GREEN STREETS AND HIGHWAYS 2010

AN INTERACTIVE CONFERENCE ON THE STATE OF THE ART AND HOW TO ACHIEVE SUSTAINABLE OUTCOMES

PROCEEDINGS OF THE 2010 GREEN STREETS AND HIGHWAYS CONFERENCE

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Preface

Our 21st Century Linear Transportation Infrastructure will be quite a different world than the current "Grey" system of one size fits all geometric designs, environmental compliance, material selections, and systems operations. As we move ahead towards rebuilding our urban, suburban and rural infrastructure we will have many substantial challenges, one of which is how transportation planners and engineers, resource agencies, and regulators address sustainable and green design. The world of highway and local street planning and design is no longer just the purview of traffic and civil engineers. Interdisciplinary project teams must be formed to address the complex multi-modal planning, regional environmental issues, context sensitive solutions, climate change, green rating systems, economic development, and other emerging and often changing issues. A new level of collaboration and understanding of how to integrate state-of-the-art practices into projects and programs will be required to meet this challenge. This first American Society of Civil Engineers (ASCE) Transportation and Development Institute (T&DI) conference on Green Streets and Highways is a major step forward and will be the foundation of many subsequent conferences and efforts for developing transportation systems that are truly sustainable. The roots of this conference began over five (5) years ago through the formation of the Green Highways Partnership (GHP). The GHP was established by the United States Environmental Protection Agency (USEPA) Region 3, USEPA Headquarters and the Federal Highway Administration (FHWA) to begin developing a transportation planning and design approach that would leave watersheds and project areas "better than before". A group of state and regional transportation agencies, environmental groups, universities, non-profit organizations, such as T&DI/ASCE, industry groups, and other stakeholders began to form a network of collaboration on developing approaches in the theme areas of **Conservation**, **Sustainable Stormwater Management**, and **Recyclable and Reuse**. This conference reflects the value of collaboration and innovation that was established in these initial efforts.

This conference is unlike many technical T&DI/ASCE conferences that focus on the presentation of papers in narrowly focused subject areas. The conference program was designed to encourage the presentation of state-of-the-art innovative practices that could be used to form a dialogue and the basis for future collaborative efforts between practitioners, industry, regulators, educators, and researchers to help develop the future direction and approach for Green Streets and Highways. The major topic areas for the conference focus around sustainable and integrated planning and design, green pavements and construction materials, watershed and environmental planning and design, and rating systems. The papers in the proceedings present the state-of-the-art in these topic areas. They include research that is focused on specific research areas as well as strategies for the integration and management of sustainable design approaches. The papers identify the technical, research, and institutional challenges that are a reflection of where our profession is on these issues. The information presented will be essential in developing the necessary tools and education that will be required to meet this challenge.

Not all conference session presenters submitted a formal written paper to be included in this proceedings. However, PowerPoint presentations received prior to the conference were compiled onto an additional CD which was distributed to conference attendees. The presentations contained on the additional CD and those presentations subsequently received can be found on the conference website at www.green-streets-highways.org.

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ABSTRACT
The Mercer Corridor Project will be an example for how integration of land use with transportation will transform a neighborhood into a more sustainable development. Implementing this requires strong partnerships, committed leadership, and clear objectives. Traditional design related to relieving congestion puts greater value on infrastructure that provides wide streets, high speeds, and limited access without considering elements that would make a community more livable, walkable, and sustainable.

In absence of formal guidance for encouraging sustainable practices in design, materials, and construction, substantial infrastructure projects like arterial roadway reconstruction become “lost opportunities” to positively impact climate change. In evaluating solutions, other performance metrics related to livability, walkability, and interaction with land use are often secondary or rely more on subjective or qualitative information. The City of Seattle’s voluntary commitment in 2005 to meeting greenhouse gas reduction targets—consistent with the Kyoto Protocols—provided direction for developing infrastructure to help meet those targets. Developing a dense urban neighborhood adjacent to Downtown and served with a streetcar along South Lake Union furthers the City’s objectives toward a more sustainable neighborhood supported by sustainable travel choices.

This paper explores the methodical approach to evaluating and creating project development tools to support City sustainability objectives; it also reviews the outcomes of applying these tools on the Mercer Corridor Project, which is currently under construction. As part of the design process, tools and applications including a sustainability workshop were developed to identify the broadest range of sustainability elements and test them on the preliminary Mercer Corridor design. Because of its strong partnership, readiness for construction, transformative impact on community, commitment to economic revitalization, and sustainability, the Mercer Corridor Project was one of only two projects in Washington State to receive Transportation Investment Generating Economic Recovery (TIGER) grants. TIGER grant funding, awarded in February 2010, has allowed this project and its sustainable design elements to start construction in the spring 2010. This paper describes workshop elements that were successful, why some were not, and lessons learned during implementation.

Creating a Sustainable Neighborhood: Mercer Corridor Project

Introduction

This paper reviews the evolution of the development of the Mercer Corridor Project in Seattle, Washington. The Mercer Corridor is located just north of Downtown Seattle in the South Lake Union neighborhood (Figure 1). As shown in the figure, along with being adjacent to a developing destination and park at South Lake Union, this area is generally underdeveloped with many surface parking lots and low density development.

This narrative discusses the following topics: the area's background and history, past solutions considered, changing land use context, stakeholder values, consideration of broader objectives, and alternatives selection. With project design complete, this paper will also report on lessons learned including tools, applications, and outcomes of incorporating sustainable solutions, flexible design, and context-sensitive solutions

Figure 1. South Lake Union Area

Background and History

South Lake Union History

South Lake Union is located approximately one mile north of Downtown Seattle on the south shore of Lake Union. Figure 1 is an aerial of the South Lake Union area. This area is cut off from other urban neighborhoods by limited-access highways: Interstate 5 (I-5) on the east and State Route (SR) 99 on the west.

This area has seen little private or public investment in the latter half of the last century, even though this area has a long history of development. Pioneer David Denny opened his sawmill on the shore of Lake Union in 1892, and that was followed by the arrival of manufacturing at the turn of the century. The advent of manufacturing brought with it shipbuilding, Boeing seaplane fabrication, and a regional Model T assembly plant. Since the Great Depression, South Lake Union has evolved into an area of small businesses, warehouses, and automobile-oriented services. Despite its natural assets and proximity to the heart of the greater Seattle region, residential and job growth that came to other Seattle neighborhoods in the 1980s and 1990s passed this neighborhood by. In part this lack of development has lead to indecision and uncertainty about major transportation projects needed to improve mobility, access, and connectivity in and around South Lake Union.

Past Transportation Proposals

In the late 1960s, the City acquired several properties between I-5 and SR 99 with the intention of constructing an elevated roadway—the Bay Freeway—to provide direct connections between I-5 and SR 99, as well as Seattle Center, the site of the 1962 World's Fair. This proposed freeway was to serve as a link in a freeway system that would encircle Downtown Seattle. In 1972, however, Seattle citizens voted to end funding for the Bay Freeway, leaving the City holding the freeway properties.

Over the next 30 years, the City completed over 50 land use, transportation, and/or open space studies for this area. The transportation system serving the South Lake Union neighborhood became known as the "Mercer Mess" because of traffic congestion, difficult access within the neighborhood, and incomplete connectivity for the road network. Several alternatives to solve the "Mercer Mess" were proposed, most of them incorporating limited access or grade-separation to move traffic through this area and to connect I-5 to SR 99 and Seattle Center. While the concepts varied, they typically had similar themes:

- Separate through traffic from local traffic
- Provide priority for high-occupancy vehicles (HOVs) and transit
- Incorporate the existing Broad Street Tunnel to cross under SR 99
- Connect to Seattle Center
- Improve connections to Downtown
- Support the development of a park on the south edge of Lake Union

Figure 2. Mercer Corridor Existing Circulation Patterns

None of the plans were implemented, however, due to disagreement among City leaders, public opposition and lack of funding. Eventually, Mercer Street was converted from a four-lane, two-way roadway between I-5 and Seattle Center to a one-way street to help move more traffic from Seattle Center to I-5. Westbound traffic was routed from I-5 via a zigzagging route that included Fairview Avenue North, Valley Street, and then Broad Street to get across SR 99; this was considered a temporary fix. Figure 2 depicts these circuitous transportation patterns.

The last major proposal for the Mercer Corridor was through the Seattle Commons proposal in the early to mid-1990s. This proposal would have created a large central park connecting Downtown Seattle to Lake Union using an expressway that would run from I-5 under the park, connecting to the Broad Street underpass across SR 99. Seattle voters, however, did not approve funding for the Seattle Commons proposal.

