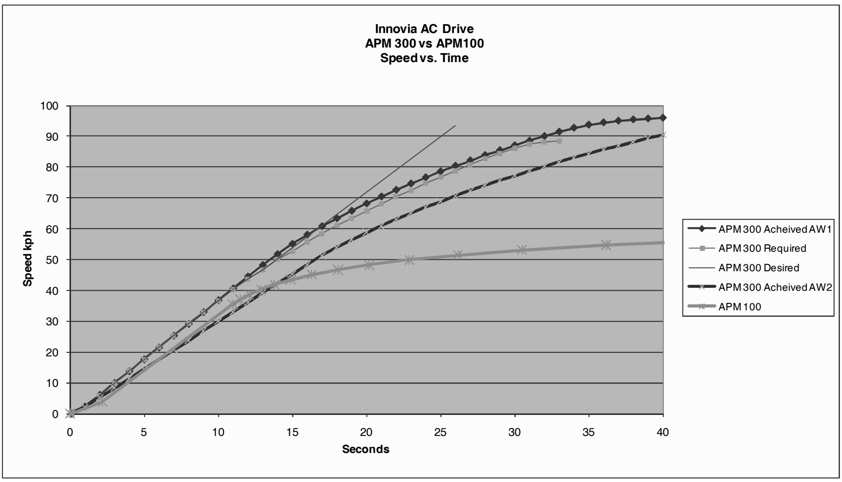

Figure 2 Speed –Time Performance

Energy Efficiency

Table 1 below shows a comparison of predicted energy consumption between the APM 100 and APM 300 vehicles on a representative 0.5 km long shuttle system. The table shows that that new AC/AC propulsion system consumes about 11% more energy per car-km when no regeneration is taken into account. This is due to the additional power converter stages of the AC/AC propulsion system as compared to the phase control rectifier. However, simulations performed for the scenario of regenerating only into the auxiliary loads, as well as for the scenarios of 50% line receptivity and 100% line receptivity, predict a continually improving efficiency. The energy consumption varies from a low of about 4% more consumption (into auxiliaries only), to an impressive maximum of 40% less energy consumed when the line is 100% receptive.

Table 1 Energy Comparison APM 300 to APM 100

	APM-100	**APM 300**	**Difference (%)**
kW-hr/car-km			
zero receptivity - no regeneration into the auxiliaries	3.5865	4.0501	-11.4
zero receptivity - with regeneration into the auxiliaries	3.5865	3.7450	-4.2
50 % receptivity - with regeneration into the auxiliaries	3.5865	3.1510	13.8
100 % receptivity - with regeneration into the auxiliaries	3.5865	2.5569	40.3
Round Trip Time (s)	1288	1248.5	3.1
Car Weight AW1 (Lbs)	50320	49980	
Total passenger per car	102	103	

AC-AC System Architecture

CM-Duo Module Configured as Line Converter – Motor Converter

As mentioned above, the single CM-Duo assembly consists of two independent converters and is configured as a cascaded Line Converter – Motor Converter combination. In effect, the converters are almost physically the same, except that the motor converter does include a dynamic brake chopper circuit. Please refer to the schematic presented in Figure 3 below to note the difference.

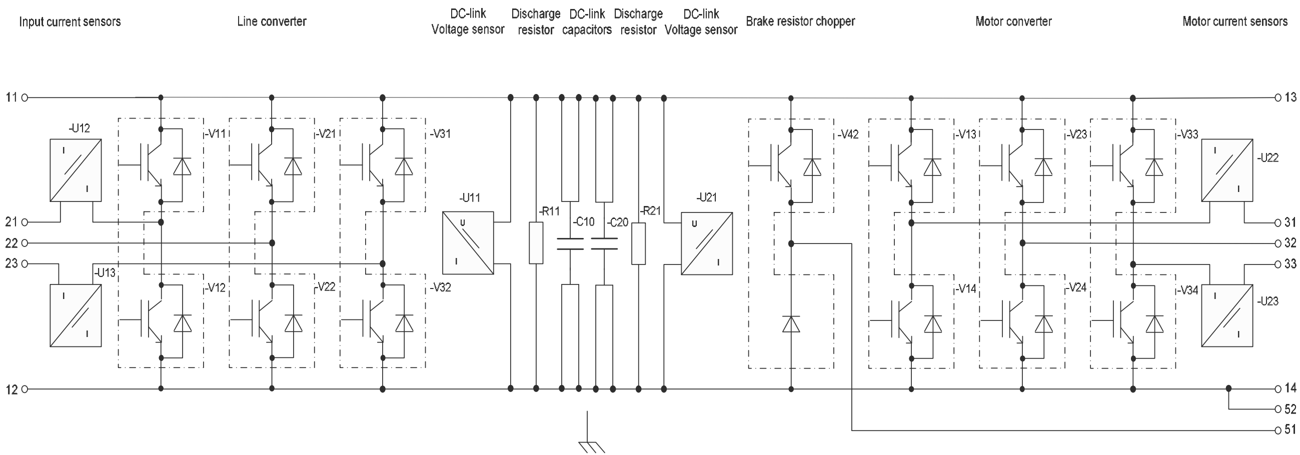

Figure 3 AC-AC Power Stage Schematic

Since both traction motors are powered individually, it is obvious that the layout within the cabinetry is easily accomplished by applying mirrored symmetry, doing so leads to nicely segregated cooling air circuits as well.

Within the cabinet assembly, each CM-Duo module is force air cooled from an independent cooling blower. In each air circuit has an independent air intake. The air, after having passed over the converter module is then routed to cool the line reactors, followed by ducting into the traction motors before exiting to ambient surroundings. Refer to photos of Figure 4 below. The photo on the readers left illustrates the symmetry of the internal cabinet layout, one CM-Duo for each of two motors. The photo on the reader's right illustrates the two independent air-intakes, take notice of the two square-holed grills located at the near field and far field of the photo.

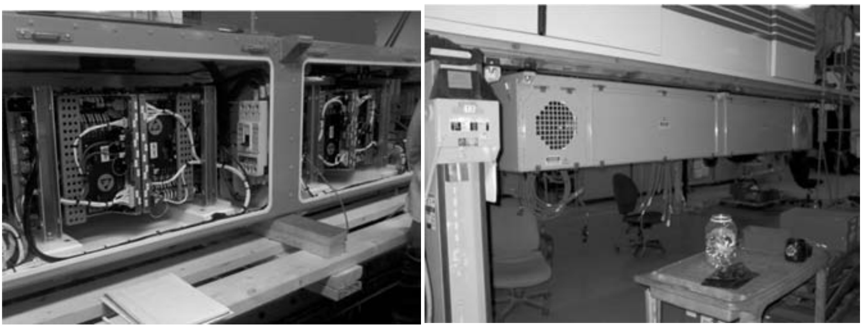

Figure 4 – Photos[1] Independent Converters(left), Independent Air Intake(right)

New 3 Phase Line Converter

Continuing the discussion of the new design, 3 phase line converter, please refer to Figure 5 below. The block diagram illustrates the modular design approach to the Line Converter and the incorporation of common supporting components and interfaces. The design concept exploits Bombardier Transportation's Propulsion and Control's Mitrac family of converter building blocks. The DCU, (Drive Control Unit), GDU (Gate Driver Unit) and IGBT block, are all Mitrac family modules shared across numerous other converter applications.

In motoring operation, this particular converter configuration, together with the 3phase line reactor, works as a step up chopper creating a DC link voltage slightly over 1000Vdc. However, prior to starting the converter, a line charging contactor engages a resistor to initially charge the DC link to near 900Vdc.

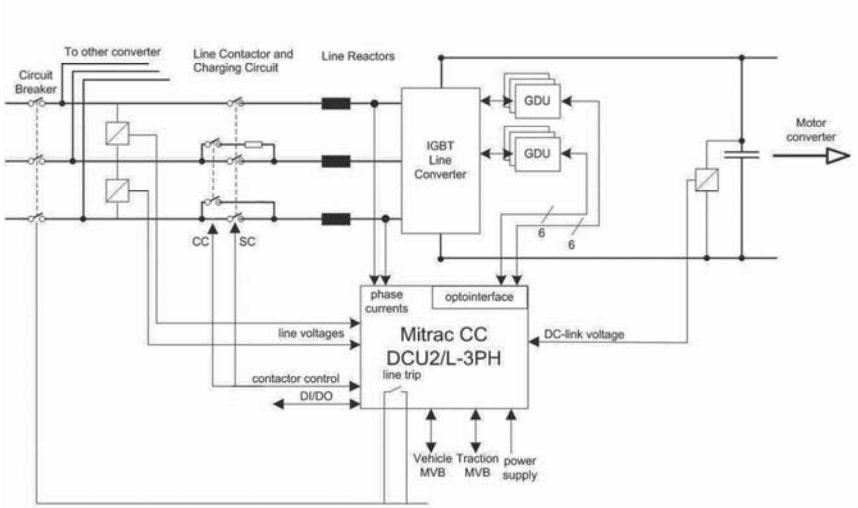

Figure 5 Line Converter Control Diagram

CM-Duo Converter Specifications

Presented next are more granular datasheet-type details of the electrical properties and photos of mechanical configuration.

Electrical data

As the line converter/motor converter pair we have:

- Input voltage 3~ AC 600V +10%-15%
- Input current 3~ AC 360A max.
- DC-link voltage 980V/1050V cont./max.
- Traction Output current 240A/435A rms cont./max.
- Brake chopper output current 180A/320A rms cont./max.

Mechanical Configuration

Photos, Figure 6, and a 3D rendering, Figure 7, of the CM-Duo module are presented below. The Photos of Figure 6 are of the initial R&D unit which was constructed in Propulsion and Controls' Mannheim, Germany laboratory facilities. The photo on the reader's left is the initial unit setting on the Mannheim testing bench, whereas the photo on the reader's right is the same unit after having been assembled into a cabinet by Propulsion and Controls' Pittsburgh, PA technical staff. A 3D rendering is included for reference.

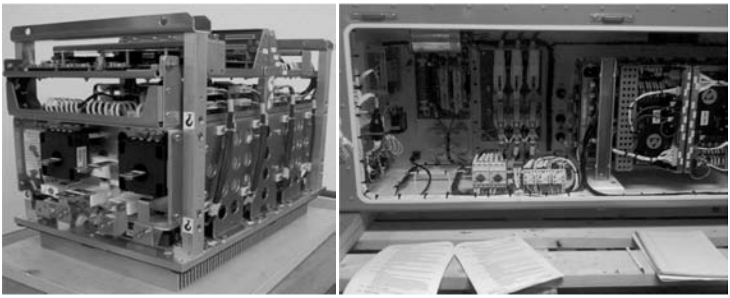

Figure 6 [1] CM-Duo initial R&D build; Test bench Mannheim Germany (left), Assembled into cabinet Pittsburgh, PA (right)

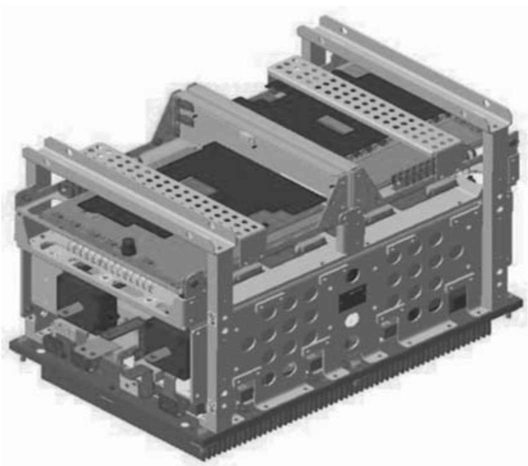

Figure 7 [2] – CM Duo Isometric View: 3D Rendering

Remaining Activity Planned

The complete, assembled, AC/AC propulsion system is presently mounted and wired to a test car. Several preliminary examinations of the unit are completed, which does include the 'characterization' of various control parameters that establish refined motor control.

There remain a number of more stress related, performance verification, examinations that will take place in 2013. The details of our intended examination and applied instrumentation are presented below.

Performance Verification tests

- Traction Power Factor correction – We will assess an isolated traction load by measuring Voltage and Current monitored at the car's current-collectors. The recordings will be referenced to the respective converter operational-states and car speed as driven along our test track. Instrumentation used will be a HIOKI 3196 Power Quality Analyzer, and our internal MVB (Multifunction Vehicle Bus) monitor.
- Traction Efficiency – We will assess an isolated traction load, by measuring Voltages and Currents independently at each Line Converters' input, and each Motor Converters' output. These signals will be referenced to each individual converter's operational-state, and car speed. Electrical information will be melded with the mechanical data (refer to below) to directly assess efficiency from track-power to the mechanical wheel-hub interface. Instrumentation used will be a TEAC LX100 data logger, and the MVB monitor.
- Harmonic content – We will assess the entire car load (traction + auxiliaries) by taking measurement at the substation line connection to our test track's track-conductors. Instrumentation used will be a HIOKI 3196 Power Quality Analyzer set to collect 50 orders of harmonic content. Pass/Fail criteria are the levels required by IEEE 519.
- Acoustic noise – We will assess acoustic noise generated from isolated auxiliaries load, and from the entire equipment compliment including propulsion and braking equipment per associated ASCE requirements. Instrumentation used will be studio grade noise canceling microphones and Brüel & Kjær sound equipment.
- Tractive Effort – We will assess mechanical performance and mechanical efficiency by measuring directly the torque produced at the wheel. Instrumentation used will be two Multi-Axis Wheel Force Transducers mounted to the same axle, and a telemetry-based torque transmitter mounted to the associated driveshaft.

Conclusion

Although more testing is planned, indications are the AC/AC propulsion system is hitting the mark with respect to the engineering objective. And the *INNOVIA* APM 300 AC/AC vehicle is on trajectory to providing our customers state of the art technology, and potentially a 40% increase in energy efficiency as compared to the APM 100.

References

[1] Bombardier Transportation, Systems. (c. 2012) ‘untitled’, “various photographs”, internal R&D project library.

[2] Bombardier Transportation, Systems. (c. 2011) ‘untitled’, “various 3D renderings”, internal R&D project library.

Challenges with System Integration

Mark V. Incorvati[1],

[1]Lea + Elliott Inc., Manager of Engineering Projects, 800 Vinial Street, Suite B307, Pittsburgh, PA 15212; PH (412) 400-0791; email: mincorvati@leaelliott.com

ABSTRACT

It has been debated which of the APM/ATS major subsystems, Rolling Stock or Automatic Train Control (ATC), is most critical to project delivery; when in fact, it is neither. In truth, the critical element is not the subsystem itself but the successful integration of the two along with the other key system components from PDS (Power Distribution System) to fixed facilities to fare collection. Without particular attention and effort by owners and suppliers as to how the various components physically and functionally interact as a comprehensive system, the end result could range anywhere from significant project delays to unacceptable safety conditions.

Growing trends in the transit industry are adding to the already existing complexity of system integration. These growing trends include changing requirements. Just as technical requirements are becoming more and more onerous, so too are commercial requirements; in particular, project schedule. Owner required shortened project design-build lifecycles are resulting in less time to thoroughly account for all subsystem interfaces. Another aspect to be explored occurs in brown field applications when 21st century technology must replace (or even interact) with non-compatible, decades old equipment still in operation. Finally, as the economy becomes more and more global, so too does the APM/ATS industry. The "one stop shops" for APM/ATS systems are being replaced by multiple sub suppliers from various parts of the world. As a result, system integrators must ensure that all parties are "speaking the same language" in terms of commercial and technical terminology as well as business and ethnic culture.

These changes have had a substantial impact on the integration efforts required on any given transit project. This paper will examine the pitfalls that accompany these growing trends as well as the methods and practices that can help avoid them.

What is System Integration?

System integration for APM/ATS projects encompasses the activities that fuse the various subsystems, as shown in Figure 1, into a complete transit system. The end result is a system that satisfies the requirements of all stakeholders.

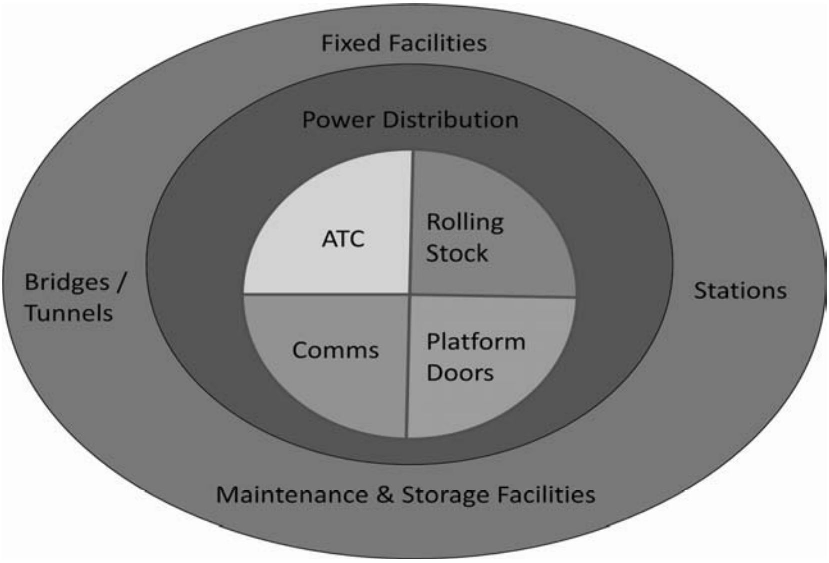

Figure 1. Major Transit System Interfaces.

System integration must be considered at every phase of a project. This includes planning, requirements and requirement allocation, design, implementation, and testing and commissioning.

Effective system integration includes the bringing together of subsystems in a logical sequence with appropriate traceability at each stage. System integration must include the testing and verification of total system performance to confirm that the operational requirements have been achieved when all components are interacting as one system. Having a completely integrated approach reduces the overall risk of nonconformance and rework for all interfacing parties.

The initial steps of System integration include producing the functional requirements of the overall system. These requirements are then augmented with functional block diagrams from which physical elements are defined. From here, interfaces between subsystems are identified and with proper interface management, traceability of these interface requirements can be made back to the functional definitions originally created.

The importance of System Integration is in direct relationship with the complexity of the final overall system. For APM/ATS projects, this complexity is rooted in the demanding system performance requirements, interfacing of multiple subsystems, automating complex system movements and providing for public safety.

However, in recent years, the industry has witnessed growing trends that further add to the challenges already experienced by transit system integrators.

Project Schedules

The definitive components of any project schedule are the start and end dates. These points of a project schedule are often constrained by external factors that are typically not in direct control of any of the project stakeholders. Start dates are dependent on owners obtaining the necessary funding and government authorizations while project end dates can be bounded by certain “non movable” events such as the World Cup or the Olympics Games. Recent examples of fixed end dates are shown in Table 1.

Constraint	System	Completion Date
Beijing Summer Olympics	Beijing Airport APM	June, 2008
South Africa World Cup	Gautrain MRT	June, 2010
King Abdullah inauguration of the Princess Nora bint Abdulrahman University	PNU APM	May, 2011

Table 1. Projects with “Fixed” End Dates

Furthermore, due to global recession and the recent debt crisis experienced by both the US and the EU, there has been increasing pressure in all aspects of government funded programs to reduce cost. In an attempt to reduce APM/ATS project cost, System owners have reduced project schedule time of the E&M suppliers. An increasingly common method for owners to accomplish a reduction in project duration is by staggering the contract releases of various suppliers. Contractors designing the facilities and superstructure might be on board months prior to the E&M (Electrical &Mechanical) contract being signed. The time between supplier contracts could increase if award disputes and contract negotiations take longer than expected to resolve. This would create a significant gap in the design efforts between key subcontractors that System Integrators must bridge to successfully execute a project.

Ultimately, system integrators are faced with the struggles of identifying all system interfaces and ensuring the details of subsystem designs have accounted for these interfaces. When various supplier project schedules do not coincide, the design of one supplier (e.g. the superstructure) might be at the 90% completion stage, while the E&M contractor has barely engaged in its preliminary design. Thus, the passing of critical interface information could be delayed, incomplete or incorrect as they have not been properly vetted via the E&M design process.

Integrators are further challenged if project durations do not allow sufficient time to identify, troubleshoot and correct issues stemming from interfaces of multiple subcontractors. If not discovered in the design phase, interface issues will for certain manifest themselves in the construction or test phase, leaving very little time to resolve. At this point, the impact to project stakeholders to correct these issues, both in terms of cost and schedule, can be orders of magnitude higher than if discovered in design.

As an example, consider if the vehicle envelope details were not properly integrated between the Vehicle Supplier and the Fixed Facility Contractor and that this discrepancy was not discover until the test phase. At this point, major modifications would be required of either a delivered fleet of train-sets or a fully constructed structure (e.g. station) or both.

Brownfield Applications

System owners are faced with major modifications to existing systems as the environment surrounding the system grows and ridership requirements change. Whether it is due to increase air travel or urban expansion, APM/ATS systems are often extended to meet growing demands. Many times, system owners will take advantage of extensions to make major modifications to particular subsystems.

Similarly, as APM/ATS technology has been deployed for years, many systems are reaching or even exceeding the designed service life of key components. System owners and operators have addressed this situation by making incremental upgrades to various subsystems. While this can help extend system usage, many transit authorities are ultimately faced with major modifications.

An extreme situation would call for total decommissioning where the demolition of an entire system, including infrastructure, is followed by a complete replacement of all transit system components. The associated cost to implement this scenario is considerably high.

To reduce costs, system owners would prefer to engage in “Brownfield” projects where certain existing subsystems such as passenger stations, M&SF, guideways and Power Distribution are maintained and upgrades and modifications are limited to subsystems such as the ATC, Communications and Vehicles as opposed to “Greenfield” projects consisting of entirely new subsystems.

An important note to point out is that system modification and extension contracts are not guaranteed to be awarded to the base or original contract supplier, especially given that many state and local statutes prohibit the award of sole-source contracts.

The above situations will each leave the system integrator with a complex challenge: how to integrate the existing subsystems with newer, perhaps vastly different technology. In Greenfield projects where subsystem and component designs are occurring concurrently, interface requirements can be incorporated into each sub suppliers design as the project progresses. For system integrators, the fundamental challenge in any brownfield project is that one or more system component is complete and to a large extent, not changing.

Interfacing challenges to this existing technology stem primarily from the lack of information pertaining to the intricacies of the base design. Although designs and specifications might have been well documented at some time in the past, the information may not be forthcoming or simply no longer exists. This could result from suppliers/vendors limited document retention plans, components becoming obsolete and no longer supported or even transit suppliers becoming insolvent. Even in cases of mergers and acquisitions, documentation retention could get lost in the transition.

As with many subsystems, technological growth has been explosive in the most recent years and has lead to growing incompatibilities between new and existing subsystem components. No subsystem has witnessed this more than ATC in the evolution of fixed block to Communication Base Train Control. A primary benefit to CBTC is its overlaying capability, making it an excellent choice for brownfield applications. However, in these cases, special care must be made by the System Integrator regarding the ATC interface to other subsystems, such as the platform screen doors, guideway switches and communication systems.

Furthermore, commercial aspect for many brownfield applications are the constraints placed on suppliers in order to address the operations on the existing system. Many brownfield project requirements call for little to no impact to existing revenue service. This places a tremendous burden on integrators as it could severely limit the time interface designers have to investigate and test component interactions.

Global Sub Suppliers

From a practical standpoint, interface complexity is not simply a function of the number of interfacing nodes (or subsystems) but also on the number of different organizations responsible for the design and implementation of the various subsystems. Traditionally, the multiple interactions of E&M subsystems have been under the control and direction of a single supplier. For these cases, requirement allocation and interfacing control documentation that governed the interactions of subsystems where developed by the same organization and most likely in the same location as the whole of the E&M design team. Likewise, fixed facilities components have fell under the control of a single General Contractor. Under these conditions, continuity between station, superstructure and facility designs are easily achieved as the interactions were lead by a single designer.

In these situations, the major interfaces between E&M and Fixed Facilities were controlled and managed as shown in Figure 2.

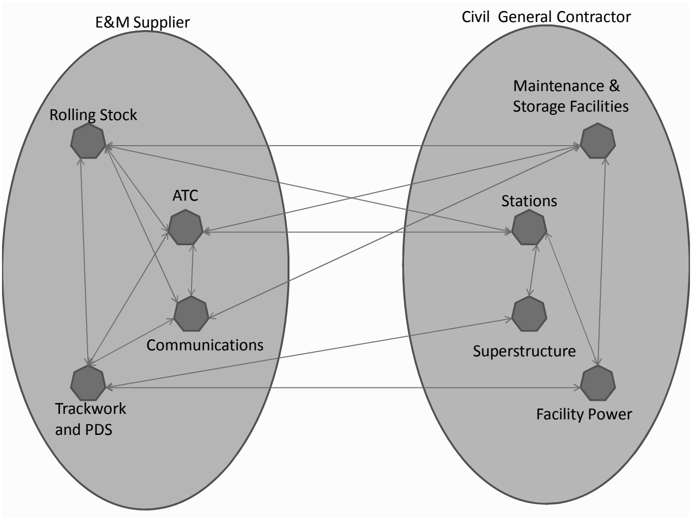

Figure 2. Traditional E&M and Civil Interfaces

However, in order to deliver a product with the most competitive price, many suppliers have turned to low cost countries to provide various subsystems and components. Not only does this outsourcing include manufactured components, but most recently, this has included subsystem designs as many emerging markets are becoming more and more technologically competent. Likewise, many system owners are requiring a significant portion of the contract value to be covered by local suppliers. While in the past, this scope of work primarily focused on labor intensive activities such as installation, recent trends have shown that "local content" now includes design and implementation components as well. This is forcing the major E&M suppliers to look beyond in house capabilities and existing knowledge bases.

This split and re-distribution of design activities can also seen in the Civil Scope as well where political and economic factors can force owners to contract multiple designers for a given project. As a result, a system with n number of stations could have an equal number of separate station designers, each of which is required to interact with the E&M supplier and their multiple subsystems.

For System Integrators, this presents a specific challenge as not only has the number of interacting parties significantly increased but each party now brings with it an individual set of documentation, terminology, nomenclature, let alone different languages and business cultures that further add to the complexity of fusing various designs into a complete transit system. This increased complexity can be seen in Figure 3.

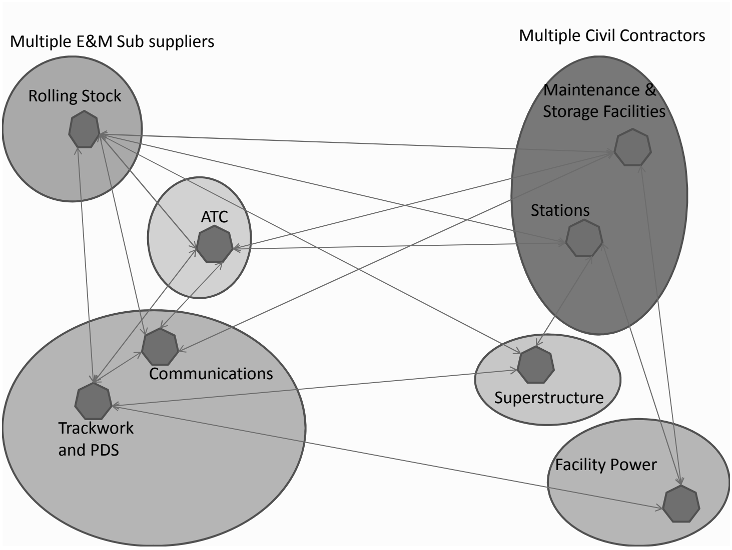

Figure 3. Complex E&M and Civil Interfaces

Mitigations to Integration Challenge

These challenges and issues with integration can all be overcome, but it will take the effort all involved parties. All project stakeholders must each be engaged throughout the project lifecycle to address the noted challenges and mitigate the risk these challenges pose to the overall completion of the project.

In the planning stage of a given project, owners should consider emphasizing functional and performance requirements in the request for proposal documents rather than dictating specifics into the technical provisions. This will allow more subcontractors to bid standard products with standard predefined interfaces. In addition, proposal requirements should include for a submission of design criteria highlighting specific interface data such a vehicle/trackwork loads, and equipment facility requirements. Likewise, suppliers can take steps in the pre bid stage to facilitate integration issues. A core set of design criteria should be developed that can be released either at the bid phase or immediately following NTP of the project. Finally for brownfield projects, where E&M suppliers must interact with existing equipment, owners should include in the RFP, all available designs, documents, and O&M manuals to enable subcontractors to develop interfacing and cutover plans. In addition, owners should specify where such documentation is not available to allow system integrators to develop strategies to investigate and obtain the needed information.

Nowhere is system integration more critical, however, than at the start of the design phase. This is the single best position in a project lifecycle to reduce integration risks whether they are induced by project schedule constraints, incompatible technologies or interaction complexity. At this point in a project, the agreed to interfaces will ultimately determine derived requirements for each subsystem's final design. While telecommunication advances provide excellent tools such as video conferencing and on line meetings, the most effective way to identify and define these interfaces is by face to face interactions of all project stakeholders. Each stakeholder must be committed to spend the time and effort to physically come together (even to the point of cohabitation) and reach consensus on interfaces. This level of interaction must necessarily be done to vet all interfaces design requirements.

Also, this stage is when brownfield interfaces are to be defined. Without sufficient design documentation, designers must be committed to be on site and reverse engineer existing designs interfaces; owners and system operators must be equally committed and allow reasonable access time to existing equipment for engineers to perform sufficient tests and investigative activities to ensure their design can be integrated to the existing system equipment.

These challenges will force integrators to strictly adhere to the practices and procedures in many standard integration planning documents. Basic integration techniques become even more important as the complexity level of integration increases. Such techniques include a master list of terms, definitions and abbreviations, which must be developed by the system integrator and adopted by all interfacing parties. In addition, integrators must develop interface matrices to keep track and trace all interface requirements throughout design, construction and testing.

CONCLUSION

Before the first APM system is implemented on Mars, we first have to get there. A blow to this endeavor was experienced in 1999, when an error between 2 separate teams led to the destruction of the $125 million Mars Climate Orbiter. The failure occurred as the 2 teams were speaking separate languages: US Standard Measurements and SI Units of Measure. As a result, instead of reaching a safe orbit, the spacecraft crashed into the Martian surface. Not only was this a major setback to NASA officials, but it is served as a painful reminder to System Integrators in every field that without proper vigilance, integration failures can lead to disastrous conclusions.