Linkage to Land Use

Concurrently, land use policies in Washington and the Puget Sound region also evolved. In response to environmental concerns, threats of sprawl, and policies such as the Intermodal Surface Transportation Efficiency Act (ISTEA); the Washington State Growth Management Act[1] was adopted in 1990 to promote efficient infrastructure use by encouraging growth to increase density

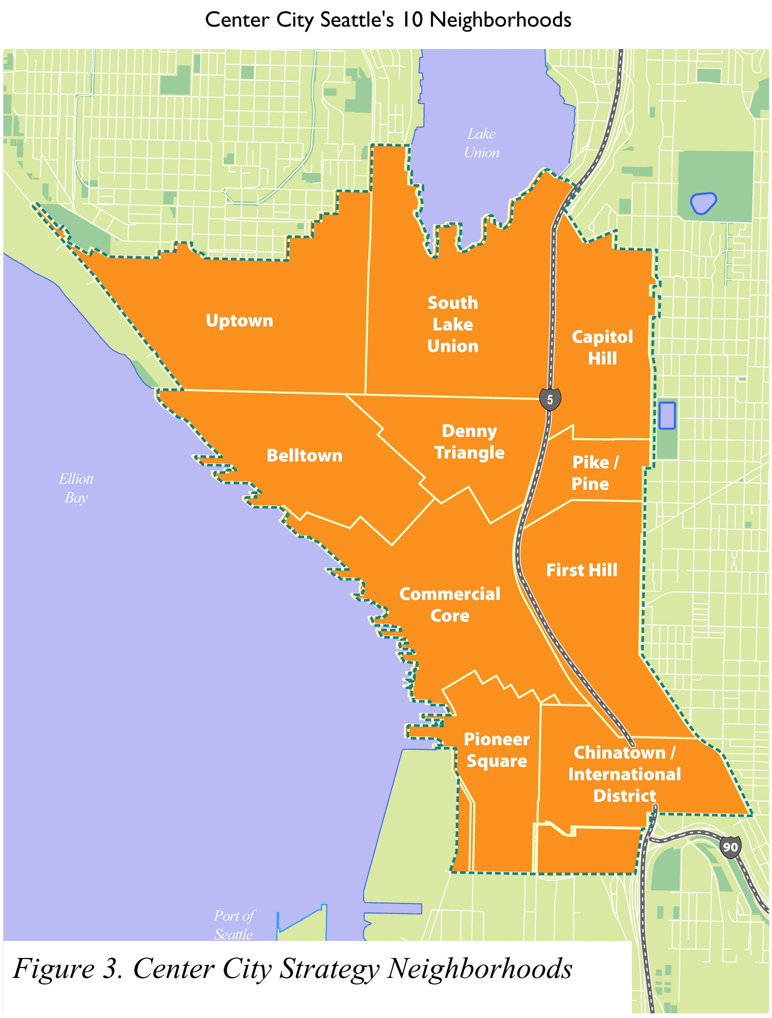

Figure 3. Center City Strategy Neighborhoods

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[1] Growth Management Act Revised Code of Washington 36.70A, 1990.

within urban areas. Regional policy-planning documents, including Puget Sound Regional Council's Vision 2020[2], sought to encourage growth within urban areas. While in-fill type development accommodated growth into the 21st century in Puget Sound, urban centers continue to be encouraged with increasing pressure for greater density within the established growth boundaries. The South Lake Union area directly adjacent to Seattle's downtown core provides an opportunity for greater density and a mix of uses, including residential, high-tech jobs, and community resources. For more than 15 years Seattle has considered a variety of land use plans for an area that has historically encompassed low rise commercial and industrial uses. When the Mercer Corridor Project began the most recent environmental process, up to 19 percent of the land was reported to be occupied by surface parking lots. Seattle's Center City Strategy, was intended to create livable and vibrant neighborhoods with easy access to the downtown core. Areas served by the project are home to 245,000 existing jobs, which are expected to grow by 50,000 new jobs by the year 2024. The Mercer Corridor Project provides a main street for the growing biotechnology hub in the South Lake Union neighborhood, connects a number of urban centers to I-5, and carries over 80,000 vehicles each day. This corridor is critical for the successful movement of freight to the Port of Seattle and provides access to the Port's facilities on the north side of Elliott Bay, the International Cruise Terminal, Fisherman's Terminal, shipping facilities, and other industrial uses

Assuming full occupancy, this development represents 22,000 jobs in space completed, under construction, or in the permitting pipeline. For more than a 20-year period, this economic development is estimated to create about $500 million in tax revenue to the State of Washington.[3]

Amazon.com and the Bill and Melinda Gates Foundation are two of the major organizations growing in the South Lake Union neighborhood. Both will establish their headquarter complexes along the Mercer Corridor, and they both are contributing funding to the project. The Fred Hutchinson Cancer Research Center and University of Washington Medical Center are also expanding along this Mercer Corridor.[4]

Increased height limits adopted by the City will encourage revitalization in this area to help meet regional growth objectives, while placing that growth in an urban environment, well served by transportation infrastructure. Transportation infrastructure serving the corridor includes a streetcar developed to link the area to the Downtown core and two major arterials: the Mercer Street-Valley Street-Broad Street arterial is a convoluted, one-way couplet system running east-west, and SR 99 is a high-speed, high-volume north-south corridor. An environmental process was initiated in 2004 to look at the east-west Mercer Corridor including Valley Street.

The Mercer Corridor is part of a greater vision for the South Lake Union area. A separate project, part of a large state highway replacement project, would remove barriers between South Lake Union and neighborhoods to the west, while providing

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[2] PSRC, Vision 2020 Draft Environmental Impact Statement, 2006.

[3] http://www.seattle.gov/transportation/ppmp_mercer_ec.htm

[4] http://www.seattle.gov/transportation/ppmp_mercer_ec.htm

additional street connections that would serve as alternative routes for some of the Mercer Corridor traffic. The vision also calls for improved transit service in the form of a streetcar connecting this area to the regional downtown transit hub; bicycle improvements; and other neighborhood pedestrian improvements. A successful alternative for the Mercer Corridor must be compatible with these improvements.

Mercer Corridor Alternatives Development and Selection

Alternatives That Were Considered

Two alternatives were identified at the beginning of the environmental review process for the Mercer Corridor, and a third was added during the scoping and alternative development phase. These are Alternative A, Alternative B, and Alternative C.

Alternative A, developed in the 1998 Neighborhood Plan, would **retain the current one-way couplet** configuration and realign the I-5 off-ramp and an adjacent intersection at the east end of the corridor to facilitate the flow of westbound traffic into South Lake Union. With this alternative, Roy Street would be improved as a westbound street with a new crossing under Aurora Avenue for traffic, bicycles, and pedestrians. Improved sidewalks and a new signal on Mercer Street and on Valley Street would provide modest access improvements for pedestrians, including a new connection to the Lake Union waterfront. This alternative does not address all of the issues identified by the neighborhood, but it was considered an attempt to make modest improvements to traffic flow with limited resources. This alternative was also motivated by a desire to bring closure to over 30 years of planning for a "big fix."

Alternative B, the **Two-Way Mercer Alternative**, would widen Mercer Street from a four-lane, one-way street to a two-way street with three lanes in each direction and a landscaped median. Valley Street would be narrowed to a two-lane street along the south end of Lake Union to enhance the environment around South Lake Union Park and planned residential and commercial development. Improved sidewalks, new signals on Mercer and Valley streets, and other intersection improvements along Valley Street would provide safe and convenient access for pedestrians. A bicycle lane along Valley Street would provide an east-west bicycle route through the neighborhood.

A third, *Alternative C*, was developed in response to public and Seattle City Council staff concerns about the ability of either alternatives A or B to reduce overall vehicular traffic delays. As a result, this alternative was developed with the primary objective of reducing travel times and delays through the corridor, and it is essentially a **freeway/expressway option**. This alternative would lower the mainline Mercer Street below grade and widen it to a two-way street with three lanes in each direction. Grade-separated vehicle and pedestrian crossings would be provided at three locations to provide north-south connections. At-grade access would be provided by a one- to two-lane frontage road on either side of the lowered Mercer Street. Similar to the Two-Way Mercer Alternative, Valley Street would be narrowed to a two-lane street along the south end of Lake Union, and a bicycle lane along Valley Street would provide an east-west bicycle route through the neighborhood.

Nontraditional Evaluation

The City has moved in new policy directions that support sustainability and complete streets. The City also envisioned the Mercer Corridor as a potential "Great Street" with enhancements to create a boulevard style place for gathering. With this shift in corridor objectives, the evaluation of alternatives to prioritize alternative modes has also changed.

The project team evaluated the three alternatives (A, B, and C) across the objectives, using traditional criteria such as traffic operations and vehicular travel time, along with *non-traditional* criteria such as mobility for non-motorized modes, and access for land use within the corridor for all modes, specifically pedestrians. The importance of pedestrians was further evaluated for build and no build proposals using a walkability index, described later in this paper.

The Two-Way Mercer Street Alternative (Alternative B) rated higher than the other two alternatives across all project objectives; the stakeholder group further confirmed the project team's evaluation. Upon further consideration, the Two-Way Mercer Street Alternative clearly emerged as the only alternative that would meet all project objectives and is, therefore, considered the preferred alternative.

Following is a summary of key findings about how the alternatives performed using the broad objectives and criteria.

Alternative A

- Improves travel times in the Mercer Corridor over the No-Action Scenario under year 2030 projected traffic demand
- Reduces the average delay per vehicle in the South Lake Union transportation network compared to 2030 No-Action Scenario
- Provides a new connection across Aurora Avenue for westbound vehicles, pedestrians, and bicycles
- This alternative does not advance other project objectives:
  - Does not improve traffic patterns or volumes on Valley Street and, therefore, does not support the plan for South Lake Union Park
  - Provides only limited improvement for pedestrians (new signalized crossings on Mercer and Valley streets at Terry Avenue North only); difficult crossings at Fairview Avenue North and Valley Street remain
  - Does not improve access to properties along the south side of Valley Street; access remains limited by the traffic patterns and design of Valley Street
- Requires right-of-way at the intersection of Fairview Avenue North and Valley Street and potentially along Roy Street near Aurora Avenue.