The most powerful tool for a system integrator is communication; upfront, honest and open communication between the interfacing parties from bid to substantial completion is the key component to overcoming integration issues. As growing trends hamper this communication, the efforts by System Integrators must necessarily be increased. This increased effort must be shared by all stakeholders as all parties involved can and will be impacted when subsystems fail to come together.

EVOLUTION OF A NEW GENERATION OF AUTOMATED TRANSIT SYSTEM — INNOVIA APM 300

Kevin Lewis[1] and Lance Schnur[2]

[1]APM Center of Competence, Bombardier Transportation, Systems Division, 1501 Lebanon Church Road, Pittsburgh, PA 15236; PH: (412) 655-5351; FAX (412) 655-5442; e-mail: kevin.lewis@us.transport.bombardier.com
[2]APM Center of Competence, Bombardier Transportation, Systems Division, 1501 Lebanon Church Road, Pittsburgh, PA 15236; PH: (412) 655-5106; FAX: (412) 655-5442; e-mail: lance.schnur@us.transport.bombardier.com

ABSTRACT

Figure 1: APM 300 Vehicle Concept

In 2009, Bombardier Transportation Systems Division ("Bombardier") embarked on a development project that was initially designated as the "APM Platform Convergence" project, later to become known as the *INNOVIA* APM 300 project. The challenge from division management was to look at our two existing Automated Peoplemover (APM) platforms, namely the CX-100 and Innovia systems, and determine if the platforms could be combined to maximize synergy, improve performance and reduce overall system cost. Product management principles were employed in comparing the two platforms. It was desired to maintain the cost saving design aspects of the Innovia platform, while also providing the ability to introduce new technology to our existing CX-100 customers and not void their wayside infrastructure.

The work over the last three years has culminated in the development of the *INNOVIA* APM 300 vehicle platform. This paper summarizes the key development efforts of this new platform, and compares its performance and design features to previous Bombardier APM platforms.

INTRODUCTION

For over 40 years, Bombardier has been at the forefront of developments in automated people mover (APM) technology. The *INNOVIA* APM 300 system is the latest in a long line of APMs for use at airports and in urban environments. In 2009, Bombardier began a project to update its APM technology by employing Design for Manufacture, Design to Cost, Design to Weight, Design for Environment, and other techniques, developing a single vehicle platform to replace its CX-100 and *Innovia* platforms. Significant features of this single platform would include an overall length equivalent to its CX-100, an all-aluminum carbody structure, increased performance, and improved energy consumption, in addition to numerous less-significant improvements.

To achieve these goals, Bombardier established a development project to "converge" the CX-100 and Innovia (the original names of the *INNOVIA* APM 100 and *INNOVIA*

Figure 2: APM 300 Prototype Vehicle Operating on Test Track, Pittsburgh, PA
Photo:Bombardier/ Kevin Lewis, 2012

APM 200 respectively) technologies into this single platform; initially known as the "APM Platform Convergence" project, it resulted in the APM 300 vehicle platform which was first operated on the Bombardier Transportation, System Division's Pittsburgh APM 200/300 Test Track in March, 2012 (Figure 2).

In the conceptual design phase of this project, several important design decisions were made, including:

- Increase the length of the Innovia vehicle to be equal to that of the CX-100 vehicle
- Upgrade the propulsion performance to incorporate AC traction motors on each axle, thus enabling top speed performance to 50 MPH (80KPH)
- Construct the new vehicle carshell from aluminum extrusions and huck bolt the assembly together, replacing the Innovia composite carshell
- Develop a propulsion system that will enable the new vehicle to operate on the existing CX-100 600VAC power supply distribution system with improved energy consumption

Design details resulting from these concept decisions were subsequently developed into the final design of the APM 300.

SYSTEM COMPARISON

In order to better understand the rationale for converging the two APM platforms, a brief overview and comparison of the typical system elements is instructive. The system scope of supply for both of these systems typically includes:

- Vehicles
- Guideway
- Switches
- Power supply and distribution
- Automatic train control
- Electrical installation
- Station equipment
- Communications systems
- Maintenance facility
- System integration
- Project management
- Product introduction
- Operation and Maintenance
- Technical Publications and Training

The major differences between APM 100 and APM 200 systems are the vehicles, guideway, switches and power distribution. The other system elements are essentially the same.

The defining difference is in the vehicle to guideway interface. The APM 100, illustrated in Figure 3, utilizes guidewheels that hang below the running surface.

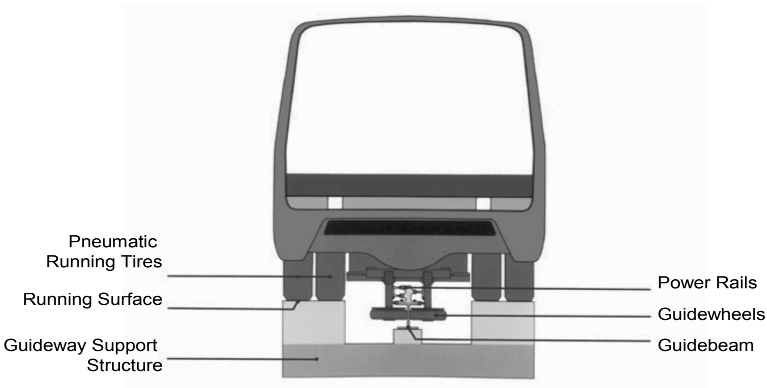

Figure 3: APM 100 Vehicle / Guideway Interface

The APM 200 (Figure 4) utilizes guidewheels that are above the running surface.

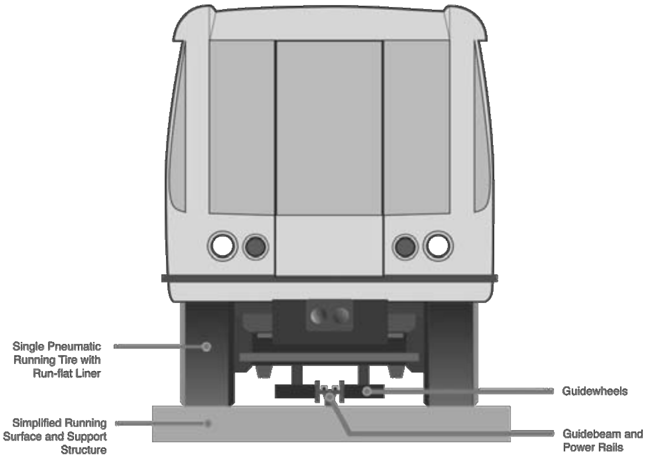

Figure 4: APM 200 Vehicle / Guideway Interface

The simplified guideway interface used on APM 200 results in a lower-cost guideway and a simpler, less expensive switch. It also means that the APM 100 and APM 200 vehicles are not interchangeable in that each vehicle is specifically designed for its guideway. There are minor dimensional differences between the two vehicles that affect interchangeability.

The major vehicle and power distribution differences associated with the two systems are summarized in Table 1.

Table 1: System Characteristics Comparison

APM 100	APM 200
DC propulsion system (no regeneration)	AC propulsion system (regeneration optional)
AC auxiliary loads fed from a step-down transformer	AC auxiliary loads fed from an auxiliary inverter
Top speed 60 kph	Top speed 80 kph
Aluminum roof and sides attached to a steel underframe	Fiber-reinforced composite body attached to a steel underframe
Dual rubber tires with run-flat between tires	Single rubber tires with run-flat inside tire
Rigid axle, motor attached to bogie, and all steer as a unit	Steerable axle; motor is mounted to carbody
Discrete on-board vehicle control	TCMS vehicle / train network
AC (3-phase) power supply	DC power supply
Flat floor (no wheel wells)	Wheel wells
6.1 m wheelbase	7.6 m wheelbase

Other variations in subsystems exist, but are not as significant to these in consideration of converging the two systems into a single platform.

Following review of the two platforms, Bombardier concluded that the new platform should be based on the APM 200 design, and incorporate design changes to improve the platform against one or more of the evaluation criteria, with variant accommodations for both AC (APM 100) and DC (APM 200) Power Supply and Distribution (PS&D) wayside systems.

WHY INNOVIA?

In 1995, a predecessor to the Systems Division embarked on a review of the "CX-100" system and the need for an upgrade. The purpose of the review was to ensure that Systems would be able to satisfy the needs of the Automated People Mover (APM) marketplace for the upcoming years. At that time, the APM 100 had been installed in 14 locations over a period of 25 years. In the course of this review, it was determined that it would not be cost-effective to simply update the APM 100, given the number of changes identified as necessary to comply with updated standards (e.g. NFPA 130, ASCE 21) and emerging application requirements. The decision was made to develop a new system and vehicle design. As a result, it was agreed that the APM 100 would be retained as is for expansion of existing fleets and systems. The *"Innovia"* would be offered for green field (new) systems. Given this premise, the resulting product was expected to achieve the following:

- 30% reduction in the cost of the overall system
- Reduced life cycle costs
- Higher performance capability to address urban as well as airport applications
- Increased modularity and use of standard options
- Reduction in guideway construction time
- Modern vehicle aesthetics with pre-designed options
- End egress from the vehicle as an option, so that the guideway could also function as the emergency walkway
- Improved ride quality and reduced steering forces
- Increased wheelbase for dynamic stability
- Improved manufacturability

During the *"Innovia"* development project, several key technology decisions were made in order to address the above criteria:

- A new guidance concept, incorporating a body-mounted motor with a Daimler-Benz steerable axle and single running tires, was developed in order to simplify guideway construction and reduce steering forces. This also allowed a simpler, less-costly switch to be designed. This switch allows for continuous power collection through the switches, an advantage for higher speed operation.
- An advanced composite material, and a manufacturing process known as SCRIMP, was chosen for the carbody. At the time, engineers in sister divisions were working with DuPont on prototypes for rail car bodies using this material.

- Two levels of propulsion capability, PL1 and PL2 utilizing one or two inverters and traction motors respectively, with 80 kph capability via the PL2 configuration for systems with suitable station spacing, was defined.
- AC drive was selected, as DC propulsion systems were no longer being used for other transit applications. While DC propulsion systems can regenerate, this had never been done on APM 100 (only rheostatic braking was used), as the Power Distribution System (PDS) is 3-phase AC. AC Drive commonly provides for regeneration (which has been done in other applications for either AC or DC PS&D).
- An end egress capability was designed, utilizing aircraft-style, manually-operated swing plug doors and coupler covers to allow car-to-car and car-to-guideway passenger movement.
- Mitrac TCMS (Train Control and Management System, a vehicle and train network) was selected to provide modern control and diagnostics.
- CityFlo 650 moving-block automatic train control was selected as the exclusive ATP/ATC system, as fixed block systems were considered to be obsolete for new applications.
- DC power supply and distribution was chosen for cost benefits on longer systems (DC substations can normally be spaced farther apart than their AC counterparts), as well as the elimination of concerns about power factor correction and harmonics filtering on AC power distribution systems.

The APM 200 systems at Dallas Fort Worth and Heathrow airports have proven to be highly reliable APM systems with many new and desirable features. The APM 200 system design meets most of the above achievement specs and advantages. However, there are several areas where APM 200 did not provide the expected benefits:

- An estimated 12% cost reduction was achieved on larger systems like DFW, but no cost benefits were seen on smaller systems.
- The SCRIMP process had not been adopted for other transit applications, as originally expected; thus there was still only one supplier for the carbody components.
- It proved to be difficult and costly for the composite carbody to meet British fire and smoke requirements, implying a risk that future fire safety standards or specifications would render the use of the SCRIMP process impractical.
- The reduced passenger capacity of a vehicle shorter by approximately 30 inches overall proved to be a significant challenge, increasing the number of vehicles necessary to provide the specified system capacity in far more cases than not.
- DC propulsion and other nearly obsolete components (such as the door operators) for the existing APM 100 platform were still available and cost less than their modern replacements, making the APM 200 less attractive in a highly price-sensitive market environment.
- The benefits of regeneration proved to be elusive in practical application.
- No applications have surfaced that would allow the guideway to be used as the emergency walkway; a separate walkway is required by most all specifications.

- The composite and steel carbody is not compatible with a "mobile factory" concept to localize assembly where there is a labor-rate advantage or a localization requirement in specification or law.
- The APM 100 had not been eliminated on bids for greenfield systems, primarily due to its higher passenger capacity (a result of the APM 200 vehicle's decreased length), and thus Bombardier was maintaining two APM platforms.

The net result of these remaining issues was that the APM 100 system remained cost-competitive internally as well as in the market. Revised standards and specifications (particularly in ASCE 21), however, continued to impact design and manufacturing costs in other areas of its design, particularly the carbody, and both cost and weight increased on each project. In order to remain competitive, the APM 100 would require significant redesign to ensure cost-effective compliance with then-current, as well as future standards.

In order to address the remaining shortcomings of the APM 200, as well as the challenges to APM 100, Bombardier took a new look at the similarities and differences of APM 100 and APM 200 systems, and concluded that an APM 200-style vehicle, lengthened to match the APM 100 and suitably modified to incorporate APM 100 guidance and power supply interfaces, could operate on a APM 100 system: The overall width and tire track width are compatible, and the wheelbase, while increasing chord intrusion of the vehicle in curves, was compatible with APM 100 switches and could accommodate its power collection, and actually reduced the comparative vehicle overhang. While station door spacing on existing systems would prove to be a challenge, an APM 200-style vehicle with a APM 100's overall length and widened vehicle doors could come close in most berthing situations, with the only compromise being that part of the vehicle sidewall would be visible through the station door opening in operation.

Having determined that there were no "show-stopper" challenges at that time, and that development of a common platform vehicle with variants capable of operating on either legacy APM 100 or new APM 200-style systems could address both the APM 200's remaining issues and the APM 100 concerns which precipitated the APM 200 development, Bombardier initiated a program to develop the "converged" platform which would become the *INNOVIA* APM 300 vehicle. This program would encompass design of the base APM 300 DC-AC which would incorporate existing or mildly-updated APM 200 PL2 subsystems with a new aluminum carshell, and the APM 300 AC-AC variant, which would: replace the PL2 propulsion system with an AC-supply system that retained the same traction motors; substitute a step-down transformer for the auxiliary inverter; modify the guidance system to interface with I-beam rather than H-beam guidance; and replace the current collectors with APM 100 collectors.

COMMON CARSHELL DESIGN APPROACH

A vehicle's carshell forms the basis of its design, and provides a common interface for integration of the remaining vehicle subsystems. The APM 100 and APM 200 vehicles differ in length, door spacing, and wheel base, but share almost identical width and height, allowing for a common vehicle cross section that would be applicable to both platforms. As noted previously, the vehicle overall length would match the APM 100 in order to maximize passenger capacity and minimize door-spacing issues. In order to minimize weight, cost, sourcing, and corrosion issues while optimizing structural strength, fire performance capability, and recyclability, Bombardier chose aluminum for the primary material, with friction stir welded large-scale extrusions forming much of the structure.

The final carbody design consists of four basic modules (see Figure 5): floor, roof, side center (2 per car), and side ends (2 left and 2 right per car). Each module is comprised of specially designed aluminum extrusions; the floor and roof joined by using friction stir welding and the sidewalls comprising posts and bonded skins. The modules are fully fabricated and machined prior to delivery, and can be shipped as "flat-packs" to localized assembly facilities, where the simple Huck® bolted modules can be spliced into a finished carbody without a need for certified welders on-site. This design concept has become commonplace within the mass transit industry, allowing Bombardier to capitalize on expertise and best practices from Bombardier sister divisions.

In addition to the aluminum primary structure, the carbody also comprises two steel subframe members, the coupler interface bracket and the suspension frame. The coupler bracket distributes and transmits draft and buff forces from the coupler into the aluminum frame, while the suspension frame transmits traction and brake forces from the axle to the carbody. Non-structural fiberglass endcaps complete the carbody.

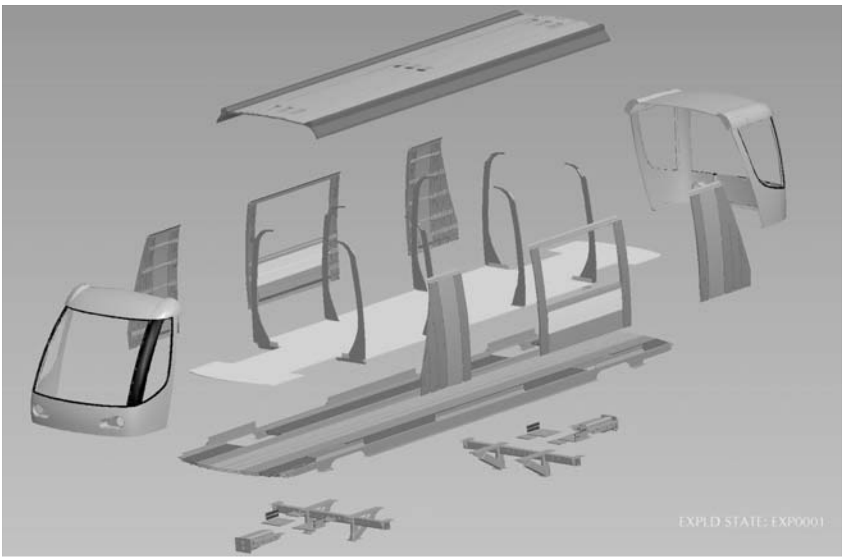

Figure 5: APM 300 Carshell Elements

INTERIOR DESIGN APPROACH

An advantage of the SCRIMP process is that it can result in two finished surfaces, ideal for a transit vehicle which requires a finished interior as well as exterior. However, this resulted in the need to develop a new interior for the APM 300. Bombardier chose FRP with a gel-coat finish as the standard interior liner material, and designed the side panels to conform to the exterior carbody profile. A typical APM 300 interior is illustrated in. Hinged access panels form equipment lockers above each of the four corner seats; each seat itself is an equipment locker as well. A combination of fixed and hinged panels form the cantrail cover above the sidewalls, and fixed ceiling panels are installed between the parallel light units.

Accommodation for fixed or flip-up seats to be mounted on the sidewall between the two doors was incorporated into the vehicle structure. Vertical stanchions are integrated into the structure and the interior design adjacent to each door opening to assist in boarding and alighting; two ceiling stanchion brackets, comprising continuous longitudinal channels, were incorporated into the structural design to accommodate additional vertical stanchions, longitudinal or lateral overhead handrails, strap-hangers, or a combination of the three.

Public Address speakers are integrated into the hinged panel above each passenger door; optional LED-based dynamic graphics displays are also housed in these panels.

Figure 6: APM 300 Interior

As part of a passenger on-board information enhancement project, video capability was added to the communication system; to accommodate this capability, each sidewall locker panel can optionally house an LCD video display monitor, or alternatively, LCD monitors can be installed in a hinged panel above each side window.

BOGIE DESIGN APPROACH

As previously discussed, prior to embarking on the APM 300 development program, Bombardier investigated the similarities and differences of the APM 100 and APM 200 system interfaces; primary among these was the bogie-to-wayside interface, a complex interaction of mechanical and electrical elements. The least-understood element within this interface was the clearance of the axle bevel gear housing to the APM 100's AC power rail "Christmas tree" bracket; a layout of this interface was made to investigate this clearance in all design conditions. The layout showed that an APM 200 bogie would clear the APM 100 power rail, even under worst case flat tire conditions. For reference, a cross section of the APM 200 bogie on an APM 200 guideway is shown in Figure 7, while Figure 8 illustrates that the APM 200 bogie can adapt to the APM 100 guideway by extending the guidewheel stems, changing the diameter of the guidewheels, and developing new linkage to interface the guidance system to the steerable bogie.

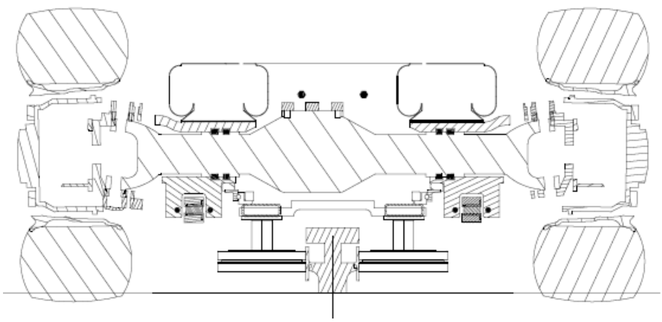

Figure 7: APM 200 Guideway Interface

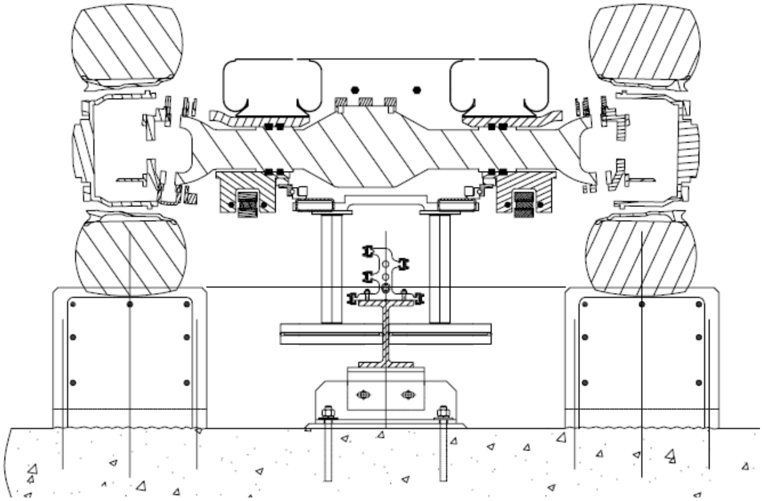

Figure 8: Modified APM 200 Bogie on APM 100 Track

While some testing, in particular strength and fatigue life verification of the guidance frame and guidewheel assembly, and more-complete clearance testing, remain to be completed, the design has been demonstrated on a vehicle on the Bombardier Transportation APM 100 Test Track in Pittsburgh, Pennsylvania.

PROPULSION DESIGN APPROACH

Due to the significant differences between the AC and DC PS&D systems, two different propulsion system designs are necessary. APM 100 uses a 600VAC, 3-phase PDS, while APM 200 uses a +/-375VDC PDS. The APM 200 PL2 propulsion system, developed in a previous project, is the propulsion element of the APM 300 DC-AC variant, providing 80 kph speed and 10% gradient capability on DC PDS systems, while a new propulsion system, based on the PL2 system but with numerous changes to accommodate the APM 100's 3-phase AC power supply, was developed in conjunction with the APM 300 project. This new propulsion system is discussed in detail in Paper 55, *New "AC/AC" Propulsion System for the INNOVIA APM 300.*

AUXILIARY ELECTRICAL SYSTEM APPROACH

As previously noted, another significant difference between the DC and AC variants of the APM 300 is that the DC vehicle's auxiliary electrical system has an auxiliary inverter supplied directly from the +/-375VDC input, while the AC vehicle carries over the APM 100's 3-phase step-down transformer. The PL2 auxiliary inverter creates 3-phase 240V power for loads such as the HVAC, Air Compressor, Low Voltage Power Supply and Battery Charger. For the APM 300 AC variant, no auxiliary inverter is required as the 3-phase equipment is fed from a simple transformer.

Bombardier has introduced a new vehicle battery for the APM 300. This battery utilizes a lithium iron magnesium phosphate chemistry, which provides the power density of a conventional lithium-ion battery but with much lower risk of thermal runaway due to cell short-circuit or puncture. The battery is also monitored for internal and external temperature as well as charging and output, with conditions and alarms reported via the vehicle TCMS network.

DESIGN FOR ENVIRONMENT APPROACH

Bombardier has placed significant emphasis on environmental protection throughout a systems lifecycle from cradle to grave. Design for Environment was a continuous consideration throughout the design of the APM 300. Specific DfE areas addressed include energy consumption, greenhouse gas generation, hazardous material reduction, and end-of-life disposal / recyclability. These areas are evaluated over the vehicle's entire lifecycle, and the result is encapsulated in an Environmental Product Declaration, a publication which is developed in accordance with the UNIFE Product Category Rules for Rail Vehicles (PCR 2009:05).

The APM 300 contributes to energy savings in several ways: The vehicle dead weight per passenger has been reduced from previous vehicles primarily through a weight-efficient carbody, and additional weight-reduction efforts continue; all vehicle lighting has been converted to LED sources (with the additional environmental benefit of waste reduction, particularly by replacement of mercury-containing fluorescent interior lights); and regenerative braking returns deceleration energy to the PDS to be consumed by other vehicles or returned to the grid.

During the design process, Bombardier addressed not only the mercury in fluorescent lamps but also chromium-VI, which is prevalent in anti-corrosion coatings (especially on fasteners) and presents a hazard to chromium miners and processors; the APM 300 utilizes a combination of stainless steel (in smaller sizes) and Geomet®-coated carbon steel fasteners for assembly and equipment installation.

CONCLUSION

Bombardier has completed the design of both DC and AC variants of the APM 300 vehicle, and both configurations have been operated on Bombardier's Pittsburgh facility test tracks. The APM 300 DC has completed all qualification testing, and the APM 300 AC will complete qualification in the second quarter of 2013. While opportunities to reduce cost through Design to Cost methodology, costs for newly-designed systems were minimized through its application.

Both DC and AC vehicles incorporate modern, energy-efficient AC propulsion systems which require less maintenance than DC systems; both utilize a transit-grade network for control and monitoring; and both incorporate Bombardier's *VORS* (Voice-Over-IP Operational Radio System) to provide audio, video, and data communications between vehicle and wayside, as well as Bombardier's *HMS* (Health Monitoring System) health monitoring and predictive maintenance system, which reduces preventative maintenance frequency by calculating maintenance intervals based on vehicle system performance.

Train Control Upgrade for the Morgantown Personal Rapid Transit System at West Virginia University

Brian Yeschenko

Senior Transportation Engineer, Lea+Elliott, Inc., 2505 N. Highway 360, Suite 750, Grand Prairie, TX 75050 PH 972-890-9734; Fax 972-890-9735; byeschenko@leaelliott.com

ABSTRACT

The Morgantown Personal Rapid Transit (MPRT) system is an automated people mover system that provides non-stop origin-to-destination service among the separate campuses of West Virginia University and the Morgantown Central Business District. The system opened in 1975 and was the first large scale Automated Guideway Transit system in the United States. The MPRT is a vital piece of the University; without it, students would be unable to take classes on the adjoining campuses.

The Morgantown system meets most of the classifications of a PRT: it is automated; it responds on customer demand; and it provides direct origin-to-destination service. However, the Morgantown vehicles can accommodate up to 20 passengers, which the industry considers to be too large to be Personal Rapid Transit. Nevertheless, the Morgantown system is the only transit system in the U.S. that has achieved the operating characteristics of a PRT system.

After nearly 37 years of operation, the Morgantown system is due for an upgrade. On the existing system, communication with the train is achieved with inductive loops, or cables, that are embedded in the concrete running surface. Over the years, these loops have begun to deteriorate, which has adversely affected the reliability of the system. An investment in an upgraded train control system was recommended to sustain operations in the long term. Replacing the existing communication loops was determined to be infeasible due to the cost and the impact on operations. The University has elected to implement radio-based train control, or CBTC, while still maintaining the operating characteristics of the existing system. A radio-based communication system eliminates reliance on inductive loops, thereby improving the availability of the system while also lowering the maintenance costs.

This paper describes the Morgantown PRT system, the benefits of upgrading the MPRT with a CBTC system, and the challenges that the train control contractor is likely to face.

THE ORIGINS OF THE MPRT SYSTEM

The idea for the transit system was born out of necessity. In the 1960s, the University outgrew its downtown campus. A new campus was constructed in Evansdale, but it was located two miles from the downtown campus. The distance between campuses required students to travel by car or by bus to their classes. Prior to the implementation of the MPRT System, Morgantown would experience total traffic gridlock. At one point, the University was forced to require students to take classes at only one of the two campuses. (Gibson, 2002)

Professor Samy Elias, Head of West Virginia University's Industrial Engineering Department, believed that a transit system could resolve the University's traffic woes. Elias was instrumental in helping WVU secure a grant from the Urban Mass Transportation Administration to implement a transit research demonstration project. (Gibson, 2002) The objective of the demonstration project was to determine the most effective method of meeting the public transportation challenge in growing cities and metropolitan areas. The project was built in two phases, with the system's first phase opening for service in October 1975.

MPRT SYSTEM OVERVIEW

The MPRT connects downtown Morgantown and WVU's main campus with the Evansdale Campus and the Robert C. Byrd Health Sciences Campus. The system consists of a fleet of electrically-powered, rubber-tired, passenger-carrying vehicles, operating on a dedicated guideway network at close headway (15 second vehicle separation). The system features year-round operation, as well as direct origin to destination service. In total, the MPRT consists of 14 kilometers (45,936 linear feet) of guideway, and it covers 7 kilometers (4.35 miles) between the two end stations. The MPRT guideway has grades as high as 10%. While the University is in session, the MPRT carries about 16,000 passengers per day. During peak periods of operation, there are 55 vehicles on the system. The entire fleet consists of 71 vehicles. An MPRT vehicle is shown in Figure 1.

Figure 1: MPRT Vehicle Traveling on the Guideway (courtesy of WVU, 2005)

Guideway

The guideway structure connects 5 passenger stations and a maintenance facility station. The system layout is shown in Figure 2. The running surface is concrete, containing distribution piping for guideway heating to allow all-weather operation. Inductive loops are contained inside the running surface to enable the transmission of messages between the vehicle and the control and communications equipment. Speed commands, station stop commands, steering switch signals, and calibration signals are received by the vehicle through inductive communication loops buried in the guideway. Steering and electrical power rails are mounted vertically along the side of the guideway.