Alternative B

- Maintains regional travel time and system-wide delays similar to the No-Action Scenario, with some improvement to the westbound travel time due to the direct route from I-5
- Maintains or improves corridor freight connections (e.g., Mercer Street to Westlake Avenue North)

- Consolidates major traffic volumes into one street—Mercer—with wider sidewalks, median, and signalized crossings for pedestrians; enables Mercer Street to become an attractive gateway to South Lake Union
- Reduces Valley Street traffic volumes and roadway width substantially, supporting the plan for South Lake Union Park
- Removes Valley Street as a barrier to the park, providing safe, convenient pedestrian access at all locations (including Fairview Avenue North) and connecting the neighborhood to the park
- With the two-way street grid, enhances local circulation for vehicles, bicycles, and pedestrians
- Provides the most convenient businesses access and least circuitous routing
- With new bicycle lanes on Valley and Roy streets, connects Fairview Avenue North to bicycle lanes on Dexter Avenue North
- Provides greater opportunity for east-west transit service, while the pedestrian network assures access to transit, with the two-way street system through the neighborhood
- Requires 65 to 70 feet of additional right-of-way for Mercer Street

Alternative C

- Proves the least compatible with City and South Lake Union Neighborhood Plan policies, which recommended against any consideration of an expressway
- Off-sets improved travel times through the neighborhood with impacts to local circulation for vehicular traffic
- Reduces east-west travel times but slightly increases systemwide delays over the No-Action Scenario because this alternative creates the most circuitous routing
- Minimizes queue impacts to I-5, restricts some movements from the I-5 ramps to the surface streets with proposed grade separation at Fairview Avenue North
- Inhibits access to businesses within the corridor by increased circuitry and limited access between the expressway and local properties
- Impacts to pedestrians and bicyclists are also mixed:
  - Bicycle lanes on Valley and Roy streets connect Fairview Avenue North to bicycle lanes on Dexter Avenue North
  - Provides pedestrian crossings on Mercer Street at Fairview, Terry and Westlake avenues north, with long crossing distance over the lowered expressway
  - Eliminates pedestrian crossing at Ninth Avenue; does not provide any pedestrian access along the north side of Mercer Street between Westlake and Dexter avenues north
  - Establishes Valley Street as similar to surface, two-way Mercer Street
- Requires approximately 100 feet of additional right-of-way; further design concepts could be modified to reduce right-of-way impacts (for example, placing the surface street over the lowered Mercer Street)

Alternative B Selected

Alternative B was selected as the best solution to promote not only mobility goals but objectives for promoting alternative modes. This alternative was also endorsed by a broad stakeholder group as part of a larger Mercer Corridor solution, including connections to SR 99, new east-west grid reconnections, and extension of the one-way couplet east.

Figure 4. Mercer Corridor Alternative B

In 2004 the City began the environmental documentation and design process. Staying true to the objectives that guided the alternative selection required diligence on the part of the design team to use design tools and create applications that would result in a functional roadway that pushed the limits for sustainability and community development.

Design Process Tools, Applications, and Outcomes

Design Tools

To bring the vision for the Mercer Corridor to fruition required that the design team be committed to the project vision of a "Great Streets"-style boulevard with broad pedestrian facilities and supportive of dense, urban residential and employment uses. Early on in project development, the emphasis was to create a destination place that travelers would want to drive *to* rather than just *through*. Following are tools used by the design team to ensure optimization to meet this vision:

- **A Walkability Index.** Given that the ultimate two-way configuration for the Mercer Corridor would be wider (and create longer walk times) for pedestrians, a walkability index was prepared to look collectively at pedestrian amenities. While the roadway vision to be a wider "Great Street" with broad sidewalks was part of the initial vision, the welfare of pedestrians and walkability of the neighborhood was paramount to the overall land use goals. The walkability index helped frame as well as gain support for Mercer Corridor by documenting both positive and negative tradeoffs of the project for pedestrians. Considering the changes anticipated to occur in the South Lake Union area an along the Mercer Corridor (consisting of both Mercer and Valley streets) the following criteria were assessed in detail:
    - Pedestrian accident location improvements
    - Sidewalk width
    - Intersection crossings and distance
    - Curb radius
    - Amenity area (between sidewalk and street)
    - ADA curb improvements

- On-street parking

Table 1 summarizes results from the walkability index[5].

Table 1. Summary of Pedestrian System Characteristics: 2030 No-Build and Build Comparison

Pedestrian System Characteristic Evaluated	Overall Impression of 2030 Build Alternative	Notes
Pedestrian accident location improvements	Better than no-build	▪ 6 existing pedestrian locations will receive improvements with the build alternative
Sidewalk width	Better than no-build	▪ 67 percent of blocks analyzed will have wide sidewalks with the build alternative ▪ The amount of linear feet of 10-foot sidewalk increases by over 2,400 feet with the build alternative.
Intersection crossings and distance	Better than no-build Worse than no-build	▪ 11 additional crossing added with the build alternative. ▪ More crossings are lengthened as opposed to shortened with the build alternative.
Curb radius	Worse than no-build	▪ 95 percent of curb radii measurements are 35 feel or less with the build alternative (compared with 91 percent with the no-build alternative). ▪ 20- and 25-foot radii are more common that 10 and 15-foot with the build alternative; 10- and 15-foot are more common than 20- and 25-foot radii with the no-build alternative.
Amenity area (between street and sidewalk)	Better than no-build	▪ 78 percent of amenity area block measurements increase amenity area width with the build alternative over the no-build alternative.
ADA curb ramp improvements	Better than no-build	▪ 50 percent of study area intersections are improved with the build alternative. ▪ 15 curb ramps improve ramps in poor condition or with limited access with the build alternative.
On-street parking	Better than no-build	▪ 28 percent of study area blocks would include new on-street parking with the build alternative.
Note: The two characteristics performing worse than the no-build are intended to be balanced by other positive characteristics. Design or technology mitigation will likely be considered for locations where curb radius or intersection cross distance appears to be an issue. Most of the increases in curb radii and crossing distances are located along the Mercer Corridor, which is intended to be somewhat secondary to the Valley Corridor in terms of pedestrian environment, because vehicles are to be concentrated along Mercer Street.		

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5 Mercer Street/Valley Street 2030 Walkability: Comparison of Future No-Build and Proposed Build Alternatives, July 2006.

While widening Mercer Street and providing longer crossing distances was seen as a dis-benefit for pedestrians, a higher quality, shorter crossing distance is created along Valley Street closest to the pedestrian amenities of South Lake Union Park and the South Lake Union Streetcar. Of the criteria applied, improvements at current pedestrian accident locations and amenities for pedestrians in the way of increased sidewalk widths, landscaping, tighter curb-radii and on-street parking afforded by the project helped quantify the benefits of the Mercer Corridor Project for pedestrians.

- **A "Complete Streets" Assessment.** While the City's "Complete Streets" ordinance was not in place at the start of the project, the City passed a Complete Streets Ordinance during project design[6]. In response to the City ordinance, the project aimed to document that the project supported the ordinance by including pedestrian amenities and bicycle facilities and addressing truck design issues (see Truck Rodeo below).
- **A "Great Streets" Assessment**. The initial vision for the Mercer Corridor as a "Great Street" required the design team to investigate the components of "Great Streets" and document their elements, including sidewalk widths, adjacent uses, amenities, and use of landscaping, in order to support that the project would be transformative. An inventory of Great Street examples was catalogued to help guide design.
- **A Sustainability Workshop.** As part of the City's commitment to reducing greenhouse gas and signing the Kyoto Protocols along with other US Mayors in 2005[7], the City has created a Climate Action Plan and Green Ribbon Committee. The Mercer Corridor project facilitated a broad structured sustainability workshop[8] to identify ways to reduce the project carbon footprint by reducing consumption, reducing impact to natural environment, supporting healthy urban communities, and supporting sustainability during implementation. The framework is shown in figure 5. The workshop was implemented during

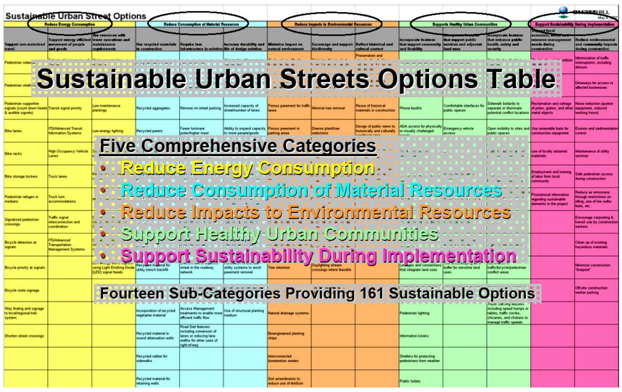

Figure 5. Sustainability Workshop Framework

6 Seattle Complete Streets Ordinance, Council Bill Number: 115861, Ordinance Number: 122386 passed May, 2007.

7 http://www.seattle.gov/climate/about.htm

8 Bevan, Mercer Corridor Improvements Project Sustainability Design Workshop, Summary Notes, January 2007

preliminary design and subsequently led to a set of recommendations to be further vetted during final design.

Applications

Applying these tools to the project by designers required commitment to the vision. Applications that supported the commitment of designers to the vision included:

- **Design Standards for large vehicles: Truck Rodeo.** In considering "Complete Streets" and addressing concerns by freight agencies, one design challenge involved developing specific design standards to accommodate large trucks—for the ongoing use of the corridor to take freight from the interstate system to the waterfront—while being mindful of the use of the corridor for pedestrians. Within this challenge was gaining and keeping the confidence of key stakeholders related to design standards for freight. A truck rodeo using GPS technology was employed to validate design assumptions for large trucks. Large trucks with professional drivers were videotaped to assess design assumptions for turn radius of the large trucks. With key stakeholders present, the rodeo confirmed that design assumptions were valid and also gained stakeholder confidence.
- **Low-Impact Development.** Stormwater drainage in Puget Sound is carefully monitored because it could affect impact water systems that support endangered species (such as various salmon species). Impervious surfaces that collect and drain water into protected streams needs to be collected and treated. As a cost-saving and impact-reducing measure, reducing impervious surfaces and treating water through natural drainage systems was explores as part of the sustainability workshop noted above identified. Applications that were explored and vetted through final design included "rain gardens" linked to the South Lake Union Park and natural drainage within project landscaping.
- **Greenhouse Gas Emissions.** Measuring and accounting for greenhouse gas emissions was critical to verify the project's sustainability performance. The project uses multimodal travel demand models to assess mode shift resulting in higher use of alternative, non carbon emission, modes of transportation.

Outcomes

The true measures of the success of a project and the design processes followed are the positive outcomes. The Mercer Corridor is expected to be the example of a green, sustainable, and efficient roadway in Puget Sound for many years to come. Construction has already begun.

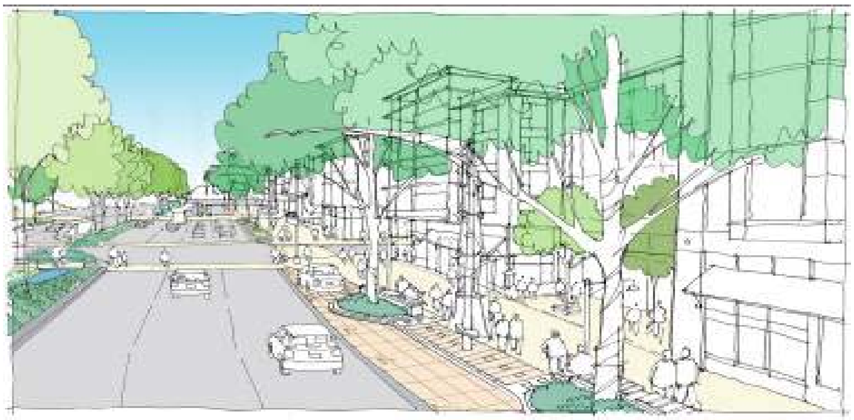

Figure 6. Green Fingers Landscape Concepts (source LMN Architects)

- **Low-Impact Development and Natural Drainage.** The project, which includes a landscaped median and planting strips along newly widened sidewalks, will reduce the amount of impervious surface area by 0.7 acre. The project also replaces water, sewer, drainage, and electrical utilities that are 80 to 115 years old. New utility systems are designed to accommodate growth, minimizing future construction impacts. Natural drainage systems will be used to store and treat stormwater, improving the environment, increasing biodiversity, reducing pollution and runoff, and increasing urban habitat along the interface with Lake Union Park. Specifically, "Green Fingers" shown in figure 6 were designed to pull landscaping into the roadway.[9]

- **Energy Efficiency.** Throughout design, optimal use of more efficient energy utilities was considered. During the sustainability workshop, ideas for reducing energy consumption included using light emitting diode (LED) lighting and renewable energy sources. The final design plans include solar power pay stations, LED pavement markings that use less energy, traffic signal coordination, and other Intelligent Transportation System (ITS) applications. SDOT estimates that, by 2024, multimodal transportation improvements along the Mercer Corridor will result in 80,000 more trips per day walking, bicycling, and riding the bus, rather than in an automobile. This reduces energy use by 10 million gallons of gasoline and over 85,000 tons of carbon dioxide emissions annually.[10]
- **Funding.** Finally, a testament to the partnerships and support surrounding the Mercer Corridor, the project was submitted for the first round of funding from the Federal Transportation Investment Generating Economic Recovery (TIGER) grants. True to the grant's intent, the project will be part of the catalyst that creates a new sustainable and walkable community. As evidence of this, the project was awarded $30 million as one of only two grants awarded in the state of Washington.

Conclusions

Because it is a large road investment, the Mercer Corridor project will continue to be viewed skeptically. Without common understanding of the notions of complete streets, walkability and sustainability, which were not well described at the inception of the Mercer Corridor Project design and environmental phase, designers were left to improvise. Without prescribed formal guidance and design process designers for this project have developed a variety of tools and applications to genuinely address these objectives. Transforming a largely low density commercial area with large surface parking areas to a thriving and vibrant community is underway with the on-going construction of the Mercer Corridor Project which will be completed in 2013. New tools and design processes are being developed and are needed; however, success will be judged as the project comes to fruition. The foresight and vision of the City of Seattle in committing to the objectives of creating a sustainable, multi-modal, Great Street have already born fruit, gaining the project funding under the desirable TIGER program.

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9 http://www.seattle.gov/transportation/ppmp_mercer_sustainability.htm

10 http://www.seattle.gov/transportation/ppmp_mercer_sustainability.htm 2010

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Applying Principles of Denver Strategic Transportation Plan

East Side Corridor

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7/21/2010

Abstract: The emphasis of the paper is to highlight the cooperative agency and community sustainability initiatives created and set forth by the Denver Strategic Transportation Plan and how these initiatives are influencing current projects. The Denver Strategic Transportation Plan (STP) project team included Denver Public Works staff, engineering and transportation consultants, an advisory committee and a technical committee. It also incorporated vast input from Denver residents. The STP incorporates previous city planning efforts into one document and moves forward to create a great and livable city for now and in the future. This is done by developing a multimodal transportation system to support a livable, connected and sustainable city. The project team created 12 travel sheds, which are study areas defined by geographical boundaries that have characteristics and facilities serving similar travel patterns. The East Side travel shed has recently become a mobility study that takes the STP initiatives to create project-based solutions for its short- and long-term transportation needs. The mobility study is focusing on multi-modal problems, not just vehicle congestion. The project team is looking at gaps within the overall transportation system that are hindering alternative transportation modes.

INTRODUCTION

As the population grows, so do the number of trips required to get people to where they need to go whether it be work, shopping or an errand. Studies have shown that in the US the majority of these trips are taken as single occupants in private automobiles rather than by more environmentally friendly options such as carpooling, walking, biking, or using transit. In addition, 78% of these trips are 3 miles or less. Although when surveyed, people have indicated they want to walk or bike more and drive less.

Specifically, the Denver metro area projections indicate a population growth of more than 1.3 million people, which leads to a total of 5.4 million daily trips, by 2030. The Denver Strategic Transportation Plan (STP) (2008) was created with an emphasis of getting people out of their cars and into other modes of transportation. Not only did the Denver STP set out to create these solutions with innovative thinking but also by using extensive public input. The emphasis of this paper is to highlight the cooperative agencies and community sustainability initiatives influencing current projects in Denver.

THE DENVER STRATEGIC PLAN PROCESS

The idea behind the Denver STP was to set up a road map for transportation policy for now and into the future. Prior to the Denver STP, Denver had several transportation planning efforts including Bicycle Master Plan Update (2001), Blueprint Denver (2002), and Greenprint Denver (2006). These previous documents began to lay out a transportation policy and plan. The Denver STP integrated the key concepts from previous planning documents.. Some of the common concepts between previous planning documents and the Denver STP include: create a city wide land-use and transportation plan, support the development of a sustainable transportation system, direct growth to Areas of Change, and improve the function of the streets. The overall goal was to improve the environment for pedestrians, bicyclists, and transit users and reduce the reliance on single-occupant vehicles. Multimodal streets accommodate more trips by more people in the same amount of space and consider all types of transportation to be equally important.

Once the intent of the Denver STP was apparent, the next step of the process was to assemble the Denver Strategic Transportation Plan team. Their task would be to take the previous planning documents and expand those ideas into a more detailed transportation study. The Denver STP project team was headed by Denver Public Works staff and included engineering and transportation consultants, an advisory committee appointed by the Mayor, a technical committee, and a key staff committee. Their make-up and responsibilities were:

- **Advisory Committee** – Included Denver City Council members, regional agency representatives and interested citizens. Their role was to provide advice on policy and political considerations, general plan direction and consistency of the Denver STP with Blueprint Denver.

- **Technical Committee** – Included representatives from the public, city agencies, technical and regional staff. Their role was to provide advice and direction for the study based on their technical expertise and assisted in guiding the final recommendations.

- **Key Staff Committee** – Included representatives from various city departments. Their role was to provide review and feedback on the STP process, and advise the project team of any interdepartmental goals or other city efforts for consideration.

- **Consultant Teams** – Various consultants were responsible for preparing analysis for the project, including a characterization of issues and a program of solutions for each of the 12 travel sheds.

Once assembled, the team then looked to reach out to the public. This was accomplished by creating a website that was used to share information and solicit public input as well as hosting several town meetings and focus groups. The website offered presentation material and minutes from community meetings as well as forms for community comments and surveys to facilitate discussion about community values and priorities for transportation in Denver. Town meetings were used during analysis and included presentations and question-and-answer sessions. Open focus group discussions were first used for three pilot travel sheds, then for all travel sheds, to determine travel areas of focus. A Community Values Worksheet was also developed as a tool to initiate public discussion about what is important to the community and how these values should be applied to decisions relating to the future transportation system.

The successful community participation events effectively conveyed citywide transportation needs to the project team. The public input results showed that Denverites would prefer to commute less by automobile and instead use alternative modes of transportation. However, there are several physical, behavioral and operational impediments to changing their reliance on the automobile. Significant planning was needed to accommodate the range of system users and their needs.

VISION

Denver is fortunate to be at the heart and soul of the Denver metro area. The city benefits from a concentration of cultural and entertainment venues, a high number and variety of jobs, and a wide range of housing choices. The city also has existing bus and rail transit systems with expanded service planned for the future, a network of bicycle and pedestrian routes, and a climate with 300 days of sunshine a year. This leads to great possibility for use of a multimodal transportation system.

The Denver STP looked to build on these assets by investing in a more balanced, sustainable and multimodal transportation system. Through community input and refinement by technical experts, the technical committee came up with five primary areas to guide the Denver STP and future improvements to the transportation system. Denver's transportation system should be:

- Multimodal
- Safe, efficient and reliable
- Connected
- Green and sustainable
- Supports a healthy, livable community

These key areas provide guidance to the city for future transportation improvements. Of course, the real success of the plan depends largely on the users of the transportation system. The users must be willing to change their transportation behavior.