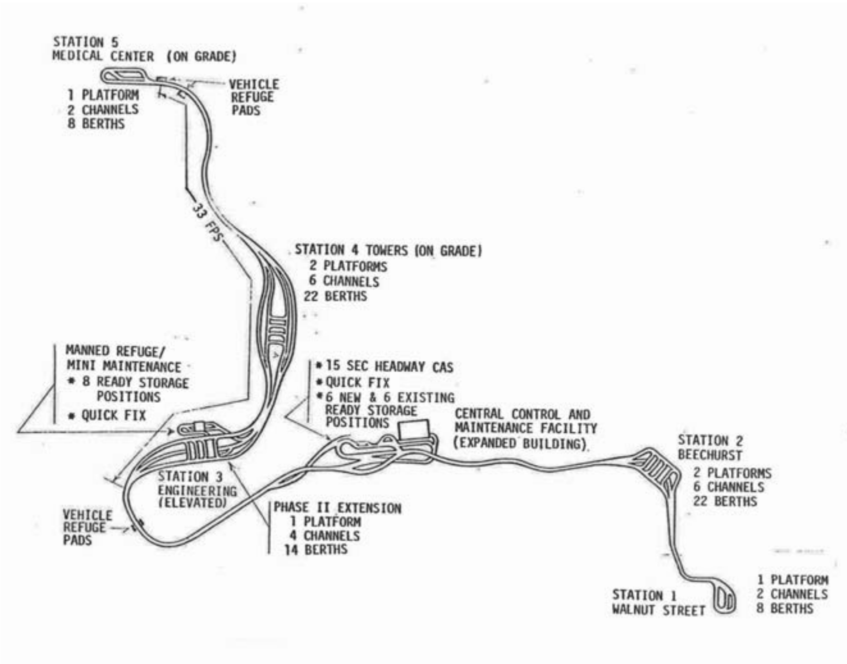

Figure 2: Morgantown Personal Rapid Transit System Layout (courtesy of WVU)

Passenger Stations

The station facilities provide access to the system, directing passengers to and from the vehicle loading areas. Each passenger station consists of multiple channels for vehicle berthing. The vehicles queue in these channels, with the forward-most vehicle for loading passengers and with two or three trailing berths for unloading of passengers. A descriptive depiction of vehicle queuing is shown in Figure 3, with an image of two berthed vehicles shown in Figure 4.

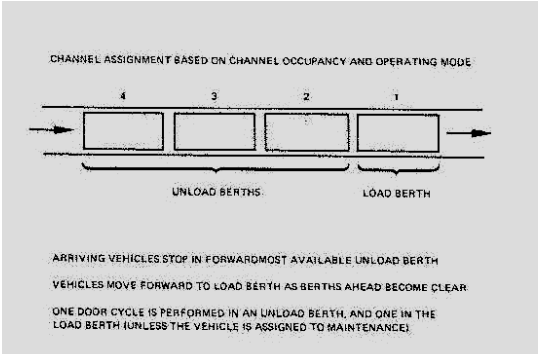

Figure 3: Station Berthing Channels (*M-PRT-1-1*, 1975)

Figure 4: MPRT Vehicles Berthed at a Station Platform (courtesy of WVU, 2008)

Maintenance Facilities

The maintenance facility station provides for operation, maintenance, test, cleaning and storage of vehicles. The facility consists of a maintenance building and associated guideway. A test loop exists for post-maintenance check. A second, smaller maintenance facility also exists on the system. This facility provides a quick-fix location for minor vehicle repair and vehicle de-icing.

Passenger Experience

At each station, passengers swipe a pass card or insert 50 cents in order to enter the loading platform. In addition to the fare collection, riders also select a button for their intended destination. With the system operating in demand mode, riders follow the overhead sign to the loading gate for their intended destination. After the rider boards the vehicle, the door closes automatically, and provided that the vehicle has not exceeded its maximum load weight, it proceeds directly to its destination, bypassing all other stations along the way.

SYSTEM RELIABILITY AND MAINTAINABILITY ISSUES

The biggest challenge that WVU currently faces is system maintainability. With the MPRT being in service for over 35 years, system components are continually being replaced and modernized. As time has passed, parts have become obsolete and finding replacements has become more difficult.

In 2009, WVU commissioned a study to assess the condition of the existing PRT system and to provide recommendations for improvement. An analysis of the MPRT System Availability shows that, from 1984 to 1998, the MPRT was available approximately 99% of the time. However, beginning in 1998, the availability has been trending downward. Despite numerous system component replacements, the availability has dropped to 97.5%. It was determined that a primary culprit for the degradation was the condition of the inductive communication loops embedded in the guideway concrete. Over the years, these communication loops have deteriorated and many are now out-of-tolerance. This results in poor communication, vehicle stoppages, and service interruptions. As these loops continue to age, the system downtime will further increase, perhaps exponentially. Figure 5 shows a picture of a weathered, defective communication loop that was replaced on the MPRT System.

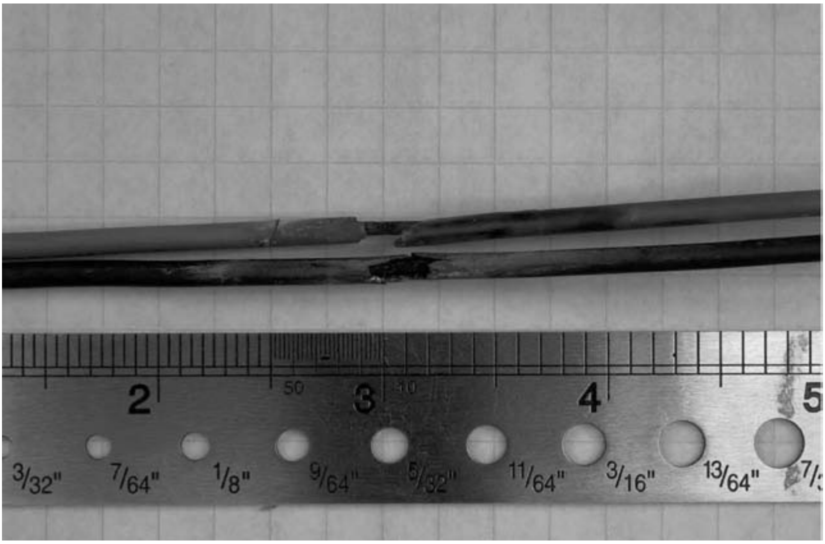

Figure 5: Defective/Weathered Inductive Communication Loop (courtesy of WVU)

The removal and replacement of all the communication loops would be difficult and time-consuming, requiring an extensive shutdown of the system. Due to the tolerances of the existing system, the loops would have to be positioned in the same location as the existing loops. The existing loops are covered with an epoxy that, in order to be removed, would require a precise sawing operation into the slots of the 14 kilometers (45,936 linear feet) of guideway. With four slots per linear foot, the system has 56 kilometers (35 miles) of loops that would require refurbishing. In addition to being costly and time-consuming, the loop replacement would marry the MPRT to its existing 1970s technology, which only enhances the probability of parts obsolescence. It was concluded that replacement of the existing communication loops was infeasible due to the cost and the impact on operations.

An investment in an upgraded radio-based train control system was recommended to sustain operations in the long term. A Communications-Based Train Control (CBTC) system communicates to trains via radio, thereby eliminating the reliability and maintenance problems of the inductive loops.

CBTC AND APPLICATION TO THE MPRT

A Communications-Based Train Control System is defined as a continuous automatic train control system utilizing high-resolution train location determination, independent of track circuits. In the case of the MPRT System, the inductive communication loops function as track circuits.

Conventional signaling/train control systems, including the MPRT, rely almost exclusively on track circuits or inductive loops to detect the presence of trains. A CBTC system offers improved reliability and reductions in maintenance costs through a reduction in wayside equipment and an increase in real-time diagnostic information. In summary, the basic characteristics of a CBTC system include the following:

1) Determination of train location, to a high degree of precision, independent of track circuits.

2) A geographically continuous train-to-wayside and wayside-to-train data communications network to permit the transfer of significantly more control and status information than is possible with conventional systems.

3) Wayside and train-borne vital processors to process the train status and control data and provide continuous automatic train protection (ATP). Automatic train operation (ATO) and automatic train supervision (ATS) functions can also be provided, as required by the particular application.

The automatic train control (ATC) is the system for automatically controlling train movement, enforcing train safety, and directing train operations.

The automatic train protection (ATP) is the subsystem within the ATC system that maintains fail-safe protection against collisions, excessive speed, and other hazardous conditions through a combination of train detection, train separation, and interlocking.

An interlocking is an arrangement of switch, lock, and signal devices that is located where rail tracks cross, join, separate, and so on. The devices are interconnected in such a way that their movements must succeed each other in a predefined order, thereby preventing opposing or conflicting train movements. Note that interlockings are not applicable for the MPRT System. For the MPRT, on-board switching would be used to control train steering where rail tracks cross, join, and separate. The vital logic for controlling the steering of the train would be performed by the train-borne CBTC equipment.

The automatic train operation (ATO) is the subsystem within the ATC system that performs any or all of the functions of speed regulation, programmed stopping, door control, performance level regulation, or other functions otherwise assigned to the train operator.

The automatic train supervision (ATS) is the subsystem within the ATC system that monitors trains, adjusts the performance of individual trains to maintain schedules, and provides data to adjust service to minimize inconveniences otherwise caused by irregularities.

A CBTC system shall establish the location, speed, and travel direction of each CBTC-equipped train.

CHALLENGES FOR THE CBTC IMPLEMENTATION

Routing and Vehicle Control

On the existing MPRT System, vehicle positioning and movement is controlled by a synchronous point follower system. The point follower system consists of moving slots that circulate the system in fixed time intervals (15 seconds). The slots are established, a vehicle is assigned a slot, and the vehicle maintains the position in the slot during its trip. The vehicle is dispatched by a station computer in time to merge into an open slot. The station informs Central of the vehicle destination, and it requests a dispatch time from Central. The dispatch time is determined so that a vehicle following the nominal dispatch profile for that station and starting position will merge on the guideway with its assigned moving slot position. An onboard vehicle clock maintains an accurate reference for the vehicle and compares distance traveled and speed, as measured by an odometer in the vehicle. Periodic calibration loops update any bias or random odometer errors. The slots are allocated by the central computer and they are monitored by the station computers; slot monitoring includes comparing the time a vehicle arrives at a presence detector with the expected time of arrival as determined by the station computer. Figure 6 illustrates the merging of vehicles from an off-line station back onto the main guideway.

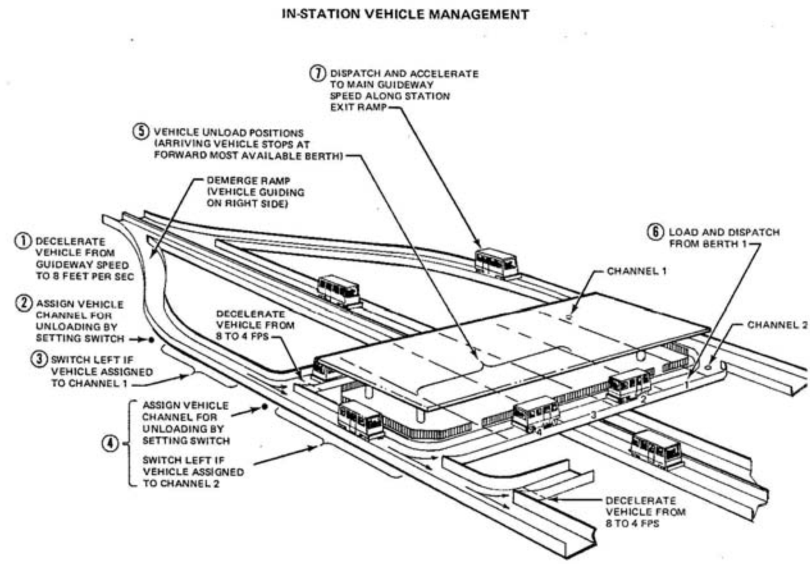

Figure 6: Movement of Vehicles at an Off-line MPRT Station (*M-PRT-1-1*, 1975)

The CBTC System will need to ensure that, just as in the existing MPRT, dispatches of vehicles from stations are properly timed so that vehicles seamlessly merge onto the main guideway without impacting any other vehicles on the system. The CBTC software will need to duplicate the functionality of the existing point follower system, which enables vehicle headways of 15 seconds.

In-Station Vehicle Management

On the existing MPRT System, passenger selection of a destination request initiates a sequence of searches by the station computer. The computer first looks for an empty vehicle currently in the station loading position. If a vehicle is not available, the computer looks for an empty vehicle in the station and directs it to the loading position. Otherwise, the computer finds the nearest available vehicle and directs it to the loading position

Routing of an incoming vehicle to an unloading berth is based on

- Channel assignment and station inventory policy
- Availability of an open berth

Routing logic decisions are implemented at the station branch points by steering commands which direct the vehicle into the proper channel. Figure 6 illustrates the movement of vehicles for a typical off-line station. Stopping deceleration is controlled by an on-board speed profile. The vehicle initiates the precise stop in response to an energized guideway stopping loop. The station computer commands energizing of the stopping loops at the channel location at which the vehicle is scheduled to unload. After door cycling, the vehicle is ready for dispatch.

The CBTC System will need to adopt the origin-destination concept into its routing algorithms, including the concept of empty vehicle management and the existence of off-line stations with multiple channels. In addition, the concept of queuing multiple vehicles (practically bumper to bumper) in a station channel may necessitate design changes.

On-Board Switching

In a typical transit system, vehicles change rail tracks by traversing a wayside switch. However, the MPRT system does not utilize wayside switches. As shown in Figure 6, vehicles exiting the main guideway onto the station ramp or vehicles exiting the station ramp to enter the vehicle berthing area are guided into the appropriate track channel by switches located on-board the vehicle. As a vehicle approaches each station, the software determines if the vehicle should be switched into the station. The vehicle receives switching commands, steers an on-board bias switch either left or right, and provides verification that a positive switching action has been completed. Failure to receive the switching verification initiates braking.

The challenge for the CBTC System will be translating all of the logic normally performed by wayside interlocks onto the vehicle and the existing on-board switching mechanisms.

CONCLUSION

This paper describes the origin and operation of the Morgantown Personal Rapid Transit System. The system, originally a research demonstration project, is now an integral part of the Morgantown community. The system, implemented in 1975, is well ahead of its time.

With components of the MPRT System degrading, the University has decided to replace the existing inductive loop-based train control with a Communications-Based Train Control System. The MPRT issues of reliability and maintainability can be addressed with a CBTC System.

The existing MPRT System contains complexities that are not inherent to CBTC Systems. These implementation challenges, which will likely require design modifications, include the concepts of off-line stations, origin-destination routing, vehicle queuing, and on-board switching.

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Communications Based Train Control Interoperability Developments at New York City Transit

Tedd L. Snyder, P.E.

CH2MHill, 2012 N. Charles Street, Ste. 1201, Baltimore, MD, 21201; PH (407) 489-9243; email: tedd.snyder@ch2m.com

ABSTRACT

The Signals and Train Control Division of the Capital Program Management department of New York City Transit has embarked on a project that will develop, demonstrate and certify interoperable elements of Communications Based Train Control (CBTC) between two prequalified suppliers, Thales and Siemens. CBTC interoperability requires that the equipment from one supplier, for both the wayside and train, fully function and interface with the corresponding equipment from another supplier in all combinations, i.e., Siemens train equipment with Thales wayside, and Thales train equipment with Siemens wayside. Developing a standard, to which all suppliers of CBTC systems must design, will not only identify the interoperability requirements, but also the interfaces, particularly those elements being provided by the Authority that define the radio and transponder interface. Safety certification will also be an important outcome of the demonstration.

INTRODUCTION

New York City Transit (NYCT) has determined that CBTC will become a standard for all NYCT signal modernization programs and will eventually replace fixed block monitoring and control equipment. It is therefore essential that NYCT establish a permanent CBTC test track to verify interoperability amongst CBTC suppliers under actual field conditions. NYCT needs to have multiple sources of interoperable CBTC systems in order to promote competition between suppliers, and ensure a long-term supply of CBTC system equipment. The goal is to reduce and anticipate technical, schedule and cost risks associated with the implementation of a fully interoperable CBTC revenue system on the entire NYCT network.

Two CBTC suppliers, Siemens and Thales, are currently pre-qualified based on the successful feasibility demonstration conducted under the Canarsie CBTC Project. Both suppliers developed systems that comply with the Canarsie Interoperability Interface Specifications (I2S). Their field demonstrations, conducted in accordance with the Interoperability Test Catalog, successfully proved the concept of interoperability and their ability to provide major Canarsie CBTC functionalities as well as the capability of interoperating with each other's systems.

NYCT is one year into a project that establishes a fixed CBTC test track facility, an Interoperable Test Facility (ITF), and a 46 month contract with Siemens and Thales (Figure 1). Under the Culver Test Track project the final revenue I2S will be developed along with an updated Test Catalog. The intent is to have Siemens and Thales (and other prospective suppliers in the future) demonstrating a complete CBTC system fully integrated with the conventional Auxiliary Wayside System (AWS) while validating their system compliance with the final I2S and Test Catalog requirements. The suppliers must demonstrate full revenue service CBTC functionalities and obtain safety certification for their systems and address safety certification issues relevant to a mixed vendor CBTC system.

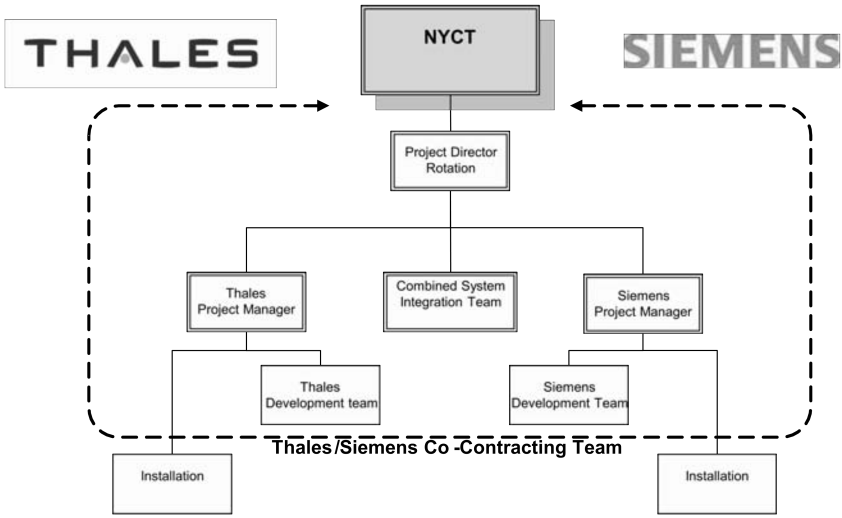


Figure 1. Culver CBTC Test Track Organization

To support this effort a comprehensive CBTC Interoperability Simulator, under the control of a master computer, will be developed and validated under this project. The simulator will be installed as part of the ITF in the NYCT CPM Signals facilities in Manhattan. Siemens and Thales will use this simulator to demonstrate that their systems comply with the latest Interoperability (I2S) prior to actual field-testing on the Culver Test Track. At the end of the project the simulator will be turned over to NYCT and will be utilized to support follow on CBTC projects.

CULVER TEST TRACK PROJECT

The feasibility of achieving interoperability between two CBTC systems was successfully field demonstrated, under the Canarsie CBTC Phase III Project. Siemens successfully implemented the CBTC technology on the Canarsie Line and provided the NYCT CBTC baseline. The Follower Contractor (Thales-Alcatel) modified their CBTC equipment and software to provide the major Canarsie CBTC functionalities along with the capability of interoperating with the Siemens CBTC equipment and software. A limited CBTC test track was installed on the Culver B4 track between 4th Avenue and Church Avenue in Brooklyn. The test track was equipped with both a Siemens and a Thales-Alcatel Zone Controller (ZC). Siemens Data Communications System (DCS) equipment and transponders were installed. A Canarsie R143 Siemens equipment 4-car unit was tested with a Thales-Alcatel equipped 4-car unit. In June 2006, major CBTC functionality was successfully demonstrated in multiple CBTC operating modes. Testing included running both the Siemens and Thales-Alcatel equipped trains through both Siemens and Thales-Alcatel equipped ZC territories. Testing also included coupling Siemens and Thales-Alcatel 4-car units together to form a full 8-car train and running the train through both territories including the overlap (handover) zone between the two Zone Controllers.

The Culver Test Track Project main objective is to test CBTC systems provided from different suppliers in order to validate, and determine the interoperability between the various wayside, carborne and radio subsystems. As extensive testing in the field will be required, a dedicated test track will allow the testing to take place with limited disruptions to daily train operations. The CBTC test track will use the Culver Line B3 track, a southbound express track between 4th avenue and Church Avenue Interlockings, with terminal stations at Church and Seventh Avenues (Figure 2).

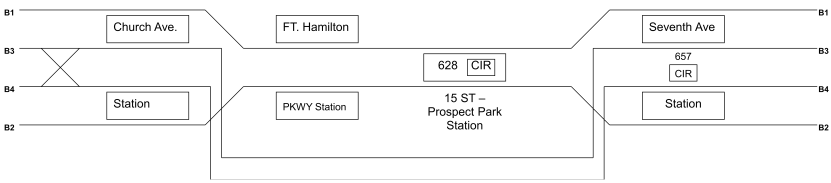


Figure 2. Culver Test Track

A secondary objective of this project is to provide a dedicated New York City based test simulation environment, or ITF. The simulation environment will include CBTC subsystems from the Siemens-Thales Consortium to replicate any CBTC field configuration found in New York City. The simulation environment will be able to simulate for example, multiple trains simultaneously in operation, including close headway moves and opposing moves. The installation will validate that the hardware and software configuration first meet NYCT requirements, followed by demonstration of Interoperability requirements between CBTC subsystems as defined in the Interoperability Interface Specifications. Environment simulators will be designed and installed so all major interfaces to the CBTC/AWS system and all major interfaces including CBTC system to train subsystems can be accurately tested.

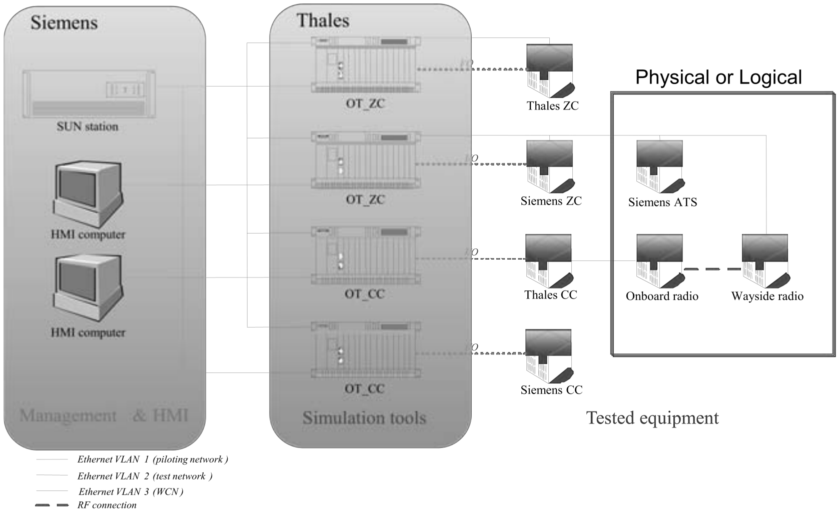


Figure 3. Interoperable Test Facility

To become qualified, prospective suppliers will have to (for one or all equipment):

- demonstrate performance, technical and functional compliance with all NYCT requirements,
- demonstrate compliance with NYCT standards (environment, etc.),
- demonstrate technical and functional compliance with NYCT interoperability requirements,
- demonstrate the safety of their equipment.

The test track will be dedicated to CBTC testing. However, the new Automatic Train Control (ATC) system will still maintain the capabilities of running non-CBTC equipped trains when needed. The proposed system will support different operating modes, for example, Automatic Train Protection Manual (ATPM), ATO, manual mode, and operational functions, including means of handling unequipped trains and disabled trains. CBTC functionalities will provide train control functions such as train detection, safe train separation, and overspeed protection to include interaction between CBTC and the Auxiliary Wayside Signaling (AWS) and to ensure hand-off of trains between zone controllers.

The availability of a test track will provide additional capabilities:

- Facilitate and speed up testing of new CBTC equipment especially for preliminary field integration,
- Allow extensive endurance testing of new equipment in various configurations,
- Allow the simulation of failures without the risk of impacting the service,
- Allow prototype and production level testing of CBTC equipped units before they are released into revenue service,

- Facilitate dynamic testing for post maintenance testing of carborne CBTC,
- Allow the installation of specific equipment for specific testing that can't easily be done on a track in revenue service,
- Allow the testing of new prototype and evaluate new products in a secure and controlled environment,
- Provide significant track access for training purposes.

The test track will allow the use of all CBTC functions as defined in the Interoperability Interface Specifications. The Culver Project CBTC architecture will consist of (Figure 4):

- CBTC Carborne Controller, Vital Speed/Distance Measuring System (odometer / tachometer), CBTC code protected Radio Receiver/Transmitter, Transponder Interrogator, Train Line interface equipment,
- Eight radio cells with overlapping coverage. The architecture of the standalone radio system will be independent of the CBTC application software. The current I2S Radio Air-Gap interface specification, based on the current 2.4 GHz ISM band scheme using a 128 ms TDMA cycle protocol, 64 Kbps rate, QDPSK modulation,
- Two zone controllers with a handover zone (one ZC per supplier). Each zone controller will interface with the AWS (Interlocking and BSC), and their corresponding territory will overlap, Wayside Radio Cell Controller, Data Communication Interface hardware to be installed in the Church Avenue and 7th Avenue CBTC rooms, AWS interface relays to be installed in the Relay Room,
- Approximately 60 Transponders installed between the running rails,
- ATS workstations, which will control the test track,
- Wayside Data Communication System with Fiber Optic backbone,
- One traffic section with auxiliary and primary traffic circuits will be provided in order to test the CBTC split traffic functionality.

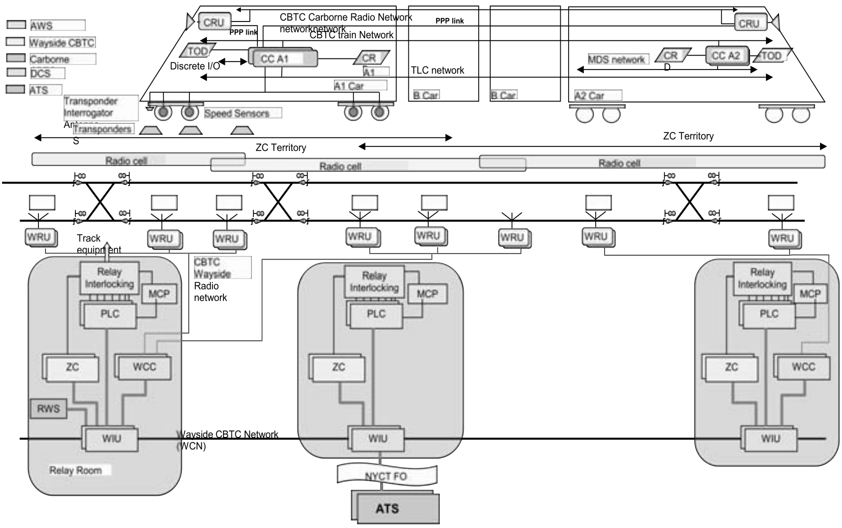


Figure 4. Culver Test Track Equipment Block Diagram

The new CBTC/AWS system will be a CBTC overlay of the conventional Auxiliary Wayside Signaling (AWS) system. Equipment from both suppliers will be installed and fully tested under various configurations. AWS and CBTC equipment will be integrated to permit both equipped and unequipped trains to operate under signal protection. The AWS system will consist of wayside signal equipment required to meet operating needs for unequipped trains while maintaining current headways (Figure 5).

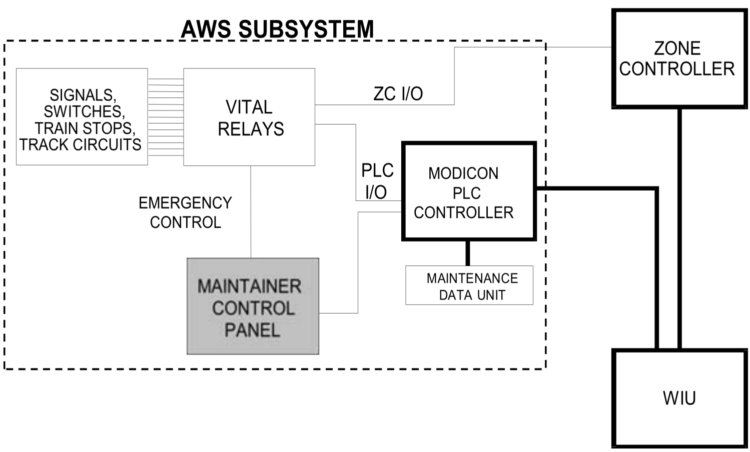


Figure 5. CBTC to AWS Interface

The final configuration will override both approach and automatic signals. CBTC trains will run in either direction on the test track. Unequipped trains will operate under current signaling constraints. When not used for testing, B3 track can be used for non-CBTC revenue service. The Contractors will provide a vital device to isolate the CBTC system so that ZC outputs do not affect the AWS system when it is not in test track mode.

Extensive carborne equipment work will be performed on R-160 cars to accommodate Thales and Siemens equipment. All modifications, installations, inspections and testing will be performed by NYCT in-house personnel under the technical guidance of the suppliers. Siemens and Thales CBTC components will include the base cars required to operate one Thales CBTC equipped 4-car unit on the Culver line and one Siemens equipped Canarsie R160 4-car unit updated to operate on the Culver Line with a tachometer-based speed/distance reference system (R160 units provide no free axle capabilities).

The final configuration will demonstrate

- the ability of both supplier's equipped trains to transition seamlessly into the other's CBTC territory under full CBTC protection with no delays,
- demonstrate the ability to inter-operate both Supplier's equipped trains in the other Supplier's zoned territory,

The Culver CBTC test track contract will provide:

- A Simulation testing facility that will be located on NYCT property and will become the property of NYCT at the conclusion of the contract,
- Upgraded safety standards by reducing procedures,
- Improved operational reliability and availability of the signal system,
- Improved maintenance as the CBTC data-driven sub-systems will require minimum re-engineering for every application, and will provide the ability to automatically download updated software and databases to all trains,
- Improved service to customers through more efficient use of track capacity,
- highest level of safety because of continuous over speed protection for equipped trains and dynamic train separation through CBTC technology,
- mixed fleet protection in test track mode and full AWS protection otherwise,
- a dedicated standalone ATS system to support testing of the interoperable system. Once control is given to the ATS, and test mode established, interlockings will not be able to establish a route into the test track territory in test mode until the local ATS relinquishes the control.