INNOVATION

In order to plan for a future that is multimodal and supports the community values, the project team developed an innovative approach that combined the technical modeling and analysis found in a traditional transportation planning effort, with a more comprehensive look at citywide transportation needs and community desires. The Denver STP process included the following key elements to plan for a multimodal future:

- Use of geographical areas called "travel sheds" to provide an analysis of the transportation system that looks at an area with similar travel patterns;
- Measurement of all trips in a travel shed instead of only studying vehicle demand in major corridors;
- Use of travel shed and program improvement recommendations that help establish priorities for transportation funding;
- Use of "person trips" instead of just auto trips to evaluate impacts caused by all types of travel, including bicycles, pedestrians, transit and private and commercial vehicles;
- Measurement of transportation capacity instead of only counting lane miles, and limiting the transportation footprint.

The idea of a travel shed was created for the Denver STP. It's derived from the theory of a watershed. A watershed is a broad look at the interconnection of streams and tributaries that drain into a large river basin. A travel shed substitutes streets and mobility routes for streams and tributaries and looks at how those "drain" into the transportation system. Each travel shed is a study area defined by geographical boundaries that have characteristics and facilities serving similar travel patterns. Another innovation of the Denver STP is the idea of "person trips" instead of looking at the vehicle trips or vehicle miles traveled. Person trips are trips created by all types of transportation including personal vehicle, transit, bicycle, and pedestrian. Person trips are a more comprehensive measure to evaluate the transportation network. The project team looked at the total number of person trips for both existing and 2030 forecast conditions compared to the capacity of the existing and future transportation system for each travel shed. When person trips exceeded the capacity, a "gap" was highlighted in the transportation system indicating areas in the city that needed further evaluation to better understand the transportation need and potential solutions. Once the mobility needs were evaluated, recommendations were then categorized into transportation improvement strategies for each travel shed.

STRATEGY

In order to achieve the desired multimodal transportation results for Denver, numerous types of improvement strategies were recommended. They include both short- and long-term projects as well as annual maintenance projects. Improvement strategies were further categorized into the following segments:

- Behavioral
- Operational
- Physical

Strategies for behavioral change would support efforts within the Denver community to reduce travel by single-occupancy vehicles and promote alternative modes of travel. Specific ideas would be to fund promotional and operational programs designed to encourage alternative travel modes such as carpooling and the more recently implemented B-cycle bike-sharing program. Strategies for operational and physical changes would improve the function or efficiency of existing facilities in the public right-of-way with minor changes to the physical footprint and equipment (operational) or create a new facility that can be added to or changed within the public right-of-way (physical). Specific operational and physical ideas included maintenance of existing infrastructure, completion of bicycle, pedestrian and street gaps, expansion of the transit system, and reconstructing intersections to increase capacity and safety. The Denver STP created a hierarchy of these strategies to maximize and prioritize investment with scarce resources.

EAST SIDE TRAVEL SHED

Many of the short-term projects identified in the Denver STP are currently underway as part of other initiatives including the 2007 Better Denver Bond Program. However, many long-term steps were identified based on community values and with future attention toward ways to fund Denver's transportation vision. They included a plan for moving people beyond 2015, support sustainable growth and urban infill, and encourage shifts in travel behavior. As mentioned above, the project team created the idea of a travel shed and identified 12 in Denver. Figure 1maps out the Denver travel sheds. One travel shed created was the East Side Travel Shed, which is area "e" shown in Figure 1. This travel shed is designated as an “Area of Change” and includes well-established neighborhoods as well as two major redevelopment projects: Stapleton and Lowry.

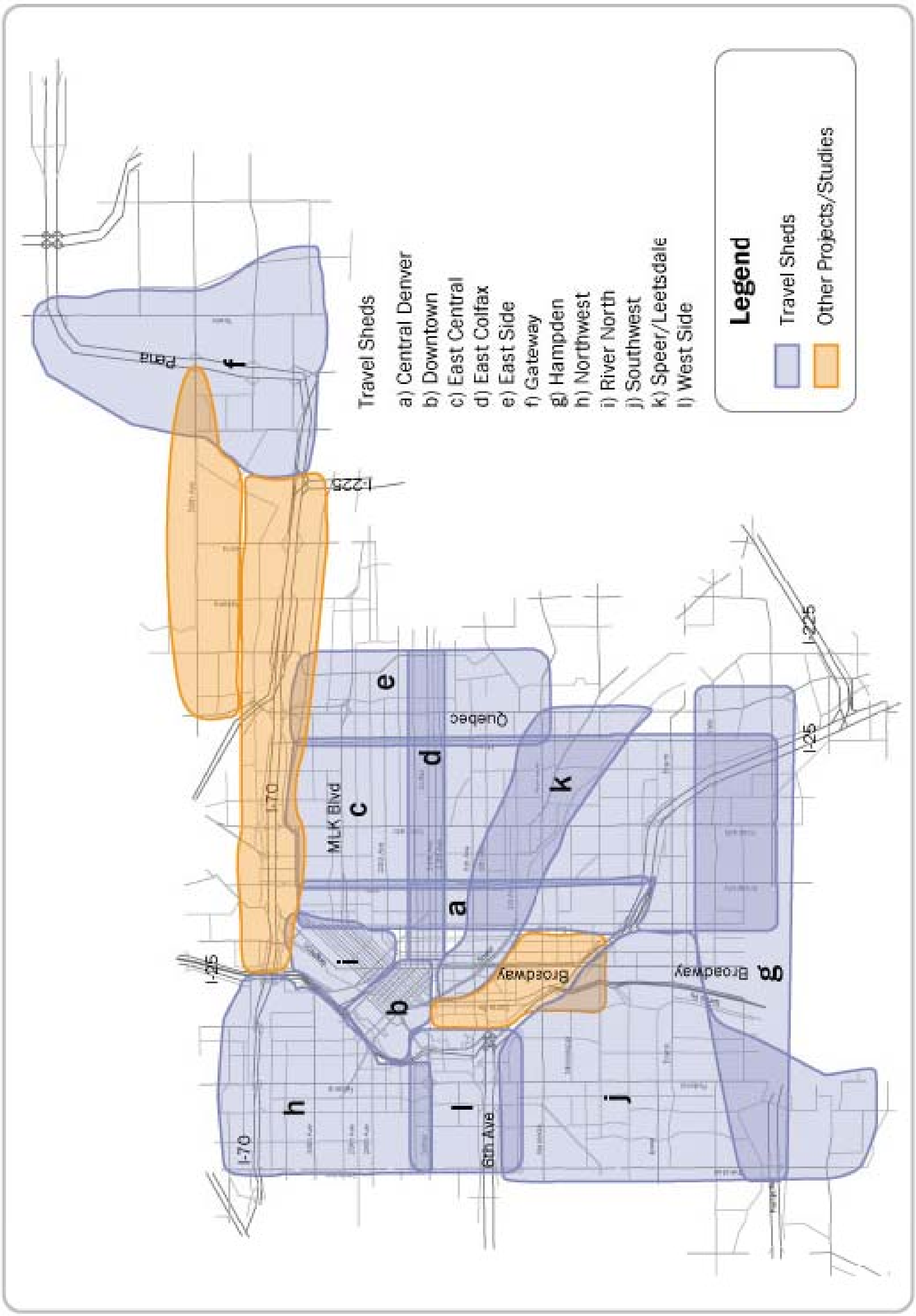

Figure 1. Denver STP Travel Sheds
(Source: City & County of Denver Strategic Transportation Plan, 2008)

EAST SIDE MOBILITY PLAN

The East Side Mobility Plan is the first travel shed-wide project resulting from the STP where multimodal solutions are identified to help overall travel mobility throughout the travel shed rather than just along a corridor. The East Side Mobility Plan takes the Denver STP initiatives and creates specific project-based solutions for its short- and long-term transportation needs. The East Side travel shed is known for its bottle necks and constant congestion along with restrictions for north-south travel connections. The boundaries of the mobility plan, which have slightly altered from the STP travel shed boundaries, are Interstate 70 (I-70) to the north, Leetsdale Drive/Mississippi Avenue to the south, Monaco Street Parkway to the west and Central Park Boulevard/Yosemite Street/Havana Street to the east.

As mentioned, there was an emphasis put on person trips and multimodal system connectivity, rather than just roads for automobiles. Through the Denver STP initiative, all modes of transportation were assessed and improvements to transit, bicycle and pedestrian routes were included. Roadway improvements developed in the East Side Mobility Plan considered multimodal functions which broadened the solutions for congestion, while also aligning with the Denver STP to make the Denver transportation system green and sustainable.

The East Side Mobility Plan is looking at the mobility issues throughout the travel shed by mode – bike travel routes, transit routes, pedestrian sidewalks and vehicle routes. Problem areas for each mode of travel were identified by city staff and through a community outreach program for people living within the travel shed.

As a community driven process, the City and County of Denver recognized the importance of neighborhood input into how their community is "fixed." Whether these fixes are broader in scale, such as creating a safe route from Stapleton to Lowry via bicycle, or at a specific spot, such as an intersection having pedestrian crossing issues, the community has a voice in how Denver improves neighborhoods. Major mobility gaps within the travel shed that were identified during the first stages of the East Side Mobility Plan are shown in Figure 2.