PROJECT STATUS

The Culver Project is currently on schedule and has passed several important progress milestones. With the major design milestones achieved, the work is transitioning to hardware manufacturing and software preparation in the near term. The first major deliverable for testing will be the ITF in 2013, while in parallel equipment for installation along the test track will be delivered to support the start of the test track use in mid-2014.

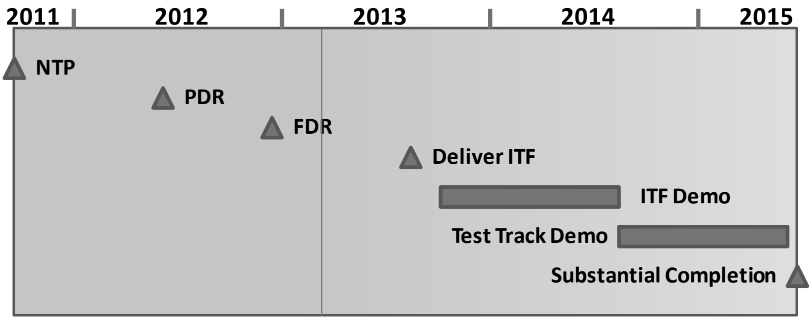


Figure 6. Project Milestones

THE INTEROPERABILITY STANDARD

The NYCT CBTC Interoperability Interface Specifications detail the necessary system architecture, subsystem function allocation, performance requirements, as well as interoperable interfaces. Standardization of the interfaces between the subsystems provides the basis for operating a train equipped by one supplier over wayside territory equipped by another supplier. This collection of documents also includes details for proper interface to the NYCT provided DCS equipment, train operators display and wayside transponder communication (Table 1).

CBTC Interoperability Interface Specifications (I2S)
System Functional Specification
System Design Document
Carborne Controller – Wayside
Wayside – Wayside
Inter-Carborne Controller
AWS-ZC Functional Specification
AWS-ZC Technical Interface
ATS / CBTC
CC – TIA Unit
Safety Principles
Software Database
System Database
TOD Man-Machine Functional Specification
CC – Carborne DCS

Table 1. I2S Document List

During the prosecution of the Culver Test Track Project the I2S documents provide the initial requirements and guidance. During the initial development of the designs by both contractors, the I2S documents are revised as necessary in order to reflect the refinements of the requirements and clarification of the detail interfaces.

FUTURE NYCT GOALS

Beyond the Culver Test Track, NYCT is looking to expand the opportunity for additional suppliers to become qualified. As a minimum this qualification effort will result in a third supplier who demonstrates compliance to the I2S using the ITF and test track facility built under the Culver Test Track project. This effort will be tied to the activities and progress first of the ITF, then the test track. Siemens and Thales will have to make sufficiently advanced progress on the validation of their interfaces, and demonstration of interoperability before support for an additional supplier will become available. The addition of a third supplier increases the number of combinations of interoperability safety cases and will place an increased demand for supporting resources from both the NYCT and the initial two suppliers.

Becoming qualified is a prerequisite for participation in forthcoming competitive CBTC procurements, the first of which is planned to be the Queens Boulevard Line. This will be the first revenue line that does not have a dedicated CBTC passenger train fleet. The deployment of CBTC on a select line section will enable an increase in peak passenger throughput by minimizing the train headways. The benefits of CBTC will be challenged by the need to operate a mixed fleet of CBTC equipped trains with unequipped trains for the foreseeable future beyond the final successful installation. A significant number of trains will require CBTC retrofit, or will be newly purchased in order to support the demands of increased service with at least a fully equipped fleet operating during the peak periods. The current fleet consists of E, F, M and R trains. The benefits of interoperability will be first realized with the Queens Blvd implementation, namely the competitively and separately sourced interoperable car and wayside equipment.

The NYCT has embarked upon a Train Control improvement program that is based on the CBTC developments of the Siemens installed system on the Canarsie Line, the Thales system to be installed on the Flushing Line, and the anticipated outcome of the Culver CBTC Interoperability demonstration. The commitment to CBTC expansion onto NYCT lines is firm, the challenges to the program success are significant, and the benefits of implementation recognized. The NYC goals for CBTC depend on the technological success of the I2S validation and the Culver Test Track demonstration.

Service Improvements to the Toronto (GTAA) Pearson Airport Link System

Alfred Stefan Fruehwirth[1]

[1]Doppelmayr Cable Car GmbH & Co KG, Operations Department, Holzriedstrasse 29, 6923 Lauterach/Austria; PH +43 (5574) 604 x1240; FAX +43 (5574) 604 x1231; e-mail: Alfred.fruehwirth@doppelmayr.com

ABSTRACT

This paper summarizes the challenges that are encountered when modifying an existing transport system. Such challenges include replacing and/or upgrading obsolesced components, adding vehicles and platform doors to existing infrastructure, upgrading and extending electrical systems, as well as improving the functionality of several diverse sub-systems (i.e. rope relocation devices, Closed Circuit Television [CCTV], in-cabin passenger information screens, platform Personal Information System[PIS] displays, vehicle suspension).

It is important to note, that system improvement should be considered as a periodic event through the lifecycle of an Automated People Mover [APM] in order to ensure a high level of operational reliability and maintainability.

INTRODUCTION TO THE PROJECT

On 15 June 2006, the Automated People Mover System , called "LINK" at Lester B Pearson International Airport in Toronto, Canada, went into public operation. The APM is a double shuttle, cable- propelled system that operates landside (landside meaning in front of the airport versus airside operation, which would mean operating inside the secured portion of the airport), and connects Terminal 1, Terminal 3 (and the Sheraton Hotel) and Viscount Station (with its parking garages and the ALT Hotel). The passenger count has been rising continuously since the system opened in 2006, and the APM is now transporting an average of 17,000 passengers per day.

The steady increase in passenger volume, combined with the fact that the construction of a heavy rail connection (the Air Rail Link) will force a six month shutdown of the APM, has allowed the Greater Toronto Airports Authority [GTAA] to proceed with the originally-designed-for increase in capacity by adding an additional cabin to each train. During this time, Doppelmayr Cable Car [DCC] will also be undertaking a number of upgrades to various sub-systems.

As mentioned before in the abstract, there are certain challenges that are encountered when modifying an existing transport system. For once they are in the design and procurement of parts and components.

DCC is the Designer and Supplier of the current APM System, however the original design engineering took part in 2003 and construction started end of 2003 and was mainly performed in 2004. So by now in 2012, eight years later, the majority of the engineering staff had changed and an extensive re-evaluation went on, studying the old documents, drawings and submittals. Also by now there are a number of components and parts, which are no longer produced and a replacement unit had to be found.

The paper also discusses the collaborative efforts of DCC and the GTAA, as the local operations company transitions from the role of an Operations & Maintenance [O&M] provider to that of a constructor. The O&M Company has been involved with this project from the preliminary design stage, which has allowed local knowledge and experience to help shape the overall project.

AIRPORT LINK SYSTEM

The LINK APM systems at Toronto's Pearson International Airport play an important role in recent improvements to passenger logistics. The 1,473 m (4.751 ft) elevated system links Terminal 1 and 3 with a large parking facility at Viscount Station, with a one-way travel time of just three minutes. The APM also provides uninterrupted service to the Sheraton Hotel at Terminal 3 Station and the ALT Hotel at Viscount Station.

The cable technology used by DCC is ideal for extreme weather conditions. Freezing rain, snow, and extreme temperature fluctuations have very little impact on the operational reliability of the Toronto system, and snow cannot accumulate on the open steel truss guideway. Due to stationary propulsion, there is no traction on the guideway and no guideway heating required. In addition, Doppelmayr silences its trains with rubber tires providing comfortable lobby-to-terminal service for the airport hotel guests.

DCC utilizes technologies that allow the APM to operate reliably in harsh winter conditions and to travel in close proximity to existing structures without disturbing the occupants. As a result, the LINK APM system is very well-suited for the mixed-use airport environment that it operates in.

Table 1, Technical Data

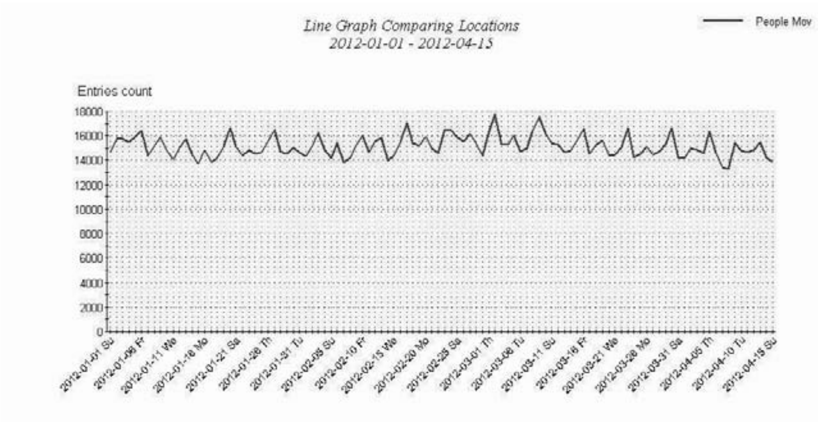
	System
System Length	1,473 m (4,833 ft)
Configuration	Cable Liner Double Shuttle
Operating Speed	43,2 km/h (26,8 mph)
Headway	250 sec
Dwell Time	36 sec
Guideway	Elevated steel guideway
System Capacity	2,150 pphpd
Stations	3
Trains	Two 6-car trains
Train Capacity	36 passengers/car, 196 passengers/Train

NEED AND OPPORTUNITY FOR SYSTEM IMPROVEMENT

Since the APM system started public operation on 15 June 2006, its ridership has steadily increased. An employee and reduced-rate parking garage (6 levels, 8,500 parking spaces) was built directly opposite of the Viscount APM station and connected via an enclosed pedestrian walkway. The majority of the airport's employees were moved to the new garage and, thus, in late-2009 ridership of the APM dramatically increased. The latest addition to the Viscount Station site was the opening of the adjacent ALT Hotel in the summer of 2012.

Prior to the opening of the Viscount Parking garage, the APM was moving an average of 10,000 people per day. By way of comparison, the monthly passenger count for the first four months of 2012 shows an average of about 16,000 passengers per day (Table 2). This amounts to approximately half a million people using the Airport LINK per month, and approximately 5.75 million people per year.

Table 2, Passenger counts Airport Link



The mechanical and electrical infrastructure (i.e. guideway, motors, gearboxes, power supplies) for the APM system were originally designed for an additional cabin. In 2011, the GTAA decided that the time was right to expand the system from two (2) 6-car-trains to two (2) 7-car-trains. Since the guideway and the propulsion systems were already built for the higher design capacity, the majority of work would be focused on the addition of the two extra cabins, as well as the required modification to existing station equipment: automated sliding doors, dynamic PIS displays, emergency call systems, CCTV, additional grip opening devices and rope positioning units, as well as all associated control wiring and monitoring.

With the construction of the heavy rail connection (the Air Rail Link), a 5 to 6 month shutdown of the APM system became necessary due to the fact that the new heavy rail system would directly impact the APM operating envelope. This shutdown will happen between March and September of 2013, and provides DCC and the GTAA will an ideal opportunity to proceed with the 7th cabin project while limiting the disruption to airport operations to a minimum level.

SCOPE OF WORK AND CHALLENGES

The scope of this upgrade project consists of four (4) main topics:

1. The 7th Car Extension of the APM system, complete with adding vehicles and related equipment and structures
2. Collaboration and support for the ARL erection/installation program during, before, and after the LINK shutdown.

3. Additional scope of work for APM modifications to be performed during the shutdown period.
4. A modified O&M program during the prolonged period of inactivity to the APM in order to maintain the present condition of the system.

THE SEVENTH CAR EXTENSION

The 7th car extension project consists of the work, services and equipment required to extend the trains and make the system fit to operate with a seventh car. In addition to the scope for extending the trains, several services and works have been added as result of the ARL Project:

- Support for the ARL erection/installation program during Link-Shutdown
- Verification of the guide way and guide way equipment after handover back to DCC/GTAA from ARL contractor
- Adaption of existing Emergency Concept due to the new ARL station and rail track overpass

Although the system was initially designed for this increased capacity, after almost ten (10) years since the original design took place, an important first step of the extension project was design engineering and verification. The Design Engineering and Verification consisted of:

- Analyses, Design and Engineering Verification of Existing system
- Interface and Design Requirement Submittals for Fixed Facilities
- Interface and Design Requirement Submittals for Operating System
- Mutual consent with owner (GTAA) and appointed-regulatory body (TSSA) on the APM Safety Assessment Project Control Document (APM-SAPCD). With this, relevant codes and standards and required documents together with the correct Verification and Validation Methods were established.
- Agreement that the submittal for the involved sub-systems would be done according to the original contract set-up (2002 agreement)
- Development of maintenance plans for maintaining the current system during the prolonged shutdown period.
- Handover procedures of the current system to the ARL project and acceptance criteria once the ARL is constructed and the APM system is handed back to the GTAA and DCC.

In order to get all involved parties working towards the same goal and deadlines, the Project Management for this job is very critical. In order to get a good start, the project managers from the parent company in Austria met early on with the onsite DCC PM together with the owner's representative and the PM of the ARL project. A meeting schedule with periodic updates was established, so that the team could react to changes immediately when they occurred. Due to the prohibitively high cost of bussing operations while the APM is shutdown, the effective coordination of both projects from early in the planning stage has been a primary focus.

One important aspect of the project was and is the desire of the GTAA to keep all of the O&M personnel employed during the shutdown. The goal is to schedule shutdown-related maintenance work and construction work in such a manner that some of the construction work will be taken care of by part of the O&M crew while all the standstill maintenance will be completed by the rest of the team. By keeping the majority of the O&M staff actively working, there should be very little need for new hiring and training after the shutdown phase.

Providing two (2) additional vehicles means to procure not only the vehicle bodies and bogies, but also: Heat Ventilation Air Conditioning [HVAC] units, train power distribution equipment, battery back-up and charging systems, Automatic Train Control [ATC] components, emergency call system and CCTV, PIS displays, additional train-to-train rescue bridges, and the adaption/extension of the Automatic Train Protection [ATP]/ Automatic Train operation [ATO] sub-systems.

The stations required adoptions and deliverables like:

- Adapting the control and protection system, the WinCC (Windows Control Center) SCADA (Supervisory Control and Data Acquisition) system and adding a video screen to view the two (2) additional cars.
- Activating additional communication systems and extending the Emergency call system
- Adapting the Video Management System at the Viscount station.
- Providing additional Passenger Information Displays at the station platform doors complete with loudspeakers and Emergency release handles
- Providing additional Platform Doors with integrated platform edge threshold heating
- Installation and adjustment of station entry monitoring equipment.

Challenges experienced during the design stage

The dynamic passenger information displays above the platform doors, which were state of the art LED (Light-emitting Diode) displays some 10 years ago, are no longer being produced by the original supplier. It is even questionable if this supplier would even remain in the PIS business, and so requesting the manufacturer to build only six (6) displays would cost a small fortune with the risk of displays never being delivered. So the decision was made to provide all new displays for one of the stations and use the existing displays of this particular station as spares for the other two (2) stations.

Another challenge is how to bring the station doors to the platform. Originally, the design of the station platform made it necessary that all of the station door for one side of the platform were fabricated as one single curtain wall. With the help of the station platform door supplier, a plan was developed for removing the old emergency doors, removing the tiles in front of the new station door, installing the floor heating and the new threshold, and then installing the new Automatic Station Doors [ASD] piece-by-piece.

The Evacuation Procedure in front of the Terminal 1 Station called for an Emergency Response team to utilize their ladders to reach the stranded train. With the new ARL track and the new ARL station in place, there will be no means of accessing the System 2 train by means of a rescue ladder from the ground. Together with ARL, GTAA and the emergency rescue team, a new Evacuation Plan is being developed.

The placement of the new ARL concrete guide way and platform will make it necessary for the W-LAN (Wireless Local Network) communication system of the APM train to be verified due to the possibility of interference. New W-LAN antennas will be installed in the area of the ARL structures to ensure proper coverage, while existing wireless access points will be re-evaluated to determine if further optimizations can be made.

Additional Scope of Work

With the original date of order being already ten (10) years past, several additional upgrades and improvements were considered by DCC and the GTAA. Time and budget constraints are always a consideration for any upgrade project, however a sizable upgrade project (in addition to the 7th cabin) could be agreed upon thanks to the good fortune of having an owner who is looking at investing in the full lifecycle of their system in order to provide a high level of passenger service.

An updated Maintenance Management Information System [MMIS] software package will be provided, as will a new operational reporting system that is integrated into WINCC in order to streamline and promote reporting accuracy. The O&M Manual will be newly-issued with a completely revised structure, which will make it very easy to import both present and future changes. The new O&M manual will also allow the reader to find information more quickly by providing a higher level of interactivity between different sections of the manual and sets of drawings, thereby making O&M more efficient and reducing the danger of misunderstandings.

The bogie suspension system will be upgraded to reflect the latest DCC design, which will improve the overall ride quality as well as the lifecycle of certain bogie and cabin components.

New cameras on the guideway and in the maintenance bays will be installed in order to improve CCTV coverage. The new equipment will be used to monitor the areas where the APM and ARL are in close proximity, as well as provide coverage in areas where maintenance personnel work in proximity to the power rail and propulsion components.

The grip opening devices will be modified in order to reduce the maintenance time required to perform a rope re-location, and to improve the ergonomics of haul rope- and grip-related maintenance tasks.

Several lights and audible signals will be installed at strategic areas in the maintenance areas in order to visually alert any personnel in the immediate area when the system is going to move under normal propulsion. Such an improvement will improve communication and increase the safety of maintenance personnel.

Although the haul ropes have an expected lifecycle of approximately two more years, it was decided by the owner to use the window of opportunity during the ARL shutdown to replace the ropes. It is very advantageous in terms of minimizing future operational disturbances to begin operations after the shutdown with a new haul rope.

Conclusion

On 19 March 2013, the APM/ARL shutdown projects will have officially started. So at the time of the next APM conference, we will be about one (1) month into the extension and modification project. By then we certainly will have experienced new challenges, as well as the solutions required to overcome them. Looking further ahead to the APM conference, it will be our distinct pleasure to summarize and reflect back on all of our experience and lessons learned, and deliver them together in a final report.

Doppelmayr Cable Car (2011). *"Technical Description Pearson International Airport Link"*

First Results of Paris Metro Line 1 Automation

Patricia CHARON[1], Emmanuel SOLOGNY[2]
[1]ING, RATP, [2]MOP, RATP

Context and Introduction

In 2004, RATP officially launched the process of automation of the Line 1, its oldest metro line and the most crowded with an average of 750 000 passengers a day. Seven years later, on 3rd november 2011, the first driverless trains are carrying passengers along with manually driven trains during revenue service. This period of mixed train traffic will continue up to the beginning of year 2013, when the whole Line 1 will be a fully driverless metro line. As evidence, six months after the first driverless train, more than half of the rolling stock fleet daily operated is made of new driverless trains.

The conversion of this centenary line into an automatic one with no significant interruption of traffic has been designed according to a complex, progressive and meticulously coordinated migration plan, whose crucial principles were defined very soon in the automation program. Indeed, lots of systems and equipment have been added or upgraded during this automation process, dealing daily with an old infrastructure which requires this progressive migration plan initiated and prepared from the design of the systems. Later on, during construction phases, the challenge has consisted in the synchronization of existing installations upgrade (platforms, signaling systems, power supply, track, …), addition of new equipments (platform screen doors, Communication Based Train Control (CBTC) equipment, Operationnal Control Center (OCC), interlocking system on parking shunting areas, …), their mutual integration as well as their integration with the operational and existing environment, and actually the qualification of the new system until its revenue service.

Project Management and Organization

To achieve the fully automatic system on the whole Line 1, the project has been divided in many steps, from feasibility studies to trial running of the system and then, revenue service. RATP put in place a dedicated structure during these 8 consecutive years of project in order to manage and organize this hard and long period of upgrades and modifications on the existing line.

The project started in the early 2000, when RATP initiated its metro modernization program, mostly based on renewal of 30 years old train control systems. Considering that Line 1 was the most crowded line of the Paris metro (213 millions passengers a year and 24 000 passengers per hour per direction during morning peak), with regularity, adaptability and reactivity issues, in addition with the necessary renewal of the entire signaling systems of the Line, and based on Paris Line 14 driverless metro experience and benefits, feasibility study Line 1 full automation program was launched in 2003.

The feasibility studies pointed out the requirements in terms of systems modifications, the technical issues due to this modernization, and the challenges induced to make this project a success.

- Systems and operation modernization:
  - Implementation of a new rolling stock based on Line 14 characteristics, transfer of the 15 years old Line 1 existing rolling stock to Line 4 allowing substitution of 50 years old Line 4 rolling stock, adaptation of maintenance facilities.
  - Unattented Train Operation (UTO) train control system including a new OCC ,
  - Implementation of platform screen doors,
  - New staff organization for the Operator, implied by the new UTO system.

- Identification of technical issues due to the automation program:
  - Platform screen doors installation on a one-century-old line,
  - Integration of this platform screen doors along the project with various signaling systems and rolling stock (from trains with drivers and existing signaling system to new driverless rolling stock with UTO system…),
  - Signaling interfaces (implementation of a new CBTC system, interface with solid-state interlocking, migration period between both signaling system, mixed train traffic operation…),
  - Management of the gap between the train and the platform due to old infrastructure and track alignment (30 meter radius curve in Bastille station, ramp…).

- Challenges induced by the automation program:
  - Taking into account Line 1 as the backbone of Paris metro, RATP and Railways authority for Paris Region (STIF) decided to realize this automation with no traffic interruption,
  - No such experience has been made in the world,
  - Construction hazards generated by a one-hundred years old infrastructure,
  - Social issues due to drivers redundancy implied by UTO,
  - Passengers and staff communication onto the project (disruptions, modifications of operating procedures…).

In order to cope with all these challenges, the project organization has been based on risk management with the identification of the main technical and social issues in the early phases of the project (as per description previously). As a consequence, the following solutions have been put in place:

- Huge works coordination by the project management team (station by station, platform by platform...), based on a detailed diagnosis of the line and infrastructure during feasibility study,
- Implementation of traffic interruption late in the evening or on Sunday morning to allow “largest” window for civil works or system testing,

- System and rolling stock tests carried out on Test Centre (Valenciennes Railway Test Centre) to reduce issues when implementing onto the line,
- Management of the system interfaces and commissioning of the transport system by RATP engineering,
- Integration of operation and maintenance requirements since the beginning of the project (operation and maintenance experts are also part of the project team),
- Anticipation of the risks for sensitive issues such as installation of platform screen doors or management of the gap between the train and the platform, development of alternative and innovative solutions,
- Mixed train traffic operation, allowing a progressive replacement of the train fleet but inducing strong constraints on the transport system,
- Early communication process with the trade unions with a guarantee of no redundancy but productivity sharing,
- Specific communication tools and involvement of Line 1 operator along the project to inform passengers and line staff on objectives and difficulties,

In addition to the project management, one of the key of the success of this ambitious program is the capacity of integration, interface and safety management by RATP engineering.

Technical Integration and Migration Phases

When the project was approved in 2004 by the Railway authority (STIF), the overall risk was transferred onto RATP (design, build, finance, operate and maintain the new transport system of Line 1), allowing RATP to manage relations between operators, designers, maintainers, safety assessors "inside" the company. Therefore, RATP decided to apply for Line 1 the same train control system architecture as for the rest of the metro modernization program, producing an industrial strategy where RATP keeps the control of interfaces for future evolutions of the system and also manages integration, migration phases and safety assessment. This organization was crucial because it gave an environment comfortable and secured for the operator and the maintainer of Line 1 along the various phases of migration of the project.

From 2005 to 2012, the migration phases from the old signaling system to the new CBTC with a new OCC have been made of 6 major steps:

- Step 1 - Signaling and trackside preparation works: consists in the modernization of the terminal station with new computerized interlocking system, still operated on site with driver's trains. Also installation of track equipment (beacons for train location, optical barriers, cables, radio antenna…) to prepare CBTC implementation.

- Step 2 – Platform screen door (PSD) deployment: consists in the integration on board the train of a remote PSD control and the installation of reception loops at station allowing driver's trains to manage PSD when implemented. Then, deployment of the PSD along the line working station by station during the night…

- Step 3 – Start of operation with new OCC: consists in the connection of new OCC to the Line with a data communication system (as the backbone of the CBTC system) exchanging data with signaling and traction equipment through Input/Output units. New Automatic Train Supervision system is provided at the OCC.

- Step 4 – New CBTC system deployment: consists mainly in the installation of zone controllers and line controller in charge of the management of safety instructions regarding trains location and train movement authority. At this stage of the project, the first driverless are tested and commissioned during the night.

- Step 5 – Mixed fleet operation: after sufficient number of trains commissioned and system testing, mixed fleet operation starts for passengers with both driverless and non-driverless trains. Transportation offer is still the same and operating staff is still managing the remaining drivers in terminal stations. System tests continue during the night for UTO upgraded functions.

- Step 6 – Full UTO operating mode: the last driver's train has left the line bringing with him the removal of PSD control system and the former trackside Automatic Train Control. The entire transport staff is at the OCC with the upgraded functions of CBTC system allowing to decrease the headway between the driverless trains on the Line 1.

For step 5 and step 6, a dedicated and efficient structure has been created in order to detect, analyze and fix operational issues from the new systems.

Conclusion and Benefits

Nowadays, even if Line 1 automation process is not fully completed (step 5 in the previous description is on-going), this period of mixed train traffic operation is very positive. Obviously, the first weeks of mixed fleet operation has turned out some issues on the transport system, despite hours of testing in test centre and on Line 1 during the night, but clearly not enough due to the commitment of RATP to minimize traffic disruptions. However, these issues were fixed with new revisions of software allowing a high level of regularity and punctuality in addition with the integration of two new driverless trains each month. From mid-march 2012, more than 50% of the transportation offer is made with driverless trains and during summer 2012, service offer has been increased by 15% thanks to adaptability of a driverless system.

As a conclusion, thanks to benefit of the successful experience of Paris Line 14, 100% automated from its launch in 1998, Metro Line 1, becoming a fully automated line at the beginning of year 2013, will offer a modernized infrastructure and a more reliable service for its 750,000 daily passengers.

Moreover, for RATP, this large, complex and unique project in the world, has demonstrated that it was possible to transform a 100 years old infrastructure into a new and modern driverless line with no significant interruption of traffic. Knowledge and skills obtained by this project will be very helpful for RATP to modernize again its transport network and beyond enable RATP group to help fellow operators willing to migrate or automate their own network seamlessly.

Contact details:
Emmanuel SOLOGNY – RATP, Railway operation expert
emmanuel.sologny@ratp.fr
T 00 33 1 58 77 12 79

Patricia CHARON – RATP, CBTC Line 1 Project Manager
patricia.charon@ratp.fr
T 00 33 1 58 76 94 60
F 00 33 1 58 77 02 81
RATP
LAC VE41
56, rue Roger Salengro
94724 FONTENAY SOUS BOIS
FRANCE

The 360 Degree Approach for an APM Infrastructure: Involving the Supplier in Every Step

Douglas V. Heitzenrater, P.E., M. ASCE, MSPM, BSCE, [1] and John P. McGinley[2]

[1] Bombardier Transportation Systems Division, Wayside Engineering Department, 1501 Lebanon Church Road, Pittsburgh, PA 15236, PH (412) 655-6990; FAX (412) 655-5442; email: douglas.v.heitzenrater@us.transport.bombardier.com

[2] Bombardier Transportation Systems Division, Construction Department, 1501 Lebanon Church Road, Pittsburgh, PA 15236, PH (412) 655-5382; FAX (412) 655-5442; email: john.p.mcginley@us.transport.bombardier.com

1.0 Abstract

Investment in an APM System is a critical venture to enable user friendly transportation now and in the future. The infrastructure of an APM System is a key cost component and is comprised of many considerations for APM System elements. The infrastructure must be carefully planned within a given project, followed up by thorough and effective design plus construction/installation to successfully execute and complete a project.

Of the points raised above, how does one effectively make the 360 degree connection amongst planning, design and construction/installation, for the said infrastructure? Well, it starts with System oriented thinking, i.e. one cannot design a System without bringing many elements to the table. For example, to design a conventional highway bridge infrastructure that carries APM System may not adequately address a number of other issues such as: lowest cost, ride quality, noise abatement, public perception, System equipment placement, etc…What is the primary guideline for design as numerous entities come together to plan and produce a System?

Understanding the key System components as well as the longer term operation plus maintenance of the key System components becomes critical in the pursuit of effectiveness. Producing a like other project design for the infrastructure does not necessarily bring best value or long term sustainability to the table. Where to start? We believe that it is critical to engage the APM System supplier(s) early on in the entire planning process continuing through the design processes in an effort develop best practice to deliver an effective System.

The paper as presented here will focus on two main areas:

1. Planning/Designing and System Design Criteria and,
2. Examples of Execution and Operations - Beyond Planning/Designing and System Design Criteria

2.0 Planning/Designing and System Design Criteria

Within the planning/designing process, involved parties must be engaged with potential vehicle equipment and system equipment manufacturer(s) and/or supplier(s) as these parties are not only able to publish key system design and interface criteria but they are also able to bring system operations and other factors such as human factors to the planning arena. In consideration of the system design criteria noted above we would like to take this opportunity to walk through elements of consideration that typically reside within a design criteria as the design criteria sets the basis for the the underlying infrastructure as a whole. Designing an infrastructure in absence of system design criteria definitely would question if a best practice approach was followed for the system.

2.1 Alignment(s) and Clearance(s)

Geometry of the system is a key consideration in any design. One must know the physical location in space to understand how the end system will function amongst all other facilities and equipment. Besides the raw physical location in space one must understand geometric constraints that are specific to a particular system vehicle plus associated equipment in an effort to understand how the system will perform during the functional operation.

Once the alignment geometric aspects of the system are established one can then use the vehicular clearance data that is available to confirm the required normal and failed conditions to ensure a safe operation clearance envelope. The system equipment manufacturer and supplier know best what to consider when examining this aspect of the system and regular present clearance data that supports operation along a typical guideway sections (tunnel, non tunnel, station, maintenance).

Within a given design criteria the following are key elements which are addressed for alignment and clearance:

Alignment	
Horizontal geometry	Vertical geometry (Profile)
Minimum horizontals	Minimum horizontal distances
Rate of change between horizontals	Minimum vertical distances
Superelevation	Crest and sag verticals
Safe stopping	Maximum grade
Lateral acceleration	Maximum/Minimum grade changes
Revenue vs. non revenue geometry	Vertical acceleration
Clearance	
Chording	Overhang
Station approach	Station berthing
Maintenance	Wayside equipment

System operations	Switching operations
Walkway egress	

2.2 Switch(s) and Component(s)

Within the prior section we have discussed merits of the alignment. One of the key requirements of the alignment relating to system operation relates to specific switch placement along the traveled route. Depending on the desired operation of the system…shuttle, pinched loop, etc…more or less switches may be placed along the alignment system route. In combination with the number of switches there are also variations in the switch types pivot, wye, turntable to achieve the appropriate flow for the desired system functionality.

When considering placement of switches within the given infrastructure there are a number of key elements that must be considered as follows:

Switch(s) - Figure 1	
Area footprint	Location relative to expansion joints
Area weight	Egress path for passengers
Component vertical stack up	Motion paths
Vertical clear	Routings (electrical/mechanical)
Horizontal clear	Penetrations (electrical/mechanical)
Relative anchorage to substrate	Drainage paths
Material variations (steel/concrete)	Standard vs. special product/components
Vibrations	Grades and transitions
Maintainability	Equipment platforms
Traffic signals	

Figure 1. Switch Area

(Source: BT Construction/Installation of Phoenix Sky Train)

2.3 Station(s)

Another pertinent feature that integrates with the infrastructure are the stations. The stations in simple format (open air and open platform) or in more complex format (closed, multi function and station doors) encompass critical points along the infrastructure for exchange of passengers. Since the stations typically require a large expanse of space to achieve a comfortable environment for the passengers it is important that the infrastructure as provided can accommodate them while it is also minimized.

Within the planning designing for the infrastructure about the station areas the following elements which directly relate to the infrastructure must be considered:

Station(s) - Figure 2	
Length of berthing	Approach to platform (ramping)
Offset to platform edge	Vehicle failure in platform area
Constant elevation	Wind load on vehicle
Vertical platform dimension	Deflection (infrastructure/platform)
Dynamic platform gap	Emergency walkway interface
Expansion joints	Architectural waterproofing slabs
Grades (zero)	Architectural finishes
Routings (electrical/mechanical)	Drainage paths
Penetrations (electrical/mechanical)	Misc. equipment

Figure 2. Station Area

(Source: BT Construction/Installation of Phoenix Sky Train)

2.4 Guideway(s)

This is a large percentage of any system and as a result it comprises the largest most direct portion of the infrastructure. Developing a cost effective cross section in conjunction with examining specialized portions such as switch areas allows for economies of scale when multiplying by length of System. For example:

Guideway 1:	Guideway 2:
Length = L	Length = L
Cross Section Cost = 1	Cross Section Cost = 1+X
Total Cost per Length = 1L	Total Cost per Length = (1+X)L

Summary: If a cross section guideway can be reduced by even a small amount this will add up across length of project. For example, reduction of running surface concrete volume placed on top of deck over length of System.

When considering minimizing in this area there are many elements that must be considered as follows:

Guideway(s) - Figure 3	
Vehicle loading	Repetitive load path and fatigue
Vehicle axle spacing and consist	Routings (electrical/mechanical)
Loading combinations	Penetrations (electrical/mechanical)
Vehicle center of gravity	Deck grade breaks
Vehicle tire footprint	Drainage paths
Vehicle guidance loads	Equipment platforms
Vehicle guidance load location	Misc. equipment
Vehicle guidance tire footprint	Emergency walkway type
Guidance system type and loading	Emergency walkway anchorage
Guidance system anchorage	Emergency walkway expansion/contraction
Guidance system expansion/contraction	Running surface anchorage
Running surface type and loading	Running surface expansion/contraction

Figure 3. Typical Guideway

(Source: BT Construction/Installation of Phoenix Sky Train)

3.0 Execution and Operations - Beyond Planning/Designing and System Design Criteria

Within the prior discussion we have realized that there are a number of elements that must be considered relative to the system and the planning/designing of the infrastructure as a whole. Beyond the actual planning/designing comes the physical execution of construction and installation along with operations of the finalized system achieved through the prior planning/design process.

Within the actual execution of the construction and installation of the system we will look at how the joint development highlights making the infrastructure a success when the system supplier join forces with others who perform the construction and installation of the system upon the infrastructure. Not only is the system supplier involved today but they also have a longer term interest in the system operations in the future.

As the issues under these topics are many in any given project we have decided to select a subject areas which directly tie to the planning/design categories above to amplify the benefit of these efforts and the positive outcomes.

3.1 Switch(s)

Within a switch area on the infrastructure there are numerous items that need to be co-located within the confines of the infrastructure which directly effect the infrastructure. We would like to take this opportunity to correlate the design/planning table to the following three (3) photos by highlighting the applicable items in the table and then explaining each item to provide an example of how the infrastructure would be influenced.

Switch(s) – Figures 4, 5, 6	Infrastructure Highlight (Examples)
Area footprint	Fig. 4 - Locally widened deck section
Area weight	Fig. 5, 6 – Multiple components
Component vertical stack up	Fig. 6 - Locally thickened conc. to accommodate switch components
Vertical clear	N/A this case
Horizontal clear	Fig. 4, 6 – Parapet + platform
Relative anchorage to substrate	Fig. 4, 6 – Concrete + equipment
Material variations (steel/concrete)	Fig. 6 – Various components
Vibrations	Fig. 5 – Isolation of components
Maintainability	Fig. 6 – Alternative routing
Traffic signals	Fig. 6 – Locating about switch
Location relative to expansion joints	Fig. 6 – No spanning of deck jts.
Egress path for passengers	Fig. 6 – Walking surfaces
Motion paths	Fig. 6 – Space about platform
Routings (electrical/mechanical)	Fig. 5 - Multiple
Penetrations (electrical/mechanical)	Fig. 6 - Multiple
Drainage paths	Fig. 6 – Where drainage occurs
Standard vs. special product/components	N/A this case
Grades and transitions	Fig. 6 - Constant
Equipment platforms	Fig. 6 - Present

Figure 4. Switch Deck Local Widening

(Source: BT Construction/Installation of Phoenix Sky Train)

Figure 5. Switch Component Install

(Source: BT Construction/Installation of Phoenix Sky Train)

Figure 6. Switch Component Install

(Source: BT Construction/Installation of Phoenix Sky Train)

3.2 Guideway(s)

Within the guideway area proper we can also examine how the infrastructure may be more or less influenced by system elements. Again, we would like to take this opportunity to correlate the design/planning tabular item listing to the following three (3) photos by highlighting the applicable items in the table and then explaining each item to provide an example of how the infrastructure would be influenced.

Guideway(s) – Figures 7, 8, 9	Infrastructure Highlight (Examples)
Vehicle loading	Fig. 7 – resolution of forces
Vehicle axle spacing and consist	Fig. 8, 9 – span lengths and types
Loading combinations	Fig. 8, 9 – span lengths and types
Vehicle center of gravity	Fig 7, 8, 9 – resolution of forces
Vehicle tire footprint	Fig 7, 8, 9 – resolution of forces
Vehicle guidance loads	Fig 7, 8, 9 – resolution of forces
Vehicle guidance load location	Fig 7, 8, 9 – resolution of forces
Vehicle guidance tire footprint	Fig 7, 8, 9 – resolution of forces
Guidance system type and loading	Fig 7, 8, 9 – resolution of forces
Guidance system anchorage	Fig 7, 8, 9 – resolution of forces
Guidance system expansion/contraction	Fig 7, 8, 9 – matching of superstructure
Running surface type and loading	Fig 7, 8, 9 – resolution of forces
Repetitive load path and fatigue	Fig 7, 8, 9 – inherent detailing

Routings (electrical/mechanical)	Fig 8 – deck openings
Penetrations (electrical/mechanical)	Fig 8 – deck openings
Deck grade breaks	
Drainage paths	Fig 7, 8, 9 – matching of superstructure
Equipment platforms	Fig. 7, 8, 9 – additional width in superstructure
Misc. equipment	Fig. 7, 8, 9 – additional width in superstructure
Emergency walkway type	Fig. 7, 8, 9 – additional width in superstructure
Emergency walkway anchorage	Fig 7, 8, 9 – resolution of forces
Emergency walkway expansion/contraction	Fig. 9 – matching of superstructure
Running surface anchorage	Fig 7, 8, 9 – resolution of forces
Running surface expansion/contraction	Fig 9 – matching of superstructure

Figure 7. Guideway Cross Section Means and Methods Development

(Source: BT Construction/Installation of Phoenix Sky Train)

Figure 8. Guideway Cross Section

(Source: BT Construction/Installation of Phoenix Sky Train)

Figure 9. Guideway Cross Section

(Source: BT Construction/Installation of Phoenix Sky Train)

Now that a number of APM system design elements and details have been discussed this allows for a greater depth understanding of what resides at the top surface of the infrastructure for an APM system and how one detail builds upon the other. We hope that you can relate to these system details and understand that these system details must be known, understood, applied in depth to design and build an underlying infrastructure that exhibits characteristics which allow:

1. Optimal cost for purpose - Less or least components for intended use as have been expressed through the tabular item listings that we have covered above.
2. Optimal performance for purpose - Build to suit the specific System by obtaining, understanding, using and integrating accordingly.
3. Flexibility for future maintenance/accessibility - Ensure that ease of maintenance is covered for limited System shutdown and optimal accessibility for specific System.

4.0 Recommendations

Within the planning/designing process, involved parties must be engaged with potential vehicle equipment and system equipment manufacturer(s) and/or supplier(s) as these parties are able to publish key system design and interface criteria to allow more proficient infrastructures. Designing an infrastructure in absence of system design criteria definitely would question if a best practice approach was followed for the system.

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PHX Sky Train® Facilities – Tailor Made for the Airport and Local Community

AUTHORED BY:

Mark Pilwallis, P.E., S.E., Senior Project Manager; Gannett Fleming, Inc., 4722 N. 24th St, STE 250 Phoenix, AZ 85016; Ph: 602-684-3335; Fax: 602-553-8816; email: mpilwallis@gfnet.com

Mary Anne Derr, P.E., Senior Project Manager; Gannett Fleming, Inc., 4722 N. 24th St, STE 250 Phoenix, AZ 85016; Ph: 602-683-3830; Fax: 602-553-8816; email: mderr@gfnet.com

Kyle Kotchou, Special Projects Administrator, City of Phoenix Aviation Department, 3400 E. Sky Harbor Blvd., Phoenix, AZ 85034; Ph: 602-757-2826; Fax: 602-683-3838; email: kyle.kotchou@phoenix.gov

ABSTRACT:

The PHX Sky Train will transform Phoenix Sky Harbor International Airport's landside transportation system by creating an efficient, easy to use transit system that connects people to all key airport facilities as well as the regional transportation system. In addition to moving people, the system was also designed to enhance the airport and the local community in the following areas:

1. Aviation Operational Enhancements programmed into the stations that include: early bag check; remote ticketing/check-in; passenger counting; station expandability for terminal services.

2. Aviation Facility Enhancements that include: future expandability; low maintenance finishes; guideway carries power and communication backbone for the Airport; automated building controls.

3. Multi-Modal Enhancements at stations including: regional light rail connection; ground transportation center; pedestrian and bicycle facilities; employee parking

4. Community Enhancements, including: a LEED certificated campus; significant traffic congestion reductions; urban redevelopment; integrated art program; transit oriented development considerations

1.0 INTRODUCTION & PROGRAM OVERVIEW

Phoenix Sky Harbor International Airport has considered a transit system to connect its key facilities in the long term planning of the airport since the development of its newest terminal in the late 1980's. After careful transportation planning and design, the Airport has constructed the first Stage of the PHX Sky Train^{TM}, an automated people mover system that goes beyond just connecting key airport facilities. The Sky Train will also: enhance the airport's long term ability to grow; provide a vital transit link to the region; utilize transit oriented design principles to enhance growth opportunities and livability for the community; reduce local roadway congestion; and use sustainable design and construction methods.

The Sky Train is a predominantly elevated, five-mile long automated people mover system that will run through and connect key existing and future airport facilities with strategically located stations: Terminals; parking areas; ground transportation centers; Metro Light Rail; and Rental Car Center. The general layout of Sky Harbor International Airport and the Sky Train project is shown in **Figure 1**.

The project is being implemented in three stages to spread the overall capital requirement. Stage 1 is 2 miles in length and will connect Terminal 4 (which carries 80% of the airport's traffic), the East Economy Parking Lot and the 44th Street Station area, which connects to METRO light rail and other ground transportation modes. Stage 1 will become operational in early 2013. Stage 1A is 0.6 miles in length and extends Stage 1 to Terminal 3 and Terminal 2 with a single station connection. Stage 1A will become operational in early 2015. Stage 2 is 2.4 miles in length and will connect west side parking/ground transportation and the Rental Car Center. Stage 2 is scheduled to be operational in 2020.

Given the project's three stage approach, detailed planning, programming and construction is currently completed only for Stages 1 and 1A. The remainder of this paper will focus only on Stage 1 and 1A facilities since Stage 2 has yet to be developed in detail. The basic elements of Stage 1 and 1A include the following:

1. Terminal 4 Station – fully enclosed, elevated, center platform station located on the south side of Terminal 4 with dual connecter bridges leading into the Terminal passenger level. The station will have two levels: an upper platform level with a lower level mezzanine that provides the connections into the terminal **(See Figure 2** for layout).

2. East Economy Station – open air, elevated, center platform station located adjacent to existing parking garages. The station will have two levels: an upper platform level with a ground level that provides the connection to a drop off curb, parking garages and surface parking (**See Figures 3 and 4** for layout).

3. 44th Street Station – fully enclosed, elevated, center platform station that is located just northeast of the airport with a pedestrian bridge connection to the METRO light rail. Station will have three levels: level 3 platform; level 2 mezzanine connector to METRO light rail; level 1 ground level with connections to various ground transportation modes. The connector bridge to METRO will also be enclosed with moving walkways to make the connection efficient and seamless (**See Figures 5 and 6** for layout).

4. Terminal 3 Station - fully enclosed, elevated, center platform station located on the south side of Terminal 3 with a single connecter bridge leading into the Terminal 3 passenger level. The Station also includes provisions for an at grade walkway from the west end of the station to Terminal 2. The station will have two levels: an upper platform level with a lower level mezzanine that provides the connection into Terminal 3 (**See Figures 7 and 8** for layout).

5. Guideway – all elevated with the exception of approximately 3,100 feet of at grade guideway between 44th Street and East Economy Stations and additional 1,000 linear feet of depressed guideway at the crossings of Taxiways Sierra and Tango. Key features include the crossing of a heavy rail line, airport parking lot, three active taxiways and four terminal concourses.

6. Maintenance and Storage Facility – located just to the east of the airport, a 40,000 square foot maintenance and storage facility will be used for operation, vehicle storage and maintenance of the Sky Train system.

The Sky Train has transformed Phoenix Sky Harbor International Airport's landside transportation system by creating an efficient, easy to use transit system that connects people to key airport facilities as well as the regional transportation system. During the planning and design of the Sky Train, program goals were identified and used as guiding principles to develop the design such that the system will also enhance airport functions and the local community. Key areas enhanced by the Sky Train are:

5. Airport related Operations
6. Airport related Facilities
7. Multi-Modal connectivity for the Airport and region
8. Local Community

This paper will focus on how the various program elements of the PHX Sky Train that help provide these enhancements and make this transportation system a solid base for further airport and community growth and pride.

Figure 1 – Project Layout

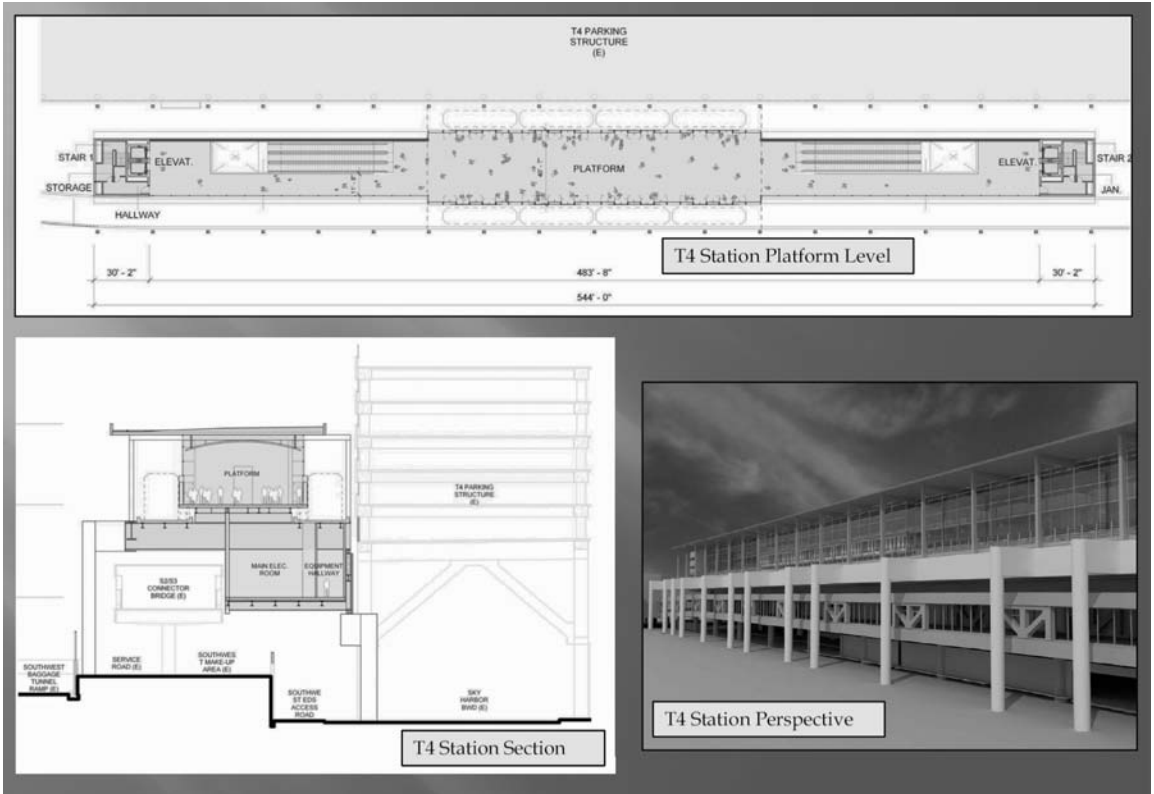

Figure 2 – Terminal 4 Station

CREDIT – HOK

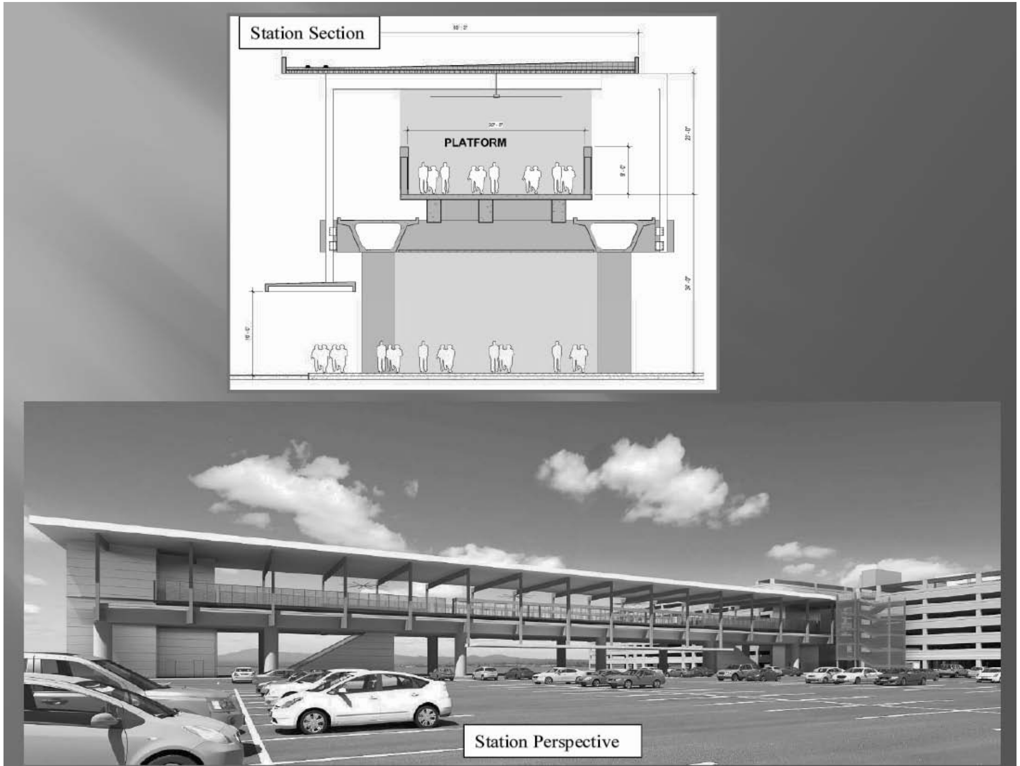

Figure 4 – East Economy Lot Station Layout

CREDIT – HOK

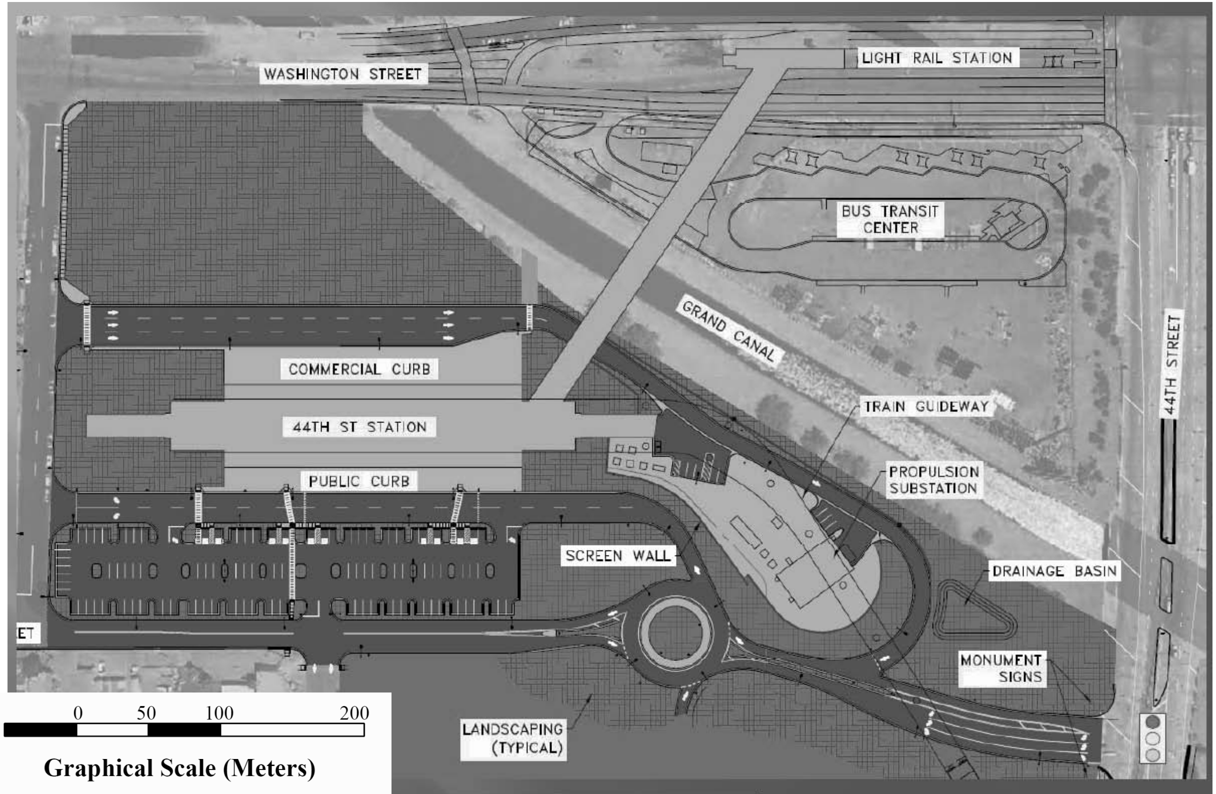

Figure 5 – 44th Street Station Site Plan

CREDIT – Gannett Fleming Inc.

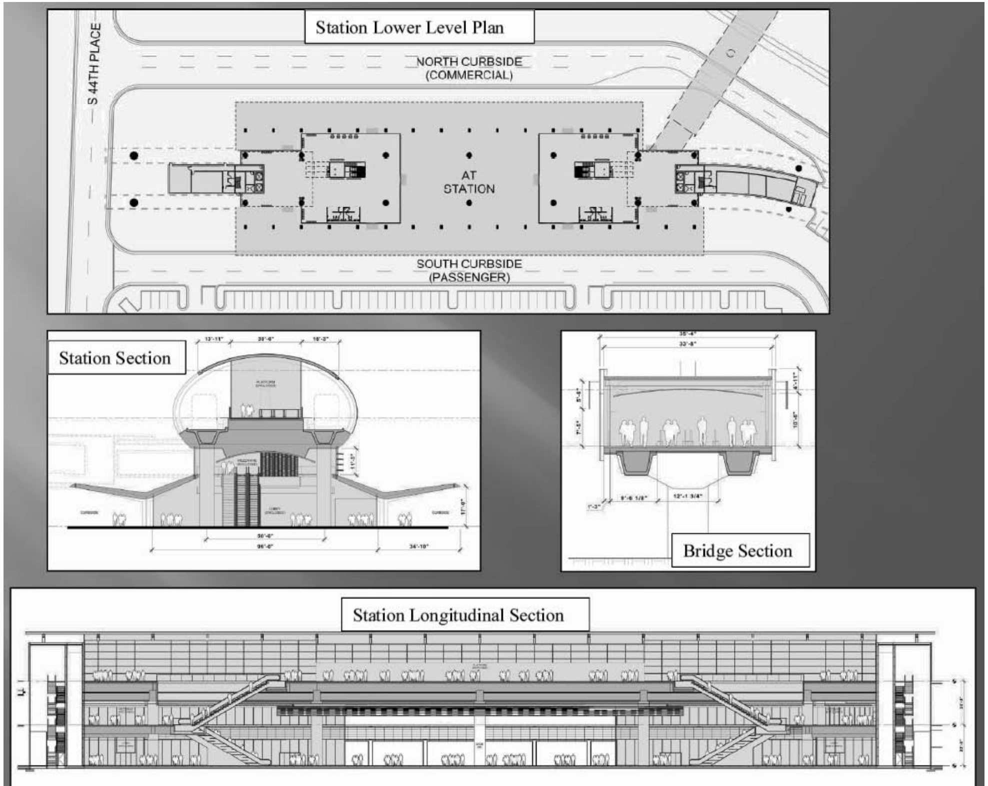

Figure 6 – 44th Street Station Layout

CREDIT – HOK

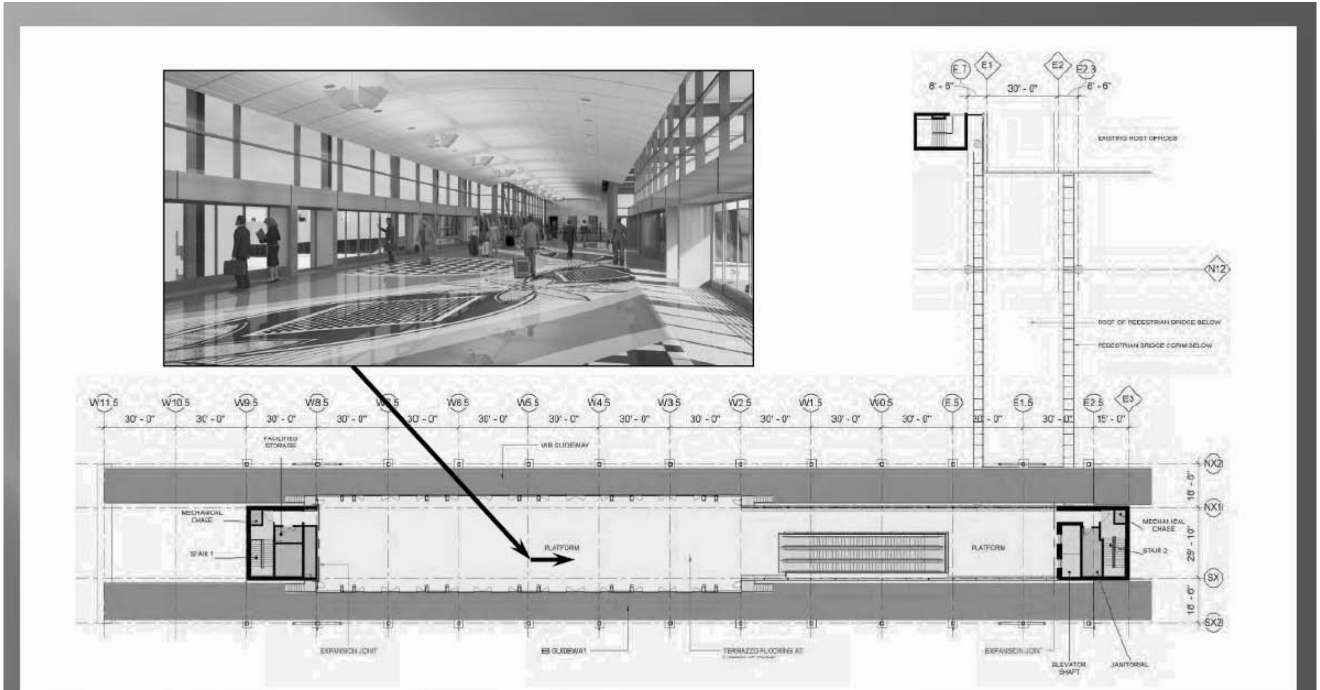

Figure 7 – Terminal 3 Station Platform Level

CREDIT – Smith Group JJR

Figure 8 – Terminal 3 Station Perspective

CREDIT – Smith Group JJR

2.0 AIRPORT OPERATIONAL ENHANCEMENTS

The Sky Train stations were designed to consider additional Airport operational functions so that the system will not only help improve ground transportation but will also help to enhance and expand other Airport operations:

1. Early Bag Check - Convenience and customer satisfaction are top priority at Sky Harbor. As such, the Airport will offer early bag check facilities at the 44th Street and East Economy Lot Stations. No additional fees will be assessed to the user of the early bag check service and the service can be used up to 45 minutes prior to flight departure. Passengers will be able to shed their bags prior to boarding the train and travel hassle free to the terminal. On opening day, after passengers drop their bags at the 44th Street or East Economy Lot Station, the Airport will securely transport the baggage to the appropriate terminal for induction into the existing baggage screening system **(See Figure 9).**

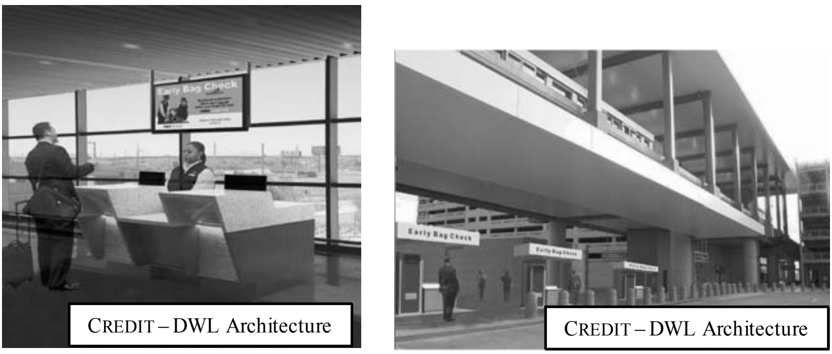

Figure 9 – Early Bag Check Services

2. Remote Ticketing/Check-In - The Airport will also feature remote ticketing at the 44th Street and EEL Stations. As with the early bag check, remote ticketing will be offered on day 1 of the PHX Sky Train's operation. Remote ticketing machines will be common-use type, such that any airline wishing to participate can utilize the same machine. This too is a free service, as part of America's Friendliest Airport customer service **(See Figure 10).**

Figure 10 – Remote Ticketing/Check-In

3. Passenger counting – The ability to track and monitor Sky Train passengers is an important tool for the Airport. It will aid in load and capacity analyses, optimization of head ways, and reduction/optimization of operational costs. Each train berthing location has been equipped with a passenger counting device, providing better than 98% passenger counting accuracy.