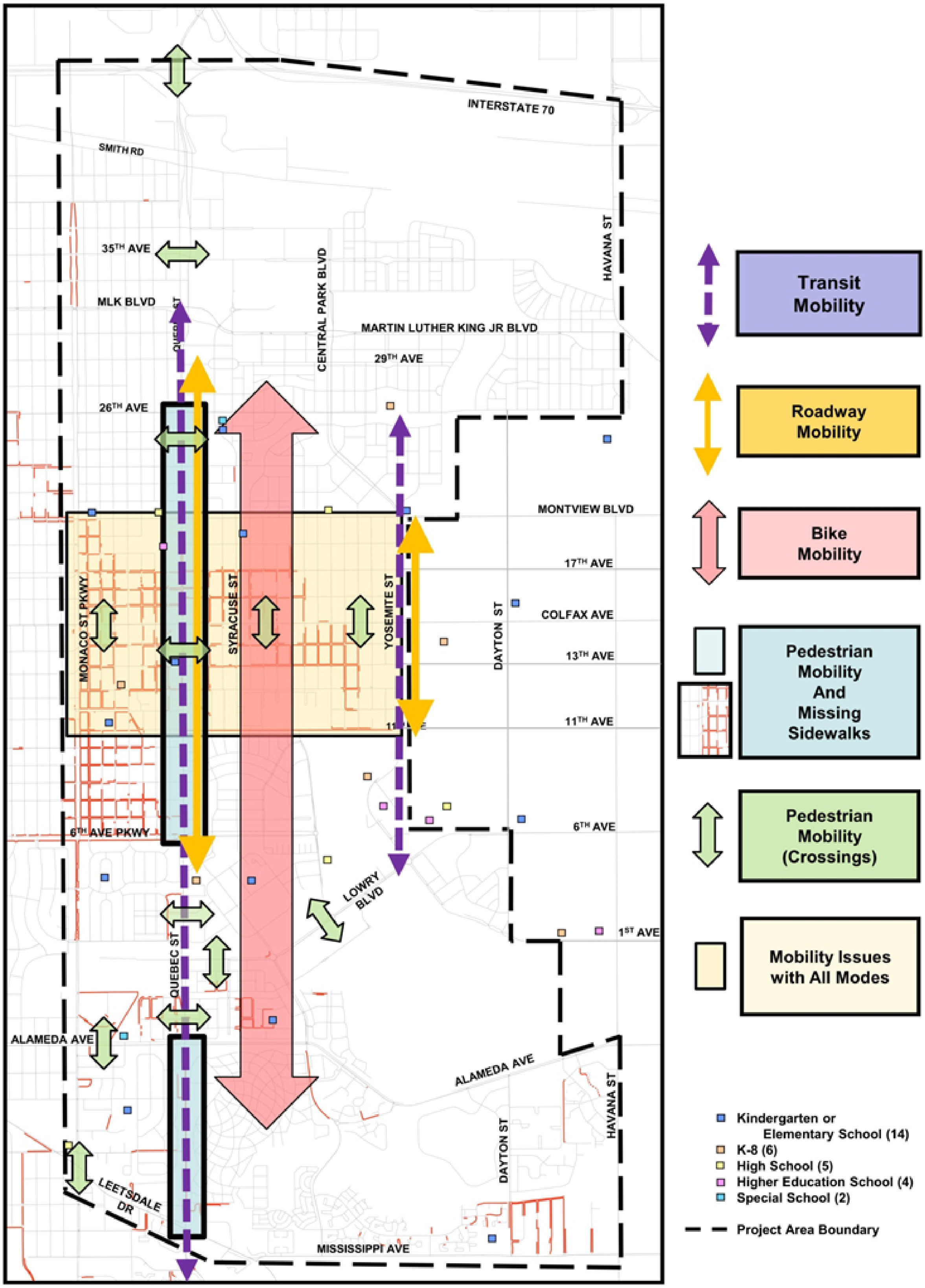

Figure 2. East Side Mobility Plan Major Mobility Gaps (needs to be most recent version of map including circles around schools.)

(Source: East Side Mobility Plan, 2010)

The East Side Mobility Plan is a finer level of analysis but certainly does not complete the efforts for transportation improvements. The final outcome of the East Side Mobility Plan will be a list of identified projects that are stand-alone and beneficial to a single mode of travel, or are packaged improvements that benefit all modes combined.

Potential identified stand-alone projects included:

- **Roadway** – roadway reconfiguration/restriping, improve signal timings, improve multimodal connections
- **Transit** – improve bus frequency and transfers with crossing routes, additional routes, improve bus stops and sidewalks
- **Bicycle** – improve bike route connectivity, add on-street route, add better bike route signage
- **Pedestrian** – add or improve sidewalks, upgrade pedestrian signal crossing equipment, improve pedestrian crossings and refuge areas improve roadside drainage

Not all identified problems and solutions could be considered as stand-alone. There was an "Area of Greatest Challenge" also identified during the mobility study. This was a subarea in the center of the travel shed that had challenges with every mode of transportation being studied. The Area of Greatest Challenge is bordered by Montview Boulevard to the north, 11th Avenue to the south, Monaco Street Parkway to the west and Yosemite Street to the east.

Preliminary packaged solutions were created that could improve mobility for all modes in the subarea. Attention was given to improving the mobility on either Quebec Street, Syracuse Street, or Yosemite Street within the area of Montview Boulevard to 11th Avenue. Five possible solutions were evaluated:

- **Widen Nodes, Not Roads**– add turn lanes at intersections, requiring some reconstruction and right-of-way acquisition
- **Within Existing Pavement** – adding multimodal capacity by only restriping the existing pavement, requiring minimal reconstruction
- **Within Existing Right-of-Way** – adding multimodal capacity without acquiring new right-of-way, requiring some reconstruction
- **Not Within Existing Right-of-Way** – adding multimodal capacity by acquiring new right-of-way, requiring major reconstruction
- **One-Way Couplet System** – modifying two existing two-way roadways to create a pair of one-way roadways, requiring some reconstruction

Various cross-section options were created within each of the categories listed above. They ranged from restriping the existing roadway for bicycle lanes, adding turn lanes at intersections, or adding a travel lane in each direction. These potential solutions were open for opinions and comments during the public involvement stages and, in combination with the task force committee, some options were removed from further consideration. A preliminary screening of the options was also conducted based on right-of-way requirements, capital cost, multimodal capacity improvement, multimodal connectivity improvements, and environmental risks. The retained options will require additional study and design before implementation; however the study was successful in reducing the field of alternatives and in engaging the community in a thoughtful discussion about the potential solutions.

CONCLUSION

The East Side Mobility Plan will be completed by Fall 2010. The conclusion of the Mobility Plan will be a series of “next steps” that the City and County of Denver can choose from as suitable funding becomes available.

With better connected bike routes, improved sidewalks, access to transit service, and reduced congestion the transportation facilities will be more complete and will provide more opportunity to reduce the number of auto trips on the congested roadways, thereby improving livability in the community and sustainability of the long-term transportation system.

County of Hawai`i La`aloa Avenue Extension CSS

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ABSTRACT

The La`aloa Avenue Extension is a highly controversial County of Hawai`i (County) project involving the extension of La'aloa Avenue from its current terminus to Kuakini Highway. The County of Hawai`i, wanting to avoid further delays and legal challenges, employed a Context Sensitive Solutions (CSS) approach to develop a consensus solution for the roadway extension. As part of the CSS process, an Advisory Group consisting of 20 members representing a wide range of stakeholder interests was established and led through the CSS process. Through a series of structured, facilitated, meetings the Advisory Group identified key issues and goals, prioritized these elements to identify additional alternatives for consideration. Employing CSS allowed the County of Hawai`i to employ an organized decision-making process that fostered constructive dialog and consensus building with the community and highlighted the power of the community's input to find solutions and maintain project momentum.

INTRODUCTION

Although the Big Island of Hawai`i consists of over 4,000 square miles, much of the population resides in the major urban centers of Hilo, Kailua-Kona, and Waimea. Due to the ideal year-round climate, the Kailua-Kona area includes a large number of full-time residents as well as a significant number of part-time residents and tourists. Historically, mauka-makai (mountain to ocean) connectors played a key role for native Hawaiians as they would travel from their mountain homes to the ocean. Today, these connectors continue to play a vital role in traffic circulation and for tsunami evacuations.

The La`aloa Avenue Extension, see **Figure 1**, is a highly controversial County of Hawai`i project involving the extension of existing La'aloa Avenue to Kuakini Highway. Once the extension is complete, La'aloa Avenue will serve as a critical mauka-makai route connecting the resorts along the coast of Kona to the main state highway. This short connector road extension within the Kona community unearthed several opinions about which direction the project should go. After the project's Environmental Assessment was sent out for public comment, the County received over 70 written letters of concerns from the public. Many of the concerns conflicted with each other. While the La`aloa project remained in the public eye, two other critical road projects were in court under lawsuits from individuals.

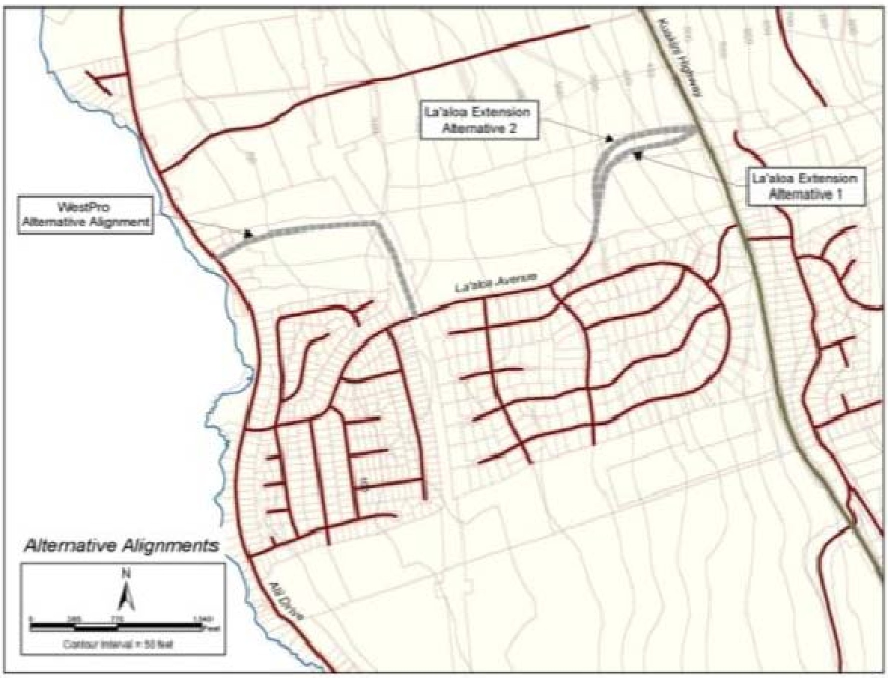

Figure 1 – La`aloa Avenue Extension Plan View

While the extension is only 0.25 miles in length, the entire roadway stretches over 1 mile. As La`aloa Avenue was constructed, the makai section was the first to be built reflecting a small residential neighborhood with no sidewalks or on-street parking. Some decades later, the middle section was developed reflecting larger plots, longer driveways and wide sidewalks. The mauka section will be developed differently than either of the existing sections including no driveway access or on-street parking. **Figures 2, 3 and 4** show the three distinct contexts of La`aloa Avenue.