   There are 3 main components of the passenger counting system:
   a. Sensors – A devices that gathers a 3D image of person/object passing beneath the device and sends it to the analyzer.
   b. Door Contacts – A module that tells the analyzer when to start and stop counting.
   c. Analyzer – A component that identifies the images and stores the information for retrieval.

   The passenger counting data is stored by the analyzer until the analyzer is queried by an on board computer. A software application captures the data from the berth, time stamps the data, and stores it to a database. Data transmittal is sent via wireless connection from the analyzer to the servers. The data is accessible through the web either in streaming or history mode.

Below is an example of one of the numerous reports that can be generated from the system **(See Figure 11 for typical data output).**

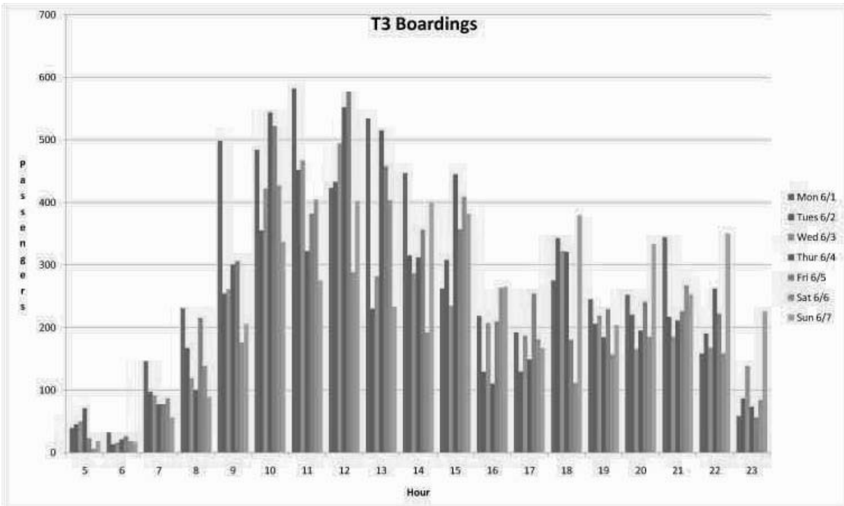

Figure 11 – Passenger Counting Data

4. Station expandability for terminal services – The ultimate vision of the Sky Train extends well beyond opening day facilities. The ability to adapt the system to accommodate the future growth of the airport and provide continued improvement to passenger service was well thought out during the planning and design stages of the project. As the terminal services begin to reach capacity, the Sky Train outlying stations have the ability to take on some of the functions that are currently performed at the terminals, such as baggage makeup and baggage screening with TSA support.

3.0 AIRPORT FACILITY ENHANCEMENTS

The infrastructure required for the Sky Train represents a significant increase in facilities that the airport must maintain and utilize. Careful thought and attention went into planning and design to create cost effective, durable and low maintenance facilities with flexible expansion capability while also providing a pleasant and seamless passenger experience. Specific features that accomplish this are:

1. Expandable Facilities - During the planning of the Sky Train stations, great effort was taken to create base station designs that could grow and expand

with future airport and adjacent development needs. Features of the stations that will help accommodate future growth are as follows:

a. 44th Street Station Site (**See Figure 12** for illustration) Station is expandable to grow into a more robust terminal type space and receive additional connections to future surrounding facilities such as parking garages and commercial development.
b. Terminal 4 Station (**See Figure 13** for illustration) Designed for a potential floor plate build out between station connector bridges to expand terminal functions.
c. Terminal 3 Station (**See Figure 14** for illustration) Designed for a potential build out along the station connector bridge and terminal south face to expand terminal functions.

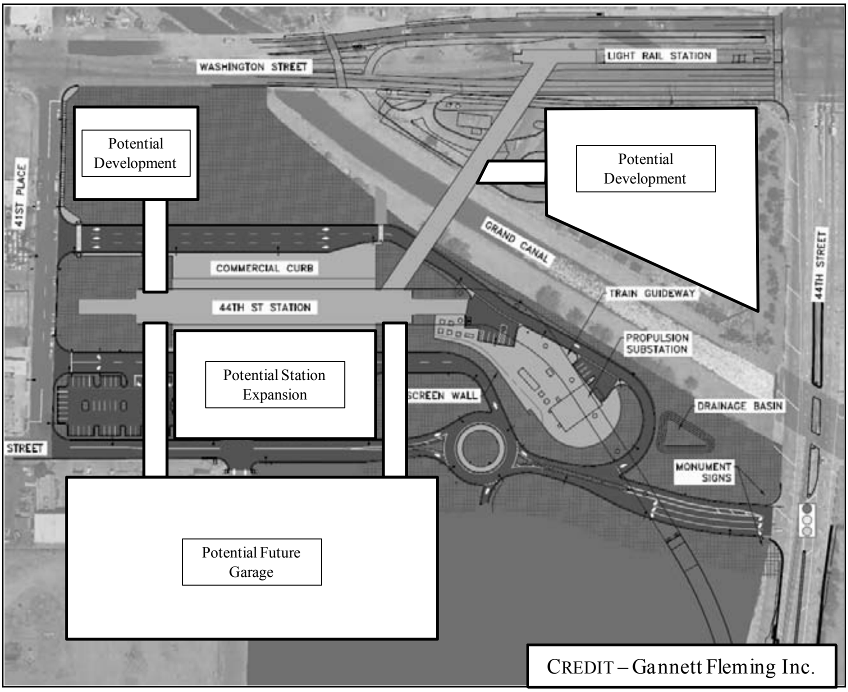

Figure 12 – 44th Street Station Expansion Potential

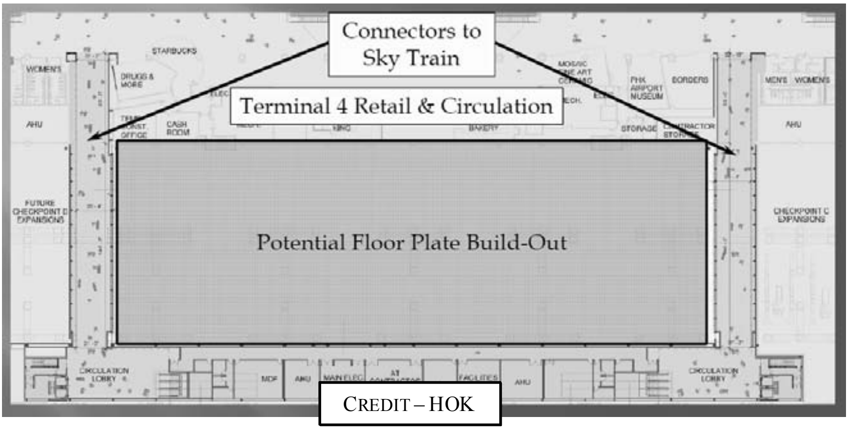

Figure 13 – Terminal 4 Expansion Potential at Station

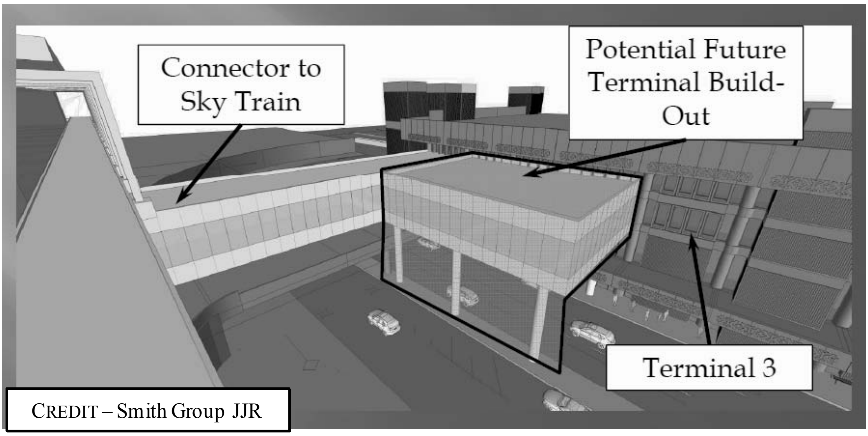

Figure 14 – Terminal 3 Expansion Potential at Station

2. Finish Considerations – finishes used throughout the Sky Train Station are selected to create an architectural theme that is a clean and modern design, consistent in look and layout throughout all stations. The design provides passengers with an intuitive sense of way-finding that will be familiar from station to station. In addition, all finishes will provide the durability and longevity that is required within a heavy traffic airport environment (**See Figures 15 & 16** for finish examples):

a. Terrazzo Floors
b. Stainless Steel and Aluminum Metal Wall Panels
c. Acoustical Metal Ceilings @ Platforms
d. Baffle Ceilings within walkways and mezzanines
e. Transit Grade escalators, elevators and moving walks

CREDIT – Gannett Fleming Inc.

Figure 15 – Terrazzo Floors & Metal Ceiling at 44th Street Station

CREDIT – Gannett Fleming Inc.

Figure 16 – Metal Wall Panels & Baffle Ceiling at Terminal 4 Station

3. Airport Power and Communication Backbone – The Sky Train creates a major line of infrastructure that extends through the middle and across the airport. To help mitigate the physical space requirements of the guideway and stations, an additional utility corridor was designed into the Sky Train alignment to provide a clear pathway for existing and future airport power and communications needs. The supplemental utility corridor consists 6 additional feeders for medium voltage (12 kv) power and 4 additional fiber optic/communication feeds.

4. Integrated Building Controls – all lighting and mechanical systems within the Sky Train stations have been integrated into the same facility management system used for the airport terminals. This enables all systems to be controlled consistently from a central location.

4.0 MULTI-MODAL TRANSPORTATION ENHANCEMENTS

In addition to providing connectivity to the major Airport facilities, the Sky Train is also designed to provide an improved Airport connection to the surrounding community and improve other transportation modes within the Airport (**See Figure 17** for intermodal details at 44th Street Station Site):

1. The 44th Street Station was designed with a seamless connection to the METRO light rail system making travel to the Airport by light rail convenient and easy.

2. The Intermodal Ground Transportation Center at the 44th Street Station provides a central and easy to use airport connection to public bus transit, commercial vehicles and private vehicles. The Center includes separate curbs for private and commercial vehicles and a cell phone lot adjacent to the station for convenient passenger pick up.

3. The 44th Street Station also includes a walkway connection to the regional trail system and local neighborhood to encourage foot and bicycle traffic to the airport. Bicycle storage lockers are located the station to help encourage bicycle commuters to the airport.

4. 44th Street Station Employee Parking Lot was added into the Sky train program to begin lumping employee parking near the outlying Sky Train Stations to free up space and congestion within the terminal core area and add additional employee Sky Train riders to the station.

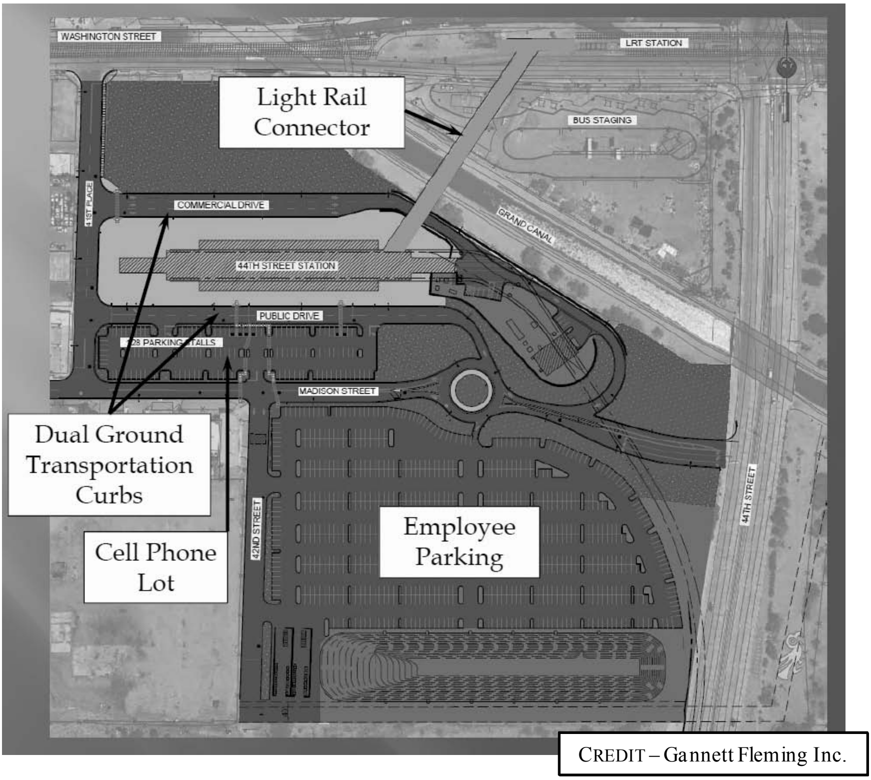

Figure 17 – Intermodal Details at the 44th Street Station site

5.0 COMMUNITY ENHANCEMENTS

The Sky Train has created a modern and efficient ground transportation system at the Airport with improved connectivity to the region. The state of the art system will also: help create economic growth opportunities for both the Airport and the Community; reduce congestion and pollution with energy efficient facilities and other sustainable design features; and provide a great passenger experience with thoughtfully designed architecture and sweeping views of the area throughout the system that will make the Sky Train a point of Community and Airport pride. Project features related these items are:

1. LEED Certification – The project Stage 1 campus is on target for LEED Silver Certification with the USGBC.

2. Traffic Reductions – Full build out of the Sky Train will result in 20,000 less vehicles per day within the airport core.

3. Urban Redevelopment - The project 44th Street Station has redeveloped and cleaned up a run-down industrial area with contaminated sites, transforming it into a community point of pride with high future development potential.

4. Art Program – the project includes approximately $7 million in integrated public art features completed by 6 individual artists. This will help in providing a great passenger experience throughout the system. Art features are fully integrated into the architectural designs and are included at each station (**see Figures 18 and 19** for project art installation examples):

    a. 44th St Station Breezeway Ceiling – reflective materials and lighting simulate a water surface.
    b. 44th St Station Connector Bridge Floor – artist design terrazzo
    c. 44th St Station Platform Floor – artist designed terrazzo
    d. Terminal 4 Station Connector Bridges – layered art glass walls containing organic designs
    e. East Economy Station Platform Floor – artist designed terrazzo
    f. Terminal 4 Station Platform Floor – artist designed terrazzo
    g. Terminal 3 Station Platform and Connector Bridge Floor - artist designed terrazzo

5. Transit Oriented Development Considerations – The 44th Street Station site layout and connectivity will be a catalyst for adjacent transit oriented development along the City's light rail corridor. See **Figure 12** for potential development opportunities.

Figure 18 – Art Glass Wall @ Terminal 4 Station Connector Bridge

Figure 19 – Artist Designed Terrazzo at East Economy Lot Station

6.0 Summary

Implementation of the Sky Train positions the Airport for "Smart" future growth; fosters continued economic progression, and enhances the local community. As the Phoenix Metropolitan area continues to grow, the Sky Train will ensure that its Airport will remain easily accessible, user friendly and well integrated into the surrounding community. The cooperation and teamwork enjoyed between the Phoenix Aviation Department, the Facilities Construction Managers, the System Supplier, the Facility Designer and Systems Consultant have created a successful Stage 1 opening. The team is looking forward a successful completion of the remainder of the program.

7.0 References

U.S. Green Building Council (2005). "LEED-NC Application Guide for Multiple Buildings and On-Campus Building Projects (AGMBC)"

DEVELOPMENT OF THE PHX SKY TRAIN GUIDEWAY ALIGNMENT

Nate Walnum, P.E., M.ASCE
Vice President, Kimley-Horn and Associates, Inc., 7740 N. 16th Street, Suite 300, Phoenix, AZ 85020, Tel 602-944-5500, *nate.walnum@kimley-horn.com*

ABSTRACT

The PHX Sky Train will serve passengers getting to and from the Phoenix Sky Harbor International Airport (Airport) from the City's light rail system, between terminals, parking facilities and eventually to the Rental Car Center west of the Airport. To do this, the train guideway must cross over and under taxiways, through Runway Protection Zones (RPZs), cross railroads, pass over existing pedestrian bridges, and connect to existing terminal buildings through a very congested and narrow corridor. Finding the right guideway alignment and station locations to best serve Sky Train users, while minimizing costs and maximizing ridership, was an extremely challenging process.

This paper reviews some of the constraints and alternatives that were considered during the guideway alignment development, including preliminary plans to tunnel under Terminal 4 and Terminal 3 and why the Airport ultimately decided to cross over Taxiway R instead. The paper discusses the interesting challenges associated with determining the best alignment for the PHX Sky Train, including the crossing of Union Pacific Railroad (UPRR), utilizing the SR-153 roadway corridor, impacts and enhancements to the East Economy Parking, crossing Taxiways R, S, and T, and connection points to each of the Terminals. The alignment development was heavily influenced by the Airport's desire to increase ridership, remove buses and traffic from the airport roadways to relieve congestion, and to provide excellent customer service.

The paper concludes with a brief look ahead to the upcoming design challenges associated with extending the train alignment to the Rental Car Center, which will be the largest driver of passenger activity on the system.

BACKGROUND

Phoenix Sky Harbor International Airport currently ranks as one of the 10 busiest airports in the United States, serving approximately 40.5 million passengers in 2011. This represents nearly double the number of passengers served in 1990, at which time Sky Harbor served 21.7 million passengers. Passenger activity peaked in 2007 at 42 million passengers, then dropped slightly as the economic recession impacted air travel volumes. Over the past few years, passenger activity has continued to increase and Sky Harbor Airport is preparing for that trend to continue by constructing the PHX Sky Train and other airport improvements.

The Airport is conveniently located near downtown Phoenix and can be accessed by the regional freeway system that serves the Airport and the Metro Phoenix area, see Figure 1. This freeway system also became congested as the region grew, which has caused impacts to the on-airport roadway network. Since there are freeway connections on both the east and west sides of the Airport, there are a number of "cut-through" vehicles that use the airport roadway as a means to bypass the congestion on the regional freeways during peak traffic periods. This cut-through traffic reduces capacity for airport uses(1). As the passenger levels continued to grow, the Airport realized that a secondary means of getting passengers to and from airport facilities was necessary to maintain high levels of customer service.

Figure 1 – Location Map, by MapQuest

PLANNING ALTERNATIVES

A number of alternatives were reviewed to ease congestion on the airport roadway network, including:

- Widen the roadways on each side of the terminals to add lanes in each direction
- Reconfigure the roadways to be a cul-de-sac or dead-end layout
- Construct a dedicated aerial roadway for buses

Figure 2 - Curbside Congestion at Terminal 4, by Kimley-Horn and Associates

Each of these alternatives were eliminated due to costs, constructability, risk, impacts to existing facilities, or reduced customer service.

THE SOLUTION

The final recommendation that came out of the planning studies was to build an Automated People Mover (APM) system on a dedicated guideway that would provide connections to each of the terminals, parking, the Consolidated Rental Car Center, and the City's light rail station at the intersection of 44th Street and Washington Street. The benefits of the PHX Sky Train APM system include:

- Provides a secondary means of accessing the Airport without driving on Sky Harbor Boulevard, which can be congested or confusing to some drivers
- Will reduce traffic at curbfront areas and airport roadways by 20%
- Moves non-essential functions away from terminals, such as commercial traffic, buses, ground transportation, and employee parking
- Connects all key Airport facilities and existing mass transit
- Utilizes lower value land, where possible, and enhances future land development potential
- Free to passengers, safe, reliable, and expandable for future growth

EARLY ALIGNMENT STUDIES

When Terminal 4 was constructed in 1989 accommodations were made to allow for a future transit line running in an east-west orientation under the terminal building. A section of the terminal floor was built as a structural slab supported by drilled caissons along the N1 and N2 gridlines. This would allow for the removal of earth and create the space for an APM station and guideway structures. However, the limited separation between N1 and N2 gridlines(2) would only allow for a narrow platform width and inadequate vertical circulation elements. Figure 3 shows the Terminal 4 underground APM concept plan which assumed that the APM would be built in a tunnel configuration east and west of the Terminal 4 station area.

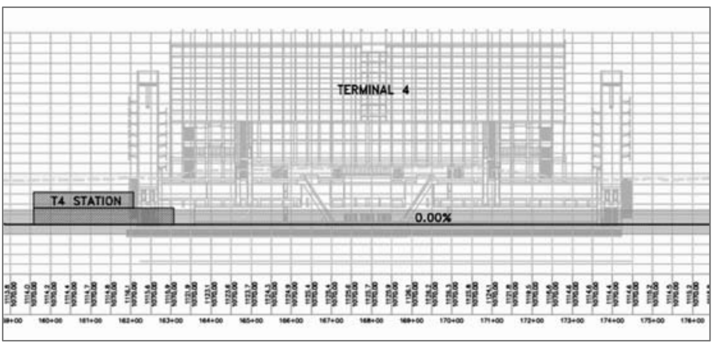

Figure 3 - Terminal 4 Tunneling Alternative, by Author

Ultimately, the Airport decided that the expense and risk of tunneling under the Terminal area was too high and they asked the design team to look for other alternatives that would improve the passenger experience and reduce costs. This was achieved by utilizing an aerial guideway with a station that connects passengers directly to the Passenger Level of Terminal 4. This change had a ripple effect throughout the rest of the alignment, particularly at the crossing of Taxiway R, which would now require the APM to cross over instead of under the taxiway.

The PHX Sky Train connection to the light rail transit (LRT) station at 44th Street and Washington Street is another area where the final design differs greatly from planning concepts. Originally, the APM was to connect directly to the LRT station as shown in Figure 4 and to the nearby maintenance and storage facility (MSF). Some of the reasons why this layout was modified include:

- The surrounding site was deemed as high-value property from an airport usage or future development standpoint and it was preferred to move the MSF site to a more remote location
- The station would have to be built over the Grand Canal, making construction and maintenance access difficult
- Dead-end station does not allow for system expansion
- The MSF site was constrained with limited test track length
- Additional track length was required to achieve the desired platform height

Figure 4 – Early Alignment at 44th Street Station, by Author

DESIGN CRITERIA

The alignment design criteria(3) that was used to layout the PHX Sky Train plan and profile geometrics is shown in Table 1. Considerable care was taken to achieve an efficient alignment while balancing the need for ride comfort, operation and maintenance (O&M) costs, system performance, and train speeds. Horizontal and vertical curves were kept as large as possible to improve train performance and to allow as many system suppliers as possible to be candidates for the project. In some cases the maximum allowable grades and minimum curve radii were required to find a pathway through the highly developed and congested airport environment. Conditions that impacted the alignment included taxiways, roadways, utilities, parking garages, RPZs, the UPRR railroad, SRP irrigation canal, Part 77 airspace surfaces, etc.

Additional clearance criteria for the vehicle dynamic envelope was provided by the Systems Designer and ultimately by Bombardier who was selected as the Systems Supplier. This vehicle dynamic envelope provides minimum clearance requirements based on nosing and chording effects for horizontal curves of varying radii. At stations, the dynamic envelope was reduced on the "platform side" to accommodate the necessary rub strips and interface between the platform edge and vehicle doors.

Table 1 - Design Criteria

Horizontal Curves	67m/220 feet minimum (passenger guideway) 50m/165 feet minimum (non-revenue guideway)
Vertical Curves	Length based on algebraic difference between grades multiplied by 60
Spirals	Clothoid type, length based on 2-second equilibrium at design speeds
Grades	As flat as possible, 6% max up or down
Superelevation	None, guideway deck is flat; superelevation provided by System Supplier in running surface design based on ride comfort criteria

PHX SKY TRAIN ALIGNMENT

The PHX Sky Train project is being constructed in phases, with Stage 1 open in 2013, Stage 1A open in 2015, and Stage 2 opening in 2020. The overall train alignment is shown in Figure 5. Stage 1 connects stations at Terminal 4, East Economy parking, and 44th Street. Stage 1A extends the system to connect passengers to Terminal 3 and Terminal 2. Stage 2 will connect the system to the Rental Car Center and may accommodate future facility connection points for parking, West Ground Transportation Center, or other Airport facilities.

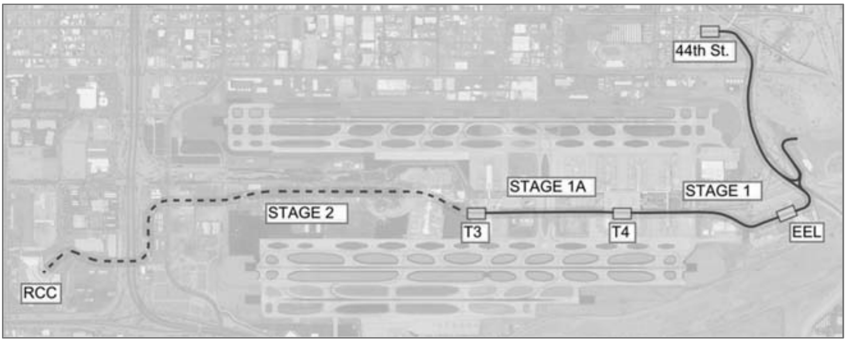

Figure 5 - Overall PHX Sky Train Alignment, by Author

The train guideway is predominantly aerial with sections of at-grade guideway between the 44th Street Station and the East Economy Lot (EEL) station in Stage 1 and under Taxiways S and T in Stage 1A. Ironically, one of the more difficult sections of guideway to design was the on-grade section in Stage 1 since it crosses the UPRR railroad property and through the Runway 8-26 RPZ. Figure 6 shows the location of the RPZ, on-grade guideway, UPRR, MSF site, and 44th Street roadway improvements.

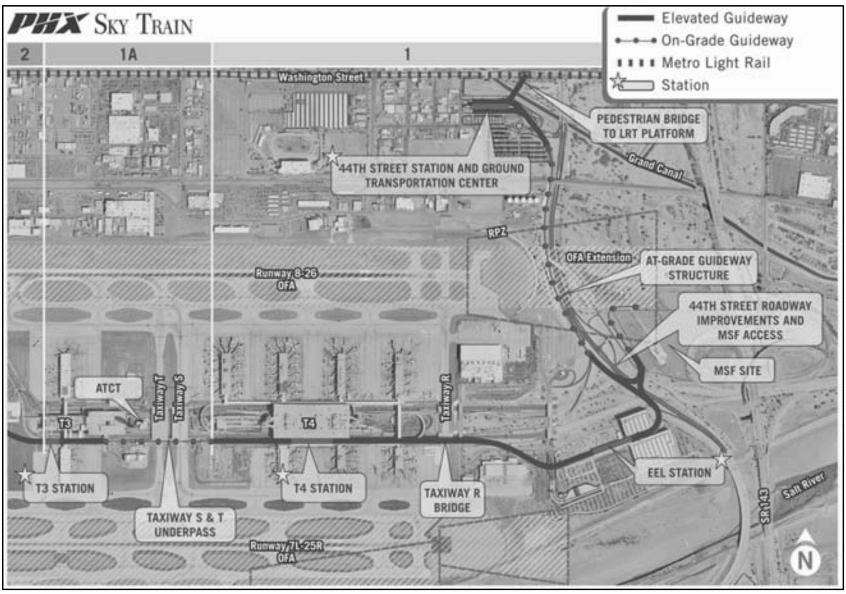

Figure 6 - Stage 1 / 1A Guideway Structures, by Author

Approval from the Federal Aviation Administration (FAA) was required to build the train guideway in the RPZ, which is established to provide an area of protection at the ends of runways. In this case, there was an existing freeway (SR-153) with three lanes in each direction that already crossed the RPZ. An agreement was made between the City of Phoenix and the Arizona Department of Transportation (ADOT) that transferred ownership of SR-153 to the City. The Facilities Design team then redesigned SR-153 to downgrade the roadway from a freeway to a City street and reduced the number of lanes from three to two in each direction.

The additional space created by downgrading SR-153 was then utilized for the PHX Sky Train. It was critical that the "footprint" of the combined train and roadway be contained within the previous right-of-way limits of SR-153. The stance of the Airport was that the new configuration with the train did not create a worse scenario than existing condition and should be "grandfathered" in for approval based on the former SR-153 criteria. The FAA agreed and approved the modified SR-153 crossing of the RPZ. Figure 7 shows the PHX Sky Train guideway and 44th Street roadway crossing under the UPRR bridge.

Figure 7 - APM Crossing UPRR, photo courtesy of Hensel Phelps Construction Co.

The location of the 44th Street Station platform was based largely on the restrictions of crossing the UPRR railroad bridge. It was not possible to cross over the UPRR railroad due to airspace restrictions, proximity to the airport fuel farm, railroad height restrictions, and lines of sight from the Pueblo Grande museum. Pueblo Grande is a National Historic Landmark and archaeological park located just east of the 44th Street station, which showcases the history of the ancient Hohokam people that inhabited the area. Being a good neighbor to and soliciting input from Pueblo Grande was a high priority in the design process.

Crossing under the UPRR bridge set the location of the 44th Street Station based on the minimum travel distance at 6% maximum grades to achieve the desired platform elevation. This also set the location of Madison Street, which connects to 44th Street under the train guideway and is critical to the traffic circulation for the station and ground transportation center. Figure 8 shows the train profile grade line and clearance under the UPRR bridge, taking into account the minimum clearances for the vehicle dynamic envelope.

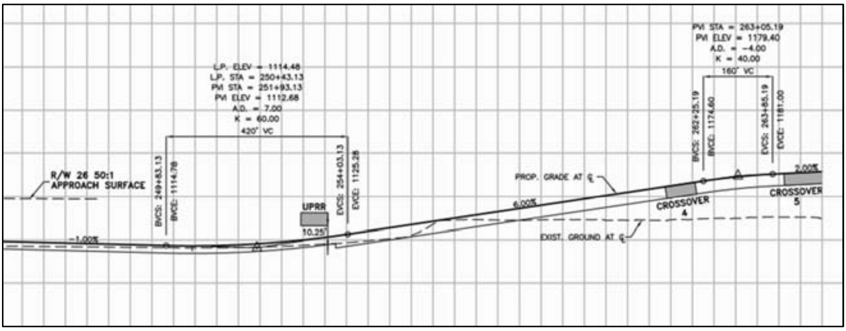

Figure 8 - At-Grade Guideway Profile, by Author

EAST ECONOMY PARKING

The EEL is a long-term parking facility comprised of approximately 6,000 parking spaces in two garage structures and 4,200 surface parking spaces, for a total of 10,200 spaces. In order to place the EEL station in close proximity to both garages, the existing entry/exit toll plaza had to be relocated. A new access roadway, toll plaza, circulation routes, bus stops, and utilities had to be constructed before the old toll plaza could be demolished and the new train station constructed. Initial alignment alternatives through the EEL in a north-south orientation were ruled out based on the Center Runway 7L-25R airspace surface restrictions. In order to stay below the Part 77 surfaces, the guideway had to drop down to ground level near the south end of the parking lot. This created impacts to traffic circulation within the lot that made large sections of surface parking less desirable.

Rather than impact the number of available surface spaces, the alignment was changed to an east-west orientation and “squeezed” between the two garage structures. The tight clearances in this area required that an existing emergency stairwell next to the elevator core for Garage B (south) be moved. With the stairwell out of the way, the guideway structure was able to pass between the two garages and turn to the north while maintaining the minimum design criteria. The horizontal curve east of Garage A (north) has the smallest curve radius on the mainline guideway at R=68m (223 feet). This east-west orientation also shortened the overall guideway length and made a more direct crossing of Taxiway R. Figure 9 shows the elevated guideway structure east of the EEL garages at the tightest horizontal curve section of the system.

Figure 9 - East Economy Garages, photo by Kimley-Horn and Associates

TAXIWAY R CROSSING

Elimination of the tunneling option under Terminal 4 required that the crossing of Taxiway R be elevated. Since there were no other transit crossings of active taxiways anywhere else in the world, careful design and coordination with the FAA were required. The Facilities Design team prepared numerous studies to show that the Taxiway R bridge would not impact aircraft circulation on the airfield or impact lines of sight from the new Air Traffic Control Tower. Figure 10 shows the train plan and profile at Taxiway R with clearance options for both Group 5 and Group 6 Taxiway Object Free Areas.

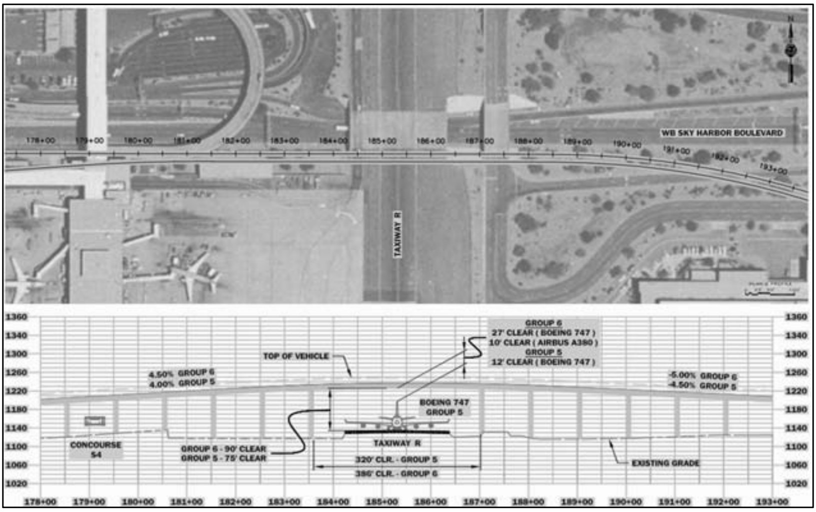

Figure 10 - Taxiway R Bridge Clearances, by Gannett Fleming Inc.

The bridge span was based on the Taxiway Object Free Area width for a Group 5 Taxiway, which is 97.5m/320 feet. Occasional Boeing B-747 aircraft use Taxiway R, but larger clearances for Group 6 aircraft such as the Airbus A380 was not justifiable based on costs and the current and expected aircraft fleet mix at Sky Harbor Airport.

Horizontal clearance for taxiways is well defined in the FAA Advisory Circular AC 150/5300-13. Vertical clearance, however, is more subjective since it is such a rare occurrence to have any obstructions over active airfield movement areas. The vertical clearance under the Taxiway R bridge was based on the tail height of a B-747 at 19m (64 feet) plus additional buffer for pilot comfort. This additional buffer clearance was also created to allow for the unlikely scenario of a nose wheel failure. If a nose wheel failed at a specific location as a B-747 passed under the bridge, the aircraft nose would drop to the taxiway surface and the tail would rise based on the geometrics of its relationship to the main body landing gear. The calculations showed that 22.5m (74 feet) of clearance would accommodate this scenario. Actual design clearance is 24.1m (79 feet), which provided for 1.2m (4 feet) to raise the Taxiway R surface in the future as part of a planned taxiway improvement project. This would leave the ultimate clearance at 22.9m (75 feet).

Figure 11 – B-747 at Taxiway R Crossing, photo courtesy of Sky Harbor International Airport

TERMINAL 4

Terminal 4 is the busiest terminal at Sky Harbor Airport, accounting for approximately 80% of the daily flights. Phoenix is the headquarters for US Airways and a major hub for Southwest Airlines, both of which operate out of Terminal 4. Some of the constraints to finding an alignment though this very congested area of the Airport included:

- Underground baggage tunnels and utilities.
- Expanded terminal parking decks surrounding T4.
- A new underground explosive detection system (EDS) facility.
- Connector bridges between S3 and S4 Concourses
- Airline coordination to shut down gates during construction.
- Locations for the new APM connector bridges.
- Clearance for connector bridges over the elevated Departures level curbfront.

Figure 12 shows the complicated relationship of the proposed guideway and T4 station support structure with the existing facilities.

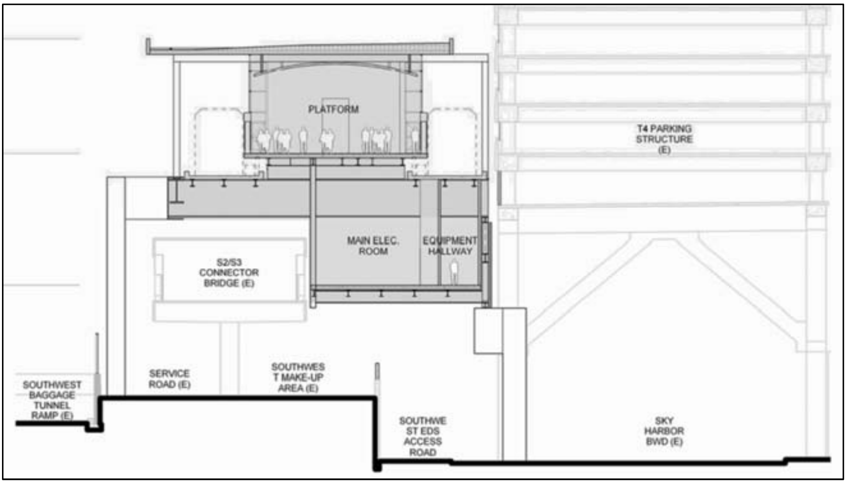

Figure 12 - Terminal 4 Guideway and Station Structure, by HOK Architecture

STAGE 1A

The APM guideway connection between Terminal 4 and Terminal 3 will provide passengers with inter-terminal access to all terminals, parking, and the Light Rail. This will also allow the Airport to remove busing service between these facilities, which will save money and reduce pollution and congestion on Sky Harbor Boulevard. Although the guideway alignment is relatively direct horizontally between T4 and T3, the required profile to cross under Taxiways S and T pushed the limits of the established design criteria.

An aerial crossing over Taxiways S and T was evaluated and discounted for a number of reasons, including cost, bridge span length and height, impacts to the nearby Air Traffic Control Tower line of sight, and Taxiway Object Free Area limitations. Crossing under the taxiways was, however, far from easy. The preferred alignment impacted a number of significant infrastructure elements, including:

- The Runway 7L-25R airfield lighting vault
- The Core Network Building, which is the main communications hub for the entire airport
- The south Triturator aircraft sewage disposal station
- The on-airport fire station access and parking
- Underground water, sewer, power, and FAA communications lines

All these facilities had to be relocated nearby and brought back operational before the existing facilities could be decommissioned and removed for the train guideway construction. An added benefit of crossing under the taxiways was that an airfield service road could also utilize the new taxiway bridge spans. This will reduce the number of at-grade taxiway crossings and potential for taxiway incursions. Figure 13 shows the proposed underpass of Taxiways S and T for the APM guideway and airfield service road.

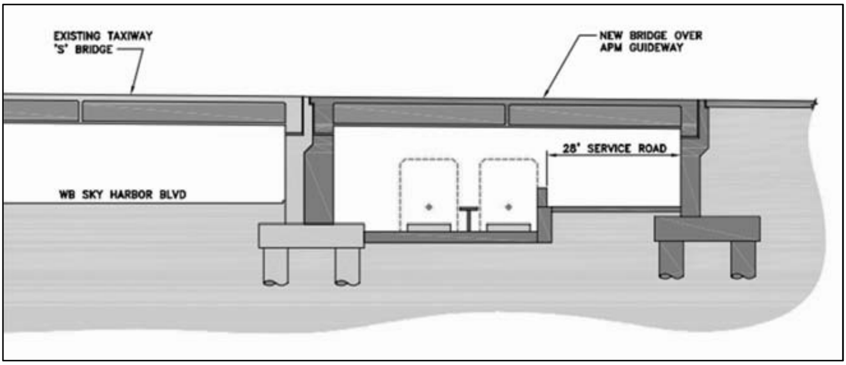

Figure 13 - Taxiways S and T Underpass, by Gannett Fleming Inc.

West of the Taxiway crossing, the guideway grade is at 6% to get over the T3 south concourse pedestrian bridge and level out for an "X" type crossover before reaching the Terminal 3 station. The "X" type crossover was required due to limited guideway length before the station, which prevents the T3 station for being located too far west of the Terminal 3 building. The crossover is also needed since it will function as an end-of-line station until the PHX Sky Train is extended west to the Rental Car Center.

STAGE 2

Extending the PHX Sky Train to the Rental Car Center is perhaps the most important segment of the entire system since the largest numbers of passengers are projected to use the system between Terminal 4 and the Rental Car Center. Currently, passengers are transferred between the Terminals and the Rental Car Center on 40' buses. At peak travel periods, it is very common to see large numbers of passengers waiting for buses at the curbs. This is both frustrating for passengers and creates a congested curbfront area. Once the Stage 2 segment is complete, Sky Harbor Airport will be able to remove all bus operations from the terminal curbs, thus improving traffic and emissions on the airport roadway network. Passengers will also enjoy a quicker transfer time, short wait periods between trains, and a more enjoyable passenger experience.

Some of the design challenges associated with extending the train alignment to the Rental Car Center include:

- Crossing under Interstate 10 utilizing an existing roadway underpass on Sky Harbor Circle
- Providing connection points for future facilities such as terminals, parking, and a west ground transportation center

- Seamlessly connecting the existing Rental Car Center building while maintaining bus operations during construction
- Crossing under planned future crossfield Taxiways U and V
- Crossing over the existing Terminal 2 Concourse
- Crossing over 24th Street and avoiding impacts to underground utilities and airport infrastructure

CONCLUSION

The evolution of the PHX Sky Train alignment presented many complex and interesting challenges for the Airport and design team. Finding the right guideway alignment and station locations to best serve airport users, while minimizing costs and maximizing ridership, was an extremely challenging process. The alignment development was heavily influenced by the Airport's desire to improve the passenger experience, remove buses and traffic from the airport roadways to relieve congestion, and to provide excellent customer service.

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PHX Sky Train™ - Mean & Methods

Dave Peskin[1], Carl Ekstrand[2], Scott Sedberry[3]

1 Field Engineer, Bombardier Transportation, 1111 S. 44th Street., Phoenix, AZ 85034-4405, dave.peskin@us.tranport.bombardier.com, (480) 273-3798

2 Field Engineer, Bombardier Transportation, 1111 S. 44th Street, Phoenix, AZ 85034 – 4405, carl.ekstrand@us.transport.bombardier.com, (480) 273-5267

3 Manager of Engineering Projects, Lea+Elliott, Inc., 500 S. 24th Street, Phoenix, AZ 85034, ssedberry@leaelliott.com, (253) 365-8002

Abstract

The PHX Sky Train System® began construction in mid-2009, and is positioned to begin passenger service in the first quarter of 2013. During the construction of the guide way running surfaces, contractors developed construction methods to improve efficiency of construction and maintenance of construction tolerances.

This paper addresses the means and methods employed in the construction of the vehicle running surfaces, fixed guide beam(s), guide beam pedestals and related components for the Stage 1 system. In addition, the paper will discuss how these creative means and methods combined with diligent quality control procedures work seamlessly together to achieve simple, scalable and repeatable manufacturing and construction, improved ride quality and cost effectiveness compared to previously implemented methods. Finally, the paper will highlight the testing and verification process used to confirm compliance with the ride quality standards and related system documentation.

Introduction

Over the course of 18 months commencing in January 2011, construction of the 1.7 mile dual lane PHX Sky Train (Stage 1) guide way running surface system was completed by Bombardier's general contractor, the Weitz Company. Work generally included construction of continuous 14,173m (46,500 Ft) of 30.48cm (20 in) concrete running surface beams, 7,700 beam support (pedestals), 4 complex switch areas, traction power rail, expansion joint assemblies, steel beams, cable tray, associated electrical and controls. This paper will focus on the means and methods implemented for the civil construction, how they were developed and the resultant level of quality achieved.

While variations in the owner provided guide way deck and superstructure were expected as a manageable field condition, development of a holistic, efficient, and flexible set of tools (process) was essential to meet the system requirements for ride quality as well as promote timely and profitable completion. This system, developed and implemented by Bombardier's general contractor with contributions from key subcontractors combined the requirements of engineering (survey), steel fabrication, field supervision and production, quality control/assurance, and sensible verification employed at discreet intervals of completion resulting in a high quality product.

Ride Quality and Comfort

In this section the objective is to show resulting ride quality data from the Phoenix SkyTrain® project in relation to the technical requirements and compare them with corresponding ride quality data acquired in 2004 from the Dallas Fort-Worth SkyLink project, Bombardier's first implementation of the Innovia 200® vehicle technology.

Ride quality for the Phoenix SkyTrain® is evaluated for compliance within the limits described in ASCE 21-98 Section 7.7.3 Tables 2-1 and 2-2 for Sustained Acceleration and Maximum Jerk Rate limits. The requirement for "Standing" passengers is the most applicable and conservative and as such is the technical criteria used unless otherwise indicated. The results are shown in the Figure 1 below.

DIRECTION	SUSTAINED ACCELERATION (STANDING)				JERK RATE (STANDING)		
	MAX ALLOWED PER ASCE TABLE 2-1	MAX ALLOWED BY SPEC.	PEAK RECORDED	AVG RECORDED	MAX ALLOWED PER ASCE TABLE 2-2	PEAK RECORDED	AVG RECORDED
	(G/SEC)	(MPH/S)	(MPH/S)	(MPH/S)	(MPH/S/S)	(MPH/S/S)	(MPH/S/S)
PHOENIX SKYTRAIN™ (2012)							
LATERAL ACCELERATION	0.10	2.19	2.39	2.068	1.32	1.17	0.92
VERTICAL ACCELERATION	0.05	1.10	1.41	1.195	0.88	0.29	0.23
LONGITUDINAL ACCELERATION	0.16	2.31	2.19	2.16	2.19	1.45	1.402
LONGITUDINAL IN BRAKING	0.32	2.19	1.91	1.865	2.19	1.09	0.89
DALLAS SKYLINK (2004)							
LATERAL ACCELERATION	0.10	2.19	1.97	1.915	1.32	1.75	1.415
VERTICAL ACCELERATION	0.05	1.10	1.32	0.96	0.88	1.32	0.923
LONGITUDINAL ACCELERATION	0.16	2.31	2.22	2.192	2.19	2.58	1.813
LONGITUDINAL IN BRAKING	0.32	2.19	2.17	2.135	2.19	1.83	1.286

Figure 1: Sustained Acceleration & Jerk Rate

The highlighted areas in the figure identify peak recordings determined to be in excess of the technical requirements for the given measurements. The degree to which a single peak recording can characterize overall system ride quality is limited and as such averages were also provided to more evenly account for major differences in system guide way profiles. For Phoenix, the peak recordings were closely approaching the technical requirements for lateral and vertical acceleration and met all the requirements for jerk rate whereas, for Dallas, all acceleration criteria was met with the exception of vertical acceleration and much of the jerk rate measurements were determined to be excessive.

In addition, ride quality was measured and verified by human response testing with the specified instrumentation in accordance with ASCE 21-98 Section 7.7.3.2 Human Response Testing. By reference, the ride quality criteria is detailed in ISO 2631 Evaluation of Human Exposure to Whole Body Vibration which specifies that for any single station to station run, RMS accelerations between 1 and 80 HZ shall fall below the levels for 1-hour exposure to reduced comfort.

The vibration instrumentation used for SkyTrain® was a Larson Davis HVM100 Type 1 Human Vibration Meter, DFW SkyLink deployed the B&K 2522 Human Response Vibration Meter. DFW data was taken using a 2 car train configuration while Phoenix used a 3 car train configuration.

Ride quality comparisons in relation to vibration are made using the calculated AEQ Sums (∑) included with the final test reports for both projects. For reference, the calculated AEQ Sums provide a basis of comparison for simultaneous multi-axis or multi-planar vibration primarily along the longitudinal, lateral and vertical axes. Refer to the latest version of ISO 2631 for more detailed information.

For the purposes of illustrating the level of ride quality achieved on the SkyTrain® project, Figure 2 delineates the recorded upper and lower acceleration (AEQ Sum) values for the Phoenix SkyTrain® and the DFW Skylink, the specified ride comfort requirements and overlays them with the exposure limits described in ISO 2631 Figure 2a. For clarity, recorded peak acceleration values are shown as a constant.

The measured vibration for Phoenix was consistent and narrow ranging from .247 m/s^2 (107dB) to .306 m/s^2 (109dB) while DFW varied from .264 m/s^2 (108dB) to .560 m/s^2 (114dB). The maximum allowable vibration is .370 m/s^2 (111dB) as defined by the reduced comfort boundary. While the values in Figure 2 are maximum acceleration peaks, DFW consistently exceeded the specified limits in the “y” and “z” axes particularly and required adjustments to the operating profile as well as concessions in system performance. Regardless, it is clear from the vibration test data that the SkyTrain® project successfully met the specified ride quality requirements.

In the sections that follow, this paper will describe the means and methods developed and implemented by Bombardier’s general contractor, the Weitz Company, to achieve a consistent high quality running surface for the Phoenix SkyTrain® project resulting in a greatly improved ride quality when compared with the DFW system. While many factors such as vehicle suspension, train control, instrumentation and advancements in manufacturing play a key role in delivering ride quality, it is the intent of this paper to highlight a few of the primary methods and processes used on the SkyTrain® project that directly contributed to the ride quality results outlined above.

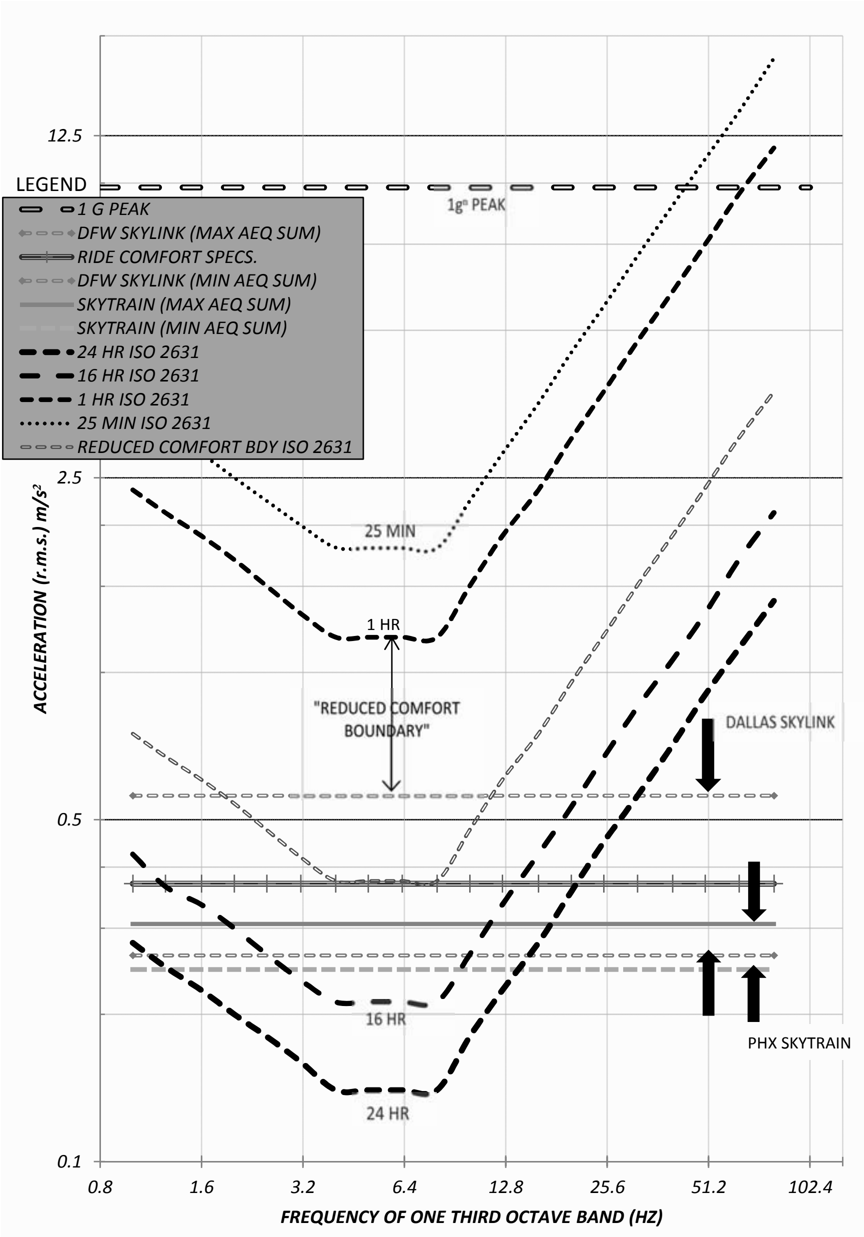

Figure 2: Ride Quality Analysis

Guide Way Mock Up

This section describes the full scale mock-ups used by Bombardier's general contractor to help identify constructability issues and develop the means and methods that would be employed.

Mock-up 1A (Figure 3): Consisted of a 12.19m x 8.22m (40 Ft x 27 Ft) wide flat straight section of guide way. The west lane was constructed as a typical straight guide way section with minimum 19.05cm (7.5 in) deep x 50.8cm (20 in) wide running surfaces (plinths) with three types of expansion joint assemblies. The east lane was similar except constructed with a maximum plinth depth of 50.8cm (20 in). These conditions side by side replicated the most dramatic tangent dual lane condition that would occur along the guide way. The mock up also included typical guide beam supports (pedestals) and a small section of straight W8x21 steel beam complete with base plates.

Figure 3: Guideway Mockup 1A – Straight Section

To account for other constructability issues, block outs (half moons), conduit runs, stub ups, cable tray and equipment pole bases were also mock assembled to confirm code clearances and dynamic vehicle clearances, quantify schedule impacts, test equipment assemblies and more completely understand the finished construction.

Mock-up 1B (Figure 4): Consisted of a 12.19m long x 8.23m wide (40 Ft x 27 Ft) single lane spiral section with a tight turning radius of 67.98m (223 Ft), maximum running surface depth of 50.8cm (20 in) and a maximum super elevation of 6.0%. The mock up also included a full 12.19m (40 Ft) section of W20.32cm x 9.52kg (W8x21) curved beam and Type 3 guide beam supports at 2.43m (8 Ft) O.C. This condition represented the worst case guide way condition anticipated on the project.

The knowledge and experience gained both good and bad, as a result of constructing a full scale mock up initiated a process of contractor questions, creativity and determination to develop a cost effective and holistic set of means and methods to simplify complex field conditions and manage them effectively. Equally important to this effort was involving key subcontractors (Bell Steel, Suntec Concrete, CK Engineering, and Wilson Electric) in the process to evaluate and/or reevaluate their approach to the project, change baseline assumptions as necessary and develop working solutions. This dynamic effort, while not painless, was pivotal to the success of this project. Success on this project is measured in the form of Ride Quality described above. The means and methods developed to achieve the ride quality requirements are categorized below and described in detail in the sections that follow.

Figure 4: Guideway Mockup 1B – Spiral Section

Means and Methods Developed from Mock-Up Construction

- Establishing and Maintaining profile grade line (PGL) during construction
- Development and use of guide beam jigs
- Placement of running surface expansion joints
- Flexible/scalable formwork/reinforcing system
- Installation and assembly of guide beam
- Cable tray supports and lighting
- Development of a detailed sequencing, production and quality control plan and ultimately the project schedule

Establishing and Maintaining Profile Grade Control

The Profile Grade Line (PGL) on this project are theoretical lines in space located 1.52m (5 Ft) above the owner-provided deck centered on each lane of train travel prescribing the primary civil information required to design and construct the trains system guideway.

From a construction perspective, systematically maintaining the PGL in the field is problematic as the assembly line of plinths, pedestals, guidebeams, and cable tray cover up or otherwise obscure survey control. While offsets can be an effective tool for on-grade work, they were deemed impractical for elevated guideway sections. Developing a systematic approach for back-checking installed work and maintaining positive design/quality control was a primary objective in constructing the full scale mock-ups discussed earlier. In conjunction with maintaining PGL control, the equally important aspect of maintaining the relationship of the guide beam to the running surface at all points whether in tangent or spiral guideway sections also had to be managed and verified on a day to day basis.

While PGL established a point in space that was transferred down to deck level, it did not provide an accurate or verifiable center point of the guide beam which varies widely in height above the deck surface. This challenge was more pronounced in spiral sections as not only is the beam curved, the running surface superelevated, but the owner-provided deck included mild cross slopes for drainage creating a constantly changing condition. Figure 5 below, part of an RFI submitted to Bombardier shortly after the mock-up was constructed, detailed a worst case condition that clearly identified the problem and ultimately helped lead the team to a solution.

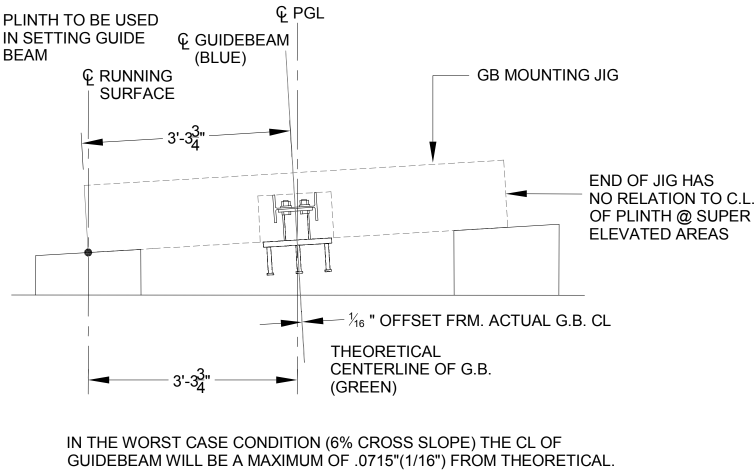

Figure 5: PGL Running Surface Relationship

Considering the complex relationship of the PGL to the actual running surface construction, the contractor simplified the thought process deviating away from managing to a theoretical pathway to a ride quality centered approach whereby control (and thus ride quality) would be based on maintaining a consistent relationship between the running surfaces and guide beams whether in a tangent or in spiral guideway section. It should be noted that there is no contractual requirement for the train system to follow the PGL permitting adjustments by the train manufacturer where required to meet the train system design requirements, and of course, providing the adjustments, if any, fit within the owner-provided infrastructure.