Figure 2 – Mauka (mountain) section of La`aloa Avenue

Figure 3 – Middle section of La`aloa Avenue

Figure 4 – Makai (ocean) section of La`aloa Avenue

PROJECT HISTORY

In 2005 the Draft Environmental Assessment (EA) was been completed for the La`aloa Avenue Extension pursuant to the Hawai`i Environmental Policy Act (HEPA). The project, which has been planned for many years, is highly controversial due to the impacts expected to the natural and human environments. Through the preliminary planning process, community concerns arose that needed to be addressed before completion of the environmental documentation and project design. Several major concerns or elements that had the potential to impact the limits of the project were brought to the County's attention during the EA review process. Numerous opposing viewpoints related to specific aspects of the extension were voiced and agreeing to a consensus solution seemed unattainable. Compounding these project specific issues was a general feeling of enmity and distrust stemming from unfulfilled past concessions by private developers and perceived County government complacency. This combination of issues resulted in a stalemate that threatened the project's progress and viability. As other projects in the County receiving similar reactions were been stalled by lawsuits, the County searched for an approach to implement the project, address community values and avoid litigious delays.

At first, town-hall type meetings were conducted in an attempt to identify issues and work towards consensus on the project alternatives and final solution. These meetings, conducted mainly as question/answer and dialogue did not resolve the issues and resulted in even greater doubt as to the project's future. All could agree that an extension was important, primarily for tsunami evacuation and regional mobility, however, coming to a consensus solution of what and where proved to be elusive using traditional engagement tools and techniques. Leaders in the County believed that a new approach would be necessary in order to move the project forward.

COUNTY'S INTRODUCTION TO CSS

The County of Hawai`i's Public Works Department oversees infrastructure improvements throughout the Big Island. Given the natural beauty and diversity of the landscape, the County acknowledged that every project has its unique context and any roadway improvement must be integrated with the community it serves and that these improvements can have far-reaching impacts, both positive and negative.

In November of 2005, the Assistant Public Works Director from the County of Hawai`i attended FHWA's 2-day Context Sensitive Solutions training course in Honolulu. **Figure 5** shows the CSS framework presented at the training. After the 2-day class, the Assistant Public Works Director was convinced that the structured, transparent CSS process would be effective at working with project stakeholders to identify issues, establish goals, discuss tradeoffs and develop a consensus solution for improving and extending La`aloa Avenue. In August of 2006, the County, wanting to avoid further delays and legal challenges, initiated the Context Sensitive Solutions process for La`aloa Avenue in order to develop a consensus solution for the roadway extension.

Figure 5 – CSS Framework

EMPLOYING THE CSS PROCESS

The La`aloa Avenue Extension CSS process involved a collaborative, interdisciplinary approach in which a diverse group of citizens and affected public agencies were part of the design team. The CSS process allowed the team to methodically identify and address key issues identified for the project. In addition to meeting the capacity and circulation needs of the region, the CSS process allowed concerns of the community to be addressed, including:

- Safety
- Mobility
- Preservation of neighborhood character
- Aesthetic characteristics
- Historic and cultural resources
- Environmental and other community values

The County organized a 20-person Advisory Group representing a diverse group of project stakeholders to work through the CSS process. The Advisory Group would advise the County on the goals, values, interests, and views relating to the La`aloa Avenue corridor. A group with diverse interests was selected to ensure that competing objectives could be discussed and that the goals and values of the wider community, not just the immediate neighborhood or any one special interest group, would be accommodated into the transportation improvements. The range of the members' background and interests included: La`aloa Avenue and neighboring community residents, business owners, landowners, bicycle & pedestrian advocates, cultural advocates, and a resident who later became an elected County official.

Each member was asked to comply with an Operating Agreement. The agreement outlined the rules and roles pertaining to each member of the project team. Rules that the Advisory Group members agreed to follow included:

- Attend all meetings and prepare appropriately (because of the importance of continuity of participation and the relationships which will develop among members, no provision is made for substitutes in the event of an unavoidable absence)
- Clearly articulate and reflect the interests you bring to the table
- Listen to other points of view and try to understand the interests of others
- Openly discuss issues with people who hold diverse views
- Actively generate and evaluate options
- Keep their agency or organization informed of the Advisory Group's work

In total, five CSS Advisory Group meetings and one public information meeting were conducted over a nine month period. Each meeting was facilitated by a CSS expert and included technical subject matter experts based on the topics to be discussed at each meeting. An important element of the CSS process was not allowing the County to "have a seat at the table" during the CSS meetings. County staff, similar to the project's technical staff, attended each meeting but only participated when asked specific questions related to their policies and procedures. This assured the Advisory Group members that the discussion topics and general flow of conversation would be related to those issues of most importance to them and would not be influenced by any assumed preconceived notions by the County.

The five CSS Advisory Group meetings were structured to build upon the discussions and results of the previous meetings. The goal was to develop a consensus solution that met the County's transportation needs while also addressing the goals and values of the community. The flow and purpose of each CSS meetings was presented to the Advisory Group at the first meeting to provide them a road map for their efforts. The main goals and objectives for the meetings were as follow:

- CSS Meeting 1 – Introduction to CSS and issue identification
    - Allows the Advisory Group to convey what issues are affecting the facility today and what they would like to see in the future
- CSS Meeting 2 – Problem definition and issue prioritization
    - Assists in determining the key elements that should be incorporated into the solutions
- CSS Meeting 3 – Review evaluation criteria and alternatives development
    - Evaluation criteria allows the Advisory Group to quantify how well an alternative addresses a goal or objective

- CSS Meeting 4 – Preferred alternatives
    - Based on comments from the Advisory Group, as well as further technical analysis, the preferred alternatives are presented for comment
- CSS Meeting 5 – Present final alternative
    - A review of the entire CSS process including how the Advisory Group made a difference was presented

The consensus solution (**Figure 6**) consisted of cross sections that were sensitive to the context of each section of the roadway. For the mauka (towards the mountain) extension on new alignment, where there will not be any driveways, a two lane roadway with striped bike lanes, wide sidewalks and no on-street parking was agreed upon. The existing mauka section (middle section), with on street parking and driveways included a center turn lane, wide sidewalks and striped bike lanes. And finally, for the makai (towards the ocean) section, where driveways are very short, the center turn lane of the middle section was replaced with two six-foot parking lanes.

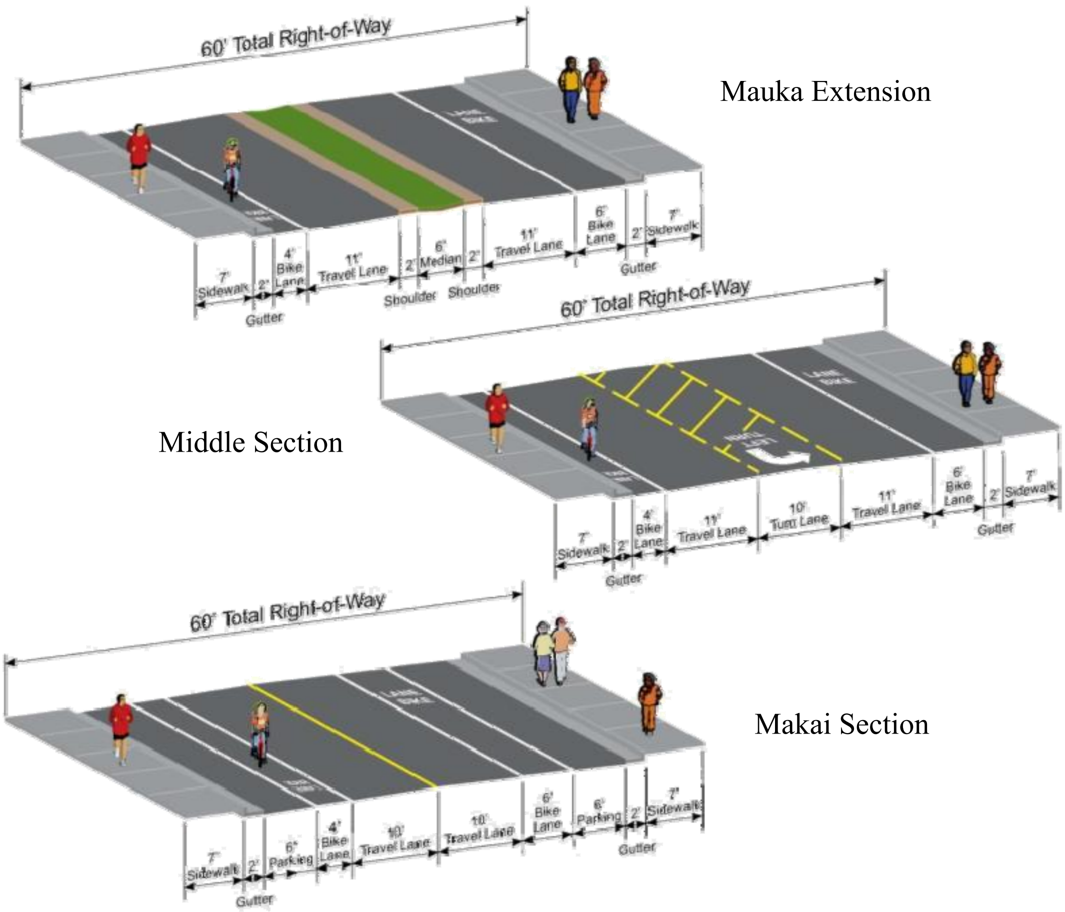

Figure 6 – Consensus Solution

Key success factors in implementing the CSS process for the La`aloa Avenue Extension, along with their tangible benefits, are summarized in **Table 1**.