To solve this problem, the contractor determined that once plinths were poured, control could be reestablished on the centerline of a designated plinth (typically the outside plinth in the direction of travel) every 2.43m to 3.05m (8 Ft – 10 Ft) and at pedestal locations. With control reestablished, using an adjustable guidebeam jig to hold the guidebeam coplanar to the running surfaces at every point along the guide way, the relationship was maintained with positive verifiable results. The guidebeam final elevation was set using the approved as-built plinth elevations moving the PGL in elevation from theoretical to match the actual plane constructed. While differences between the actual and theoretical PGL varied up to 2.54cm (1/16 in), the running surface size was sufficient to accommodate these variations within the tire pathways (system tolerances). However, this approach placed greater emphasis on ensuring the quality and geometric accuracy of the running surfaces.

Guide Beam Jigs and Quality Control

As referenced in the preceding section, one of the more pronounced successes of the mock-up effort proved to be the development of the guide beam jigs. The overall approach of the mock up was not to confirm what was already known, but to identify what was not known and develop an assembly line methodology that would support accurate and efficient installation, quality control, scheduling, and fabrication of the entire guideway construction effort. While a successful tool once finalized, it required several attempts before an acceptable jig was produced.

Figure 6: Guidebeam Jig Prototype #2

The initial attempt consisted of a lumber based jig that proved to be unworkable and as such was discarded unceremoniously. The second prototype jig (Figure 6) consisted of a small section of steel beam approximately 203cm (80 in) in length spanning the distance between plinths with fixed vertical supports set on angles at the interior edge of the plinths and at a constant height from the centerline of beam web to top of running surface plinths. If constructed perfectly, the distance between the running surface plinths and the centerline of the guidebeam(s) would remain constant. The guidebeam cradle was fixed between welded angles and included two adjustment bolts for minimal lateral adjustment. While this prototype did achieve some of the objectives, the contractor determined the jig had insufficient height and beam adjustability needed for adapting to as-built conditions.

In an effort to address the height adjustability, the contractor modified the prototype to include threaded rods and bolts at the ends of the jig to provide for field height adjustments where needed (Figure 7). Even with these modifications, it was determined that this prototype introduced too many fabrication variables, numerous moving parts, raised concerns about durability and lacked the overall simplicity to implement project wide.

Figure 7: Guidebeam Jig Prototype #2A

To incorporate the lessons learned to date and further refine the jig design, a final prototype effort was undertaken (Figures 8 and 9). These refinements greatly simplified the jig and provided more reliability than previous versions. Since the height of the guidebeam to the running surface is a fixed dimension regardless of running surface condition, the jig was constructed at a predetermined depth such that the top of the guidebeam is tight to the bottom of the 10.16cm (4 in) tube steel cross member. The beam cradle was constructed to precisely place the beam centered between the plinths, thereby ensuring the guidebeam was always in the proper geometric relationship to the running surface(s). Minor lateral adjustments to accommodate as-built conditions were permitted with the use of the threaded side bolts.

The larger tube steel surface area resting upon the running surfaces provided greater stability for the jigs and accurately mirrored the constructed running surface conditions, i.e.….slope, grade, deviations and imperfections while maintaining the critical relationship between the guidebeams and running surfaces. Placing the jigs every 2.13m to 2.43m (7 Ft to 8Ft) permitted the jigs to adjust and hold guidebeams in place and protect their position during construction. In order to accommodate construction in several locations simultaneously, the contractor fabricated roughly 120 jigs total for use on this project.

Figure 8: Final Guidebeam Jig Assembly

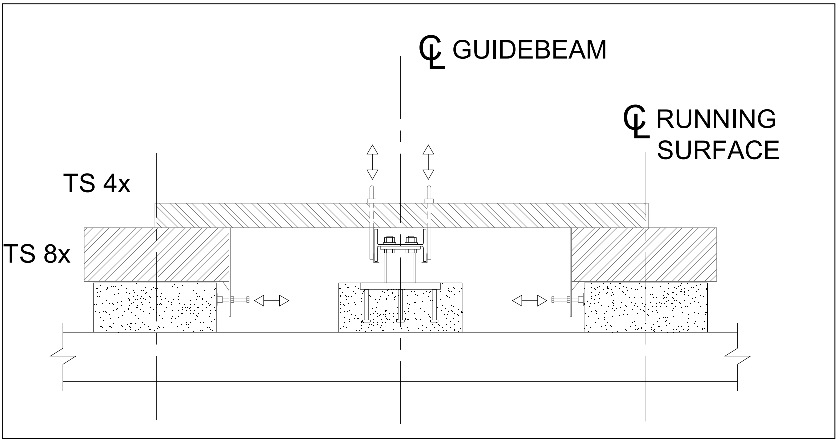

Figure 9: Final Guidebeam Jig Assembly Schematic

In conjunction with the guidebeam jig design, the contractor recognized the need to positively verify and back check beam alignment before, during and after placement of guidebeam pedestals. As such, an effective "GO/NO GO" beam tool was created for use by installers to ensure a fixed distance from the revised control to the center of the guide beam was always maintained (Figures 10 and 11). The beam tool was fabricated out of durable 3.81cm (1.5 in) tube steel with sharp hardened steel points to place in the center of the survey marks. When placed on the controlling plinth survey mark (revised control), the beam tab aligns with the outside face of the beam flange providing a simple and effective means by which to verify proper alignment and/or make adjustments where needed saving time, ensuring quality and simplifying the work.

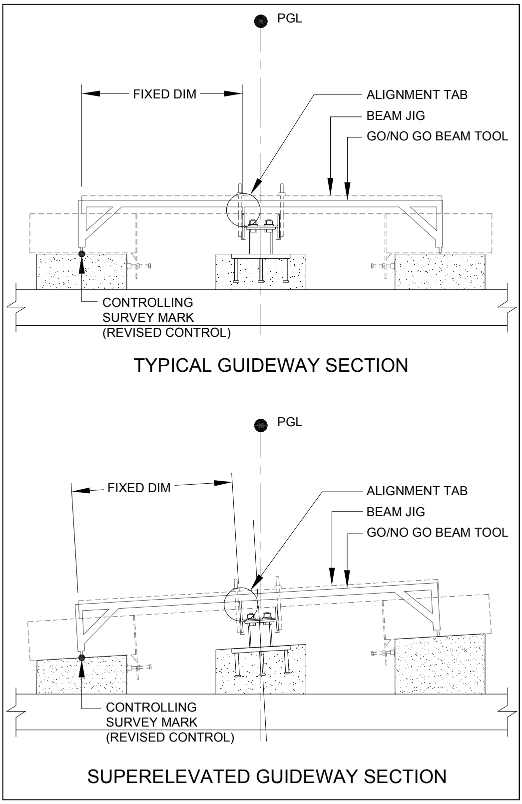

Figure 10: Beam Alignment Tool

Figure 11: Beam Alignment Tool in Use

The greatest value of this tool was that beam alignment could be verified quickly and easily at any location on the guideway. If the beam tab aligns with the beam flange, the beam is in its proper location and within tolerance. Final quality control checks (Bombardier Field Test Procedure 702) and acceptance testing would further prove installation accuracy. Any resulting adjustments to beams would be made at the bolted connections and generally were less than 1.58mm (1/16 in).

In support of the guide way construction, additional early quality control was performed on the guide beam steel by the steel fabricator (Bell Steel) using 3-piece test fits to verify beam geometry, curvature and alignment prior to finishing. The procedure requires use of a piano wire stretched centerline of guide beam flanges end to end of the curved section(s) measuring perpendicular distances from specified beam work points to the wire recording tolerances within 3.175mm (1/8 in) (Figure 12). This procedure replicated and displaced much of the formal Bombardier Field Test Procedure 702 initially intended as a field effort after beam installation.

Implementing this procedure with a finished installed product in the field would have been impractical requiring substantial time (in desert conditions) to reestablish beam geometry and working points in the field from which to verify measurements. More importantly, to discover faulty geometry at this point of the construction would carry significant schedule and cost implications completely averted as a result of the timing and execution of this effort. When considering the adjustability of the beam jigs, the guide beam tool and shop quality control, once the beams arrived on site, there was a high level of confidence that not only would the beams would be geometrically correct, but that any issues had already been identified/corrected early in the process at a much lower cost and schedule impact.

Figure 12: Guide Beam Shop Test Fits

Placement of Expansion Joints

There were three distinct expansion joints assemblies; Type 1, Type 2 and Type 3. The Type 3 expansion joint also known as a ride plate is designed for the maximum longitudinal movement rating of up to 17.78cm (7 in). It is constructed of 2.69cm (1 1/16 in) solid steel plate and weighs in the range of 166 kg (365 lbs) per side and more as the plinth depths increased. This was a newer Bombardier ride plate design intended to strengthen and increase design life of the expansion joints assemblies.

During the mock-up concrete placement, it was discovered that pressure from the concrete and associated vibration created unexpected buoyancy of the expansion joints assembly causing them to move (float) out of position (Figure 14). While somewhat counter intuitive, it was concluded that tie wire to the reinforcing bar was an insufficient means to secure the joint assembly during concrete placement and a more substantial tie down was required. As a result, the contractor installed threaded rods secured to the deck through the 1.27 cm (½ in) bleed holes provided as part of the joint fabrication effectively locking down the ride plates (Figure 13). It is worthy to note that without the experience of the mock up, placement of the first set of expansion joints could have been time consuming and costly.

Two additional 2.54cm (1 in) bleed holes (not shown in the Figure) were added at select locations through the top of the ride plate steel to increase bleed through particularly on uphill slopes. Unlike flat guideway sections, uphill slopes offer a more challenging set of construction conditions. At 5.6% grade, the contractor failed several times to achieve full consolidation under the uphill joint assembly as the concrete naturally seeks to comply with the rules of gravity. These attempts resulted in complete removal and replacement on at least two occasions. The larger bleed holes provided visual indication that concrete under the assembly was consolidated.

Figure 13: Expansion Joint Tie Downs

Figure 14: Floating Exp. Joint Assy.

Flexible – Scalable Slip Form System

As would be expected, surveying and layout was pivotal to maintaining tolerances and overall quality of the running surface. The specified tolerance for the running surface was a cumulative maximum deviation of .3175cm (1/8 in) in 304.8 lineal centimeters (10 Ft). Initial detailed layout based on PGL (profile grade line) provided layout for forms every 2.43m to 3.048m (8 Ft to 10 Ft) as well as the required cuts and fills in relation to civil stationing. Additional surveys were conducted prior to concrete placement (form verification) and after stripping of forms to establish running surface center point(s) characterized as the revised control. These center points were central to establishing and verifying proper location of the guide beams discussed earlier.

Horizontal slip forms (Figure 15) were determined to be the most cost effective and flexible forms for use on this project. Dimensional lumber with knee bracing was sufficient for typical running surface depths. Deeper plinth depths utilized form whalers and MDF plywood with adjustable form braces and ties at 45.72cm (18 in) O.C. All forms utilized a 15.24cm (6 in) galvanized steel plate slotted at the top of the forms to permit vertical field adjustments up to 5.08cm (2 in) where fine tuning for additional fill was desired. The initial steel plate incorporated a small hem

Figure 15: Horizontal Slip Forms

or fold at the top with the philosophy being added stiffness to the plate or (top of form) against which final tooling would be guided. However, it was concluded that the hem created an inconsistent guiding edge and was ultimately replaced with a flat plate and the maximum height adjusted down to 5.08cm (2 in). This system provided a strong, flexible and reusable system without of the need of corner chamfer strips often used to mitigate edge cracking. Simple 6.35mm (¼ in) radius edging tools were used instead.

Figure 16: Plinth Reinforcing

In general, running surface reinforcing consisted of #4 rebar 12.7mm (5 in) deep placed at 45.72cm (18 in) O.C. with additional #5 reinforcing at half pipe crossings. Maximum embedment into the owner’s deck was 12.7mm (5 in) and was controlled by means of a drill gauge stop. Typical longitudinal reinforcing consisted of #4 bars typically with #5 bars at crossings. As plinth depths varied in depth between 19.05cm (7.5 in) and 60.96cm (24 in), reinforcing steel (L-bars) would vary in depth as well. The procurement of reinforcing is commonly a time consuming critical path item with direct production implications. Contractors dramatically simplified the process by limiting L-Bar lengths to 3 basic sizes – 30.48cm, 40.64cm and 50.8cm (12 in, 16 in and 20 in) understanding that select areas might require unique sizing for a specific condition (Figure 16). This expedited the entire effort from fabrication to delivery to installation. Occasional costs incurred as a result of cutting reinforcing in the field to proper lengths were easily offset by the simplicity of the procurement, fabrication and management processes.

Quality control of the running surface was managed at multiple stages of completion by a multitude of subcontractors. Using a 3.048m (10 Ft) aluminum straight edge and a simple feeler gauge, the concrete contractor checked running surface for flatness compliance within the specified 3.175mm (1/8 in) cumulative in 3.048m (10 Ft). In most cases, tolerances were kept to 1.58mm (1/16 in) or less. Surface deviations were corrected by means of a hand grinder to bring flatness into compliance. In addition, minor sections were completely removed and replaced to be brought into compliance. Official quality control was performed and documented by Bombardier's general contractor on a section by section basis with the same methodology and additional grinding was performed where directed. Ground spots were treated with an acid etching agent to maintain roughness on the concrete surfaces once accepted. The final quality check was performed by Bombardier field engineers as part of the Guide Way Civil Inspection Test Procedure 701 (Figure 17). Together, the attention to the level of quality at this phase provided for greater confidence in the related follow on work.

Figure 17: Flatness Testing

Guide Beams and Supports

Upon stripping of the running surface forms, control joints were cut within 24 hours to accommodate inevitable shrinkage cracking. This proved successful with a few isolated exceptions at deep plinth locations in Section 9.

Reinforcing holes for the 508mm (20 in) and 711.20mm (28 in) (types 1, 2, and 3) guide beam supports were installed with use of a template drill guide. With the primary reinforcing cages in place, initial setting of the 12.20m (40 Ft) guide beam sections could be completed. There are several important distinctions about the means and methods here which were derived fundamentally from the investment of time and resources into the mock ups described above.

Traditionally, guide beam support pedestals and base plates or embeds were cast together in accordance with the design locations. Guide beams would be placed later. Once cast, adjustments to field conditions, fabrication or design changes were time consuming and expensive.

The general contractor's approach on this project cleverly reversed the process simplifying the work and eliminating construction errors while maintaining the highest

Figure 18: Guide Beams and Jigs

level of quality for the train system. The creation of an adjustable guide beam jig discussed earlier in the report provided stable support for the guide beam and the guide beam base plates. The guide beam jig not only provided support throughout construction, but also provided a verifiable location of the GB center point in relation to the running surface(s). As the beams have some flexure to them, field adjustments up to 12.7mm (½ in) or more could be held in place by the jigs until the beam supports had been cast (Figure 18).

Forms for the guide beam supports were constructed using a break down set of plywood forms once the beam's final position was determined (Figure 19). If adjustments were required, formwork or reinforcing could be easily shifted as required. This emphasizes the value of the effort placed on the quality of the running surface construction phase. Regardless, with the use of the jigs, the relationship between the guide beam and running surfaces would always be coplanar and correctly maintained eliminating potential errors. These were utilized successfully throughout the entire project.

Figure 19: Guide Beam Pedestal Forms

Base plates were preassembled on site by the steel fabricator onto the guide beams prior to initial setting. As a practical measure of protection, beams and base plates were covered in plastic and painters tape to protect finish coatings. Concrete was allowed to cure for 3 days or 75% strength prior to releasing the jigs.

Guide beam installation consists of several different bolted connection types. The typical guide beam supports consisted of 120.64mm (4 ¾ in) bolts with washers and bushings through the upper plate already attached to the beams. To assure proper alignment of guide beams prior to final tightening and torqueing of the connections, installers employed the use of a simple, yet highly effective beam alignment tool developed by the steel fabricator. Using the running surface survey center points every 2.12m to 3.04m (7 Ft to 10 Ft) provided a quick means by which to determine if the beam was properly aligned. Alignment was verified by aligning the tool point on center point marks and outside beam tab. If the tab aligned with the outside beam flange, the beam was in the proper design position. Continuous use by the steel installer and as part of the Guide Beam Test procedure 702, Bombardier was able to minimize errors and corrections in beam guide way alignment limiting adjustments between beam segments to the tolerances permitted by the bolted connections. Field adjustments generally required less than 1.58mm (1/16 in) to provide acceptable alignment.

Figure 20: Guidebeam Placement

Due to the use of these tools (means and methods), the published Test Procedure 702 was dramatically simplified without sacrificing quality. Upon verifying proper alignment and proper curing of the concrete, a detailed quality control process of torqueing, marking, permanently deforming (fouling) the bolt threads and documenting each part of each connection was undertaken. This effort provided positive visual assurance to follow on activities that the beam and/or sections of beams are fully complete.

Figure 21: Power Rail Brackets

With alignment of guide beams verified, the installation of traction power rail and ground rails was simplified. DC Traction power is provided by (2) each power rails slid over the power rail brackets installed at approximately 1.82m (6 Ft) O.C. Installation of these rails is labor intensive requiring 3 to 4 men pushing and pulling 12.19m (40 Ft) rail sections horizontally onto the brackets (Figure 21). With friction, weight and awkward positioning providing the primary obstacles, accurate beam alignment assured best case power rail bracket alignment optimizing the installation effort.

Figure 22: Power Rail Installed

On past projects, power bracket locations were field measured, drilled and installed. On the PHX Sky Train® project, under Bombardier direction, the steel fabricator pre-drilled for all brackets and beam penetrations not only speeding up installation, but also greatly improving bracket spacing and installation. With over 7,000 brackets, efficiency was improved and installation costs reduced (Figure 22).

Cable Tray and Lighting

The primary purpose for cable tray on this project is to provide a continuous accessible and NEC compliant raceway for train system communications, controls, signaling, low voltage power (non-propulsion) and emergency walkway lighting. Partitioning within the cable tray separate fiber Optic cable (communications), low voltage emergency lighting, control conductors (<50V), and low voltage AC (480V/208V/120V). On this project, the cable tray also serves as a landing or step down for passengers egressing from a vehicle in an emergency and as such is capable of supporting 223 kg/m (150lbs/lf).

Figure 23: Cable Tray Mockup

As part of the guideway mockup (Figure 23), the contractor performed a detailed analysis evaluating lighting options, weight, constructability, lead time, and long term operating costs. As a result, changes to the cable tray shown in Figure 23 were made to include a 45 degree slant on the walkway side for optimal lighting dispersion and installation which can be seen in many of the following figures in this section.

The initial cable tray system consisted primarily of galvanized sheet metal tray and fluorescent fixtures. Fixtures, ballasts, wiring were to be mounted to the underside of the cable tray on both sides of the emergency walkway in order to achieve the specified lighting levels of .25Fc. all along the egress pathway. The exact details were to be determined by the contractor and its electrical installer.

In the process of evaluating the initial cable tray concept, it was determined that the specified product had several limiting factors foremost being weight, cost, constructability and lead time. Based on the weight of the trays, lids, partitions, live and dead loads, structural supports were required at estimated intervals of 60.96cm (24 in) requiring approximately 11,500 individual supports. Further investigation indicated the product did not accommodate some of the tighter turning radiuses nor did it provide (or manufacture) custom pieces (blank-off plates & transition) necessary to navigate through the complex switch areas. From a procurement standpoint, purchase and acquisition of the specified cable tray product was accompanied by significant shipping costs and time including a quoted 8 week shipping cycle after fabrication.

In response, the contractor elected to propose a more creative cost effective alternative substituting aluminum cable tray and an LED lighting array system in lieu of the specified sheet metal with florescent lighting. Their analysis is captured in part in Figure 24 below. At a 57% reduction in weight, the aluminum tray option reduced the number of supports by an estimated 27% saving substantial labor and material costs without compromising performance.

Description	Specified System	LED Option
Cable Tray Materials	Sheet Metal	5052 Aluminum
Weight (2mm thickness) excludes cable	16Kg/Sqm (3.27lbs/Sqft)	6.8Kg/Sqm (1.39lbs/Sqft)
Weight per Assembled Ft	7.98Kg/Ft (17.56lbs/Ft)	3.4Kg/Ft (7.5lbs/Ft)
Qty. of Tray Supports	11500 (Est.)	8400 (Est.)
Fixture Type	32W Florescent	3W LED
Qty. of Fixtures	5433	2700
Qty. of Ballasts	5433	65
Mounting	4' OC (Both Sides)	4' OC (one side)
Design Load	174 KW	9750W
Design Voltage	277 VAC	12VDC
Current @ System Design Voltage (Instantaneous)	628A	40A
Lamp Life	7000 Hr/1.6Yrs	43,800Hrs/5Yrs
Annual Operating Costs (@.10 per kWH)	$76,212	$4,250

Figure 24: Cable Tray and Lighting Analysis

Other advantages of the LED Option included hot swappable low voltage snap-in fixtures that allowed for variability in the installation angle to customize dispersion of light onto the walkway without tools. Because LED assemblies are low voltage, DC Assemblies (LED) can be replaced without power shutdown impacting system availability.

Figure 25: LED Fixture

The approved cable tray design with the LED lighting option consisted of rectangular 11.43cm x 50.8cm (4.5 in deep x 20 wide) nominal width tray partitioned in three sections and constructed of 5052 high tensile aluminum with a .254cm (.100 in) polished aluminum diamond tread plate. Cable tray support frames consisted of threaded rods varying from 1.58cm to 2.54cm (5/8 in to 1 in) diameter depending upon support height welded to a 5.08 cm x 5.08 cm (2 in x 2 in) angle spanning a width of 45.72cm (18 in). Leveling and height adjustments were made in the field with the use of bolts threaded onto the vertical support rods prior to epoxy grouting bolts into 10.16cm (4 in) drilled shafts. Cable tray height was fixed with the top of the running surfaces. As part of the mock up effort, the contractor was able to determine the absolute minimum cable tray heights necessary to accommodate minimal plinth heights on the downhill side of the plinth (Figures 26). In areas with super elevation, plinth heights were reduced to bare minimum structurally allowed and as such so was the cable tray and related supports.

Figure 26: Cable Tray Superelevated Guideway

Emergency lighting requirements along the emergency walkway are established by ASCE 21-00 which requires .25 foot candles over the entire emergency egress route. The emergency walkway lighting system was tested using a light meter in August 2012 and was determined to meet or exceed the above specified requirements.

Project Schedule and Sequencing

The experience with the mock-up played a primary role in the development and maintenance of the overall project schedule. The Guide way was divided into 10 sections each differing in length, site conditions and complexity. The elevated guide way sections offered more challenging logistics impacting production and scheduling. Sections with switches and crossovers provided increased level of complexity not typical with normal guide way sections requiring greater quality and flatness control over large varying concrete areas.

GUIDEWAY CIVIL CONSTRUCTION SEQUENCE		CAL	2011												2012											
AREA / SECTION	START - FINISH DATES	DAYS	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
SECTION 8 (3040LF)	1/10/11 - 5/2/11	112																								
SECTION 4 (740LF)	1/03/11 - 6/24/11	172																								
SECTION 5 (1725 LF)	1/5/11 - 8/23/11	230																								
SECTION 6 - EEL STATION (480 LF)	3/7/11 - 9/23/11	200																								
SECTION 7 (1950 LF) SWITCH/CROS	2/15/11 - 8/19/11	185																								
SECTION 9 (730 LF) SWITCH/CROSS	3/21/11 - 12/14/11	268																								
SECTION 10 (600 LF)	9/16/11 - 12/11/11	86																								
SECTION 3 (1080 LF) SWITCH/CROS	7/25/11 - 1/24/12	183																								
SECTION 2 - T4 STATION (600 LF)	8/2/11 - 3/7/12	217																								
SECTION 1 (600 LF - PARTIAL)	2/17/12 - 6/22/12	125																								

Figure 27: As-Built Civil Construction Schedule

Guide way construction was conducted in an efficient assembly line fashion in 45m (150 Ft) section lengths whereby each phase of work would give way to the next phase and move onto the next section. Break points were generally established at control joints or expansion joints in the owner provided deck. Eastbound and westbound lanes were staggered to maintain access to the least accessible lane(s) generally maintaining a lead distance of 45m to 91m (150 Ft to 300 Ft) ahead of the opposing lanes. As work

progressed to the elevated guide way sections, staggering and phasing became more important in order to maintain access for labor, materials and equipment. As the schedule above shows, there were multiple sections under construction simultaneously.
Below is a generic example (snap shot) of the assembly line work activities proved out as part of the mock up effort months earlier.

Engineering	
Survey & Construction Layout	2 Days
Concrete Subcontractor	
Formwork	2 Days
Rebar Subcontractor	
Drill Epoxy Rebar	2 Days
Engineering	
Form QA – Verify Cut/Fills	
Concrete Subcontractor	
Pour Concrete	1 Day
Strip Forms	1 Day
(Move to Next Section)	
General Contractor	
Running Surface Flatness QA	
Concrete Contractor	
Surface Grinding/Acid Etching	1 Day
Engineering	
Survey – Reestablish PGL	1 Day
Drill Epoxy Pedestal Rebar	1 Day
Steel Fabricator	
Set Steel Guide Beams/Base Plts	1 Day
Set Guide Beam Jigs (6’ O.C.)	1 Day
Concrete Contractor	
Form Pedestals (22-25ea.)	1 Day
Form QA	
Beam Go/No Go Alignment	
Pour Concrete	1 Day
Pedestal Cure Time	3 Day
Torque Base Plates Blts.	1 Day
General Contractor	
Torque QA	1 Day
Bombardier	
Guide Beam Alignment QA	
Total Duration	20 – 25 Days per 150’ Section

Discussion

From the data, photographs, narrative and other documentation presented herein, it is our assessment that the construction of the guideway mockup was pivotal in understanding and developing a set of tools and procedures that led to a high quality running surface and commensurate level of ride comfort. The resulting shift away from managing to a theoretical pathway to a ride quality centered approach based on maintaining a consistent relationship between the running surfaces and guide beams was a major contributing factor to the high quality of this project. The evidence of this is clearly discernible from the test reports and related documentation above. It is worthy to note that since the formal ride quality testing was completed, Bombardier has made further adjustments to the (24) switch assemblies anticipated to have further improved ride quality beyond the published test reports.

While the process was not easy, the guidebeam jigs and alignment tool, derived directly from the mockup effort, provided an indispensable mechanism to ensure quality control at each section was independently maintained and verifiable. Not only did the jigs stabilize and hold the guidebeams in their final position, but they also permitted the support pedestals to be placed after the final beam position was secured eliminating beam connection tolerances, errors and rework.

By challenging established thinking and involving key subcontractors/suppliers early, historically complex manufacturing, scheduling, procurement and construction efficiency was greatly simplified leading to fewer errors, false starts and uncertainty. With the means and methods clearly defined, the staggered assembly line scheduling and production became predictable and reliable requiring only minor adjustments for varying site conditions at each guideway section. As a result, the guideway construction was completed as scheduled. These means and methods in conjunction with established contractor/subcontractor know-how greatly aided the construction of a quality system with improved ride quality when compared with similar systems.

REFERENCES

Phoenix SkyTrain® is a registered trademark of the City of Phoenix.

Figures 1 and 2: Test data collected and calculated by Bombardier Transportation. Phx Sky Train Vehicle Ride Quality Test Report No. 913 October 15, 2012 & DFW Miscellaneous (Ride Comfort) CDRL 47.65 July 12, 2005.

Figure 2: Exposure time and limits established by ISO 2631/1 Part 1 Evaluation of human exposure to whole-body vibration Figure 2a.

Figure 3: Photograph by Author April 15, 2010.

Figure 4: Photograph by Author July 8, 2010.

Figure 5: Construction Document Request for Information #107 "Guidebeam Layout" provided by The Weitz Company and Bombardier Transportation created June 6, 2010.

Figure 6: Photograph, Guidebeam Jig Prototype #2 provided by The Weitz Company April 22, 2010. Fabrication by Bell Steel.

Figure 7: Photograph, Guidebeam Jig Prototype #2A provided by The Weitz Company April 27, 2010. Fabrication by Bell Steel.

Figure 8: Photograph, Final Guidebeam Jig Assembly by Author August 12, 2010.

Figure 9: Drawing, Final Guidebeam Jig Assembly Schematic by Author.

Figure 10: Drawing, Beam Alignment Tool by Author.

Figure 11: Photograph, Beam Alignment Tool in Use by Author April 14, 2011.

Figure 12: Photograph, Guide Beam Shop Test Fits by Author November 22, 2010. Location: Bell Steel.

Figure 13: Photograph, Expansion Joint Tie Downs by Author February 14, 2011.

Figure 14: Photograph, Floating Exp. Joint Assy. Provided by the Wietz Company April 15, 2010.

Figure 15: Photographs, Horizontal Slip Forms by Author November 5, 2011 and April 11, 2012.

Figure 16: Photograph, Plinth Reinforcing by Author June 14, 2011.

Figure 17: Photograph, Flatness Testing by Author April 25, 2011.

Figure 18: Photograph, Guidebeam and Jigs by Author February 2, 2011.

Figure 19: Photograph, Guide Beam Pedestal Forms by Author April 7, 2011.

Figure 20: Photograph, Guidebeam Placement by Author February 24, 2011.

Figure 21: Photograph, Power Rail Brackets by Author August 2, 2011.

Figure 22: Photograph, Power Rail Installed by Author March 21, 2012.

Figure 23: Photographs, Cable Tray and Electrical Mockup provided by The Weitz Company July 8, 2010.

Figure 24: Cable Tray and Lighting Analysis, Provided by The Weitz Company.

Figure 25: Photograph, LED Fixture by Author September 19, 2012.

Figure 26: Photograph, Cable Tray Superelevated Guideway by Author July 11, 2012.

Figure 27: As-Built Civil Construction Schedule, as-built schedule data provided by The Weitz Company, assembled by author.