CSS Success Factor	Benefit
Senior management at the County, including the Mayor, fully endorsed the process	Enabled the CSS team to fully apply the processes on the project
Advisory Group members were selected to represent a broad cross section of interests	Ensured that all user interests were represented in the alternatives and analysis
Advisory Group members were notified of the time/date/location for all of the CSS meetings at the onset	Allowed Advisory Group members to plan/make arrangements easier
Meeting materials for upcoming meetings were disseminated at least one week prior to each meeting	Provided ample time for the Advisory Group members to review the material and come to the CSS meeting prepared to discuss the issues
The CSS facilitator maintained contact with Advisory Group members before and after each meeting	Established a level of trust and commitment with the Advisory Group
Comments and questions between meetings were encouraged and were responded to by the CSS facilitator in a timely manner	Further established technical competency and fostered trust
One on one meetings between Advisory Group and the study team were documented and shared with all other Advisory Group members	Ensured equal treatment fostering transparency
The public was invited to attend the CSS Advisory Group meetings but were asked to hold comments and questions until after the formal meeting	Allowed the Advisory Group to focus on the issues
The public was included on all correspondence to the Advisory Group	Engaged a broader range of users and maintained transparency
Each meeting was started on-time and each item on the agenda was allotted a certain time for discussion	Respected the Advisory Group's time and allowed Advisory Group members to focus on the issues and not wander off topic
Technical staff were present at each CSS meeting	Allowed the Advisory Group to ask specific questions and receive accurate responses instantly
Meeting materials were clear and written in easy to understand language	Facilitated the conveyance of project issues and elements (see **Figure 7** for examples of CSS meeting materials)
The facilitator instructed the Advisory Group to direct contentious issues and criticism towards him and not at other Advisory Group members	Allowed open conversations and critical comments without offending other Advisory Group members

Table 1 – Key CSS Success Factors

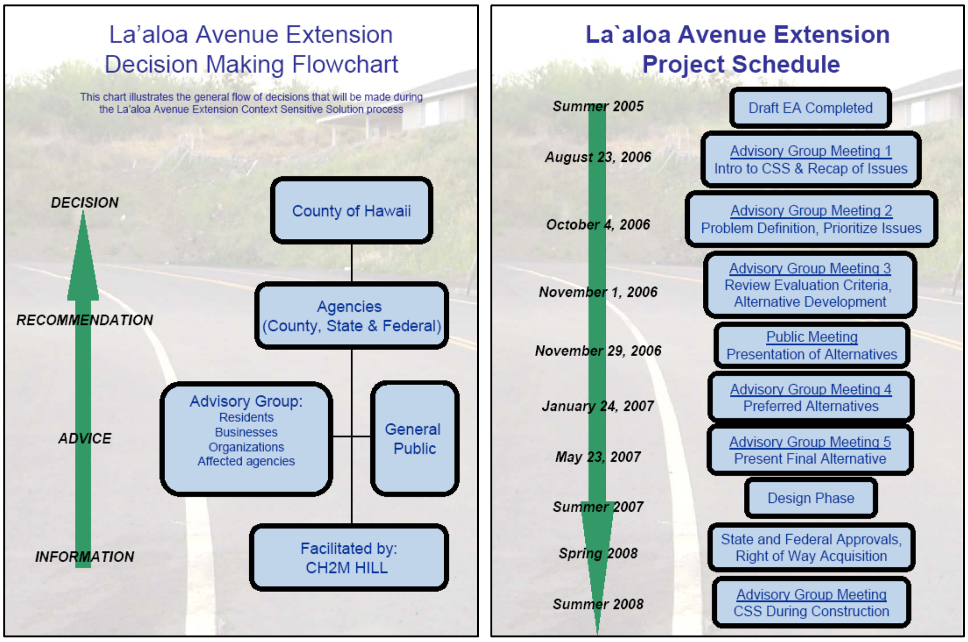

Figure 7 – CSS Advisory Group Meeting Materials

CONCLUSION

To account for the differing contexts of these sections, the preferred alternative identifies separate cross-sections for each portion of the roadway. Community suggested elements of the preferred solution include bicycle and pedestrian facilities as well as traffic calming features. Other aspects of the design include on-street parking provisions and green drainage elements.

The CSS process allowed for an opportunity for organized dialog with the public and the power of the community's input to find solutions, while continuing to maintain project momentum.

The resultant stakeholder recommendations modified the 1,500' extension alignment to address speeding, cultural and property impacts and developed several context sensitive cross-sections to address vehicle, pedestrian, bicycle and green drainage needs along the roadway. The final corridor, slightly over 1 mile long, transitions between three distinct cross sections, each sensitive to the area context.

In addition to working through contentious and conflicting comments, the County was able to gain respect and trust of the community. Upon completion, many participants, including some originally opposed to the project, were very complimentary of the CSS process and expressed their gratitude in helping make a difference for their community. A number of the Advisory Group members suggested that the CSS process be use on all future County projects.

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Educational Toolkit for Context Sensitive Solutions

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Abstract

This paper describes Oakland County's innovative planning tool for Context Sensitive Solutions (CSS) based transportation and community planning using a CD educational tool. Oakland County, Michigan offers cosmopolitan urban centers, lakefront living, historic town centers, and natural country settings within close proximity to an array of employment and recreational opportunities. Strengthening this diversity is critical to maintaining Oakland County's competitive edge and high quality of life. Parsons Brinckerhoff (PB) provided technical assistance to Oakland County Planning & Economic Development Services in the development of an interactive CD educational tool to provide an introduction to Oakland County's diverse living environments, historical development patterns, and resources that can maintain and strengthen that diversity. The tool is also an informational primer on CSS and will be used to educate local government leaders and the public on methods to develop transportation projects that fit into the County's physical settings.

Introduction

Oakland County, Michigan offers cosmopolitan urban centers, lakefront living, historic town centers, and natural country settings within close proximity to an array of employment and recreational opportunities. Strengthening this diversity is critical to maintaining Oakland County's competitive edge and high quality of life. Oakland County Planning & Economic Development Services is working to promote Context Sensitive Solutions (CSS) planning and education in Oakland County. The group provides consultative services and products that address county and local economic, community, and environmental topics. The Road Commission for Oakland County is a separate governmental agency that maintains more than 2,700 miles of county roads, over 230 miles of state highways and more than 1,200 county, city, and state traffic signals in Oakland County.

In 2006, PB was hired to assist in the development of a "technology planning" guidebook to be used by Oakland County and the Road Commission to establish an Oakland County Context Sensitive Solutions program. The RFP requested consulting services to develop and analyze existing CSS programs, and to make recommendations on the steps needed to implement an Oakland County CSS program. In response, PB proposed to develop a series of "before and after" visualizations for a proposed roadway design project in Oakland County. A CSS demonstration project would also be undertaken in conjunction with an actual programmed local road design project.

However, the project was scaled back due to a lack of funding for the local road design CSS demonstration project. A revised project work plan would focus on working with the project steering committee to develop goals, objectives and steps to incorporate CSS within the operations of Oakland County Planning & Economic Development Services and the Road Commission for Oakland County. In the first phase of the project, a series of structured focus group meetings were held with planning and engineering staff from local municipalities, county staff and the Road Commission.

The purpose of the focus groups was to measure local official awareness of the Federal Highway Administration's (FHWA) CSS Program and the Michigan Department of Transportation (MDOT) CSS program. In 2003, the Governor, Jennifer Granholm issued an Executive Directive that requires MDOT to incorporate Context Sensitive Solutions (CSS) into transportation projects whenever possible. In succeeding years, MDOT hosted a series of training meetings for MDOT employees and municipal planning organizations to address the implementation of a statewide CSS policy in Michigan. Under MDOT's CSS program, MDOT would solicit dialogue with local governments, road commissions, industry groups, land use advocates, and state agencies early in a project's planning phase (MDOT CSS Program).

MDOT's policy is framed in context of federal and state funded transportation projects. CSS at MDOT would affect all levels of the organization, all project delivery processes, and all projects implemented by the agency. In Southeast Michigan, MDOT had implemented several projects incorporating CSS. However, local road agencies, such as Oakland County Road Commission, are not required to implement CSS under the Governor's Executive Directive.

The Road Commission for Oakland County is the county-level road agency in Oakland County, Michigan. The commission maintains more than 2,700 miles of county roads, over 230 miles of state highways and more than 1,200 county, city and state traffic signals in Oakland County. The mission of the Road Commission for Oakland County is to provide basic repairs, alterations, renovation and expansion of the County's local road network. Funding sources for projects may come from a diversity of sources including county and municipal taxes, local governments, MDOT, and FHWA.

Focus group participants were asked "When should the Road Commission employ CSS principles and/or processes"? In general, the Road Commission activities fall within three categories of "Mission" based activities. Table 1 summarizes the potential for adopting a local Oakland County CSS program and general comments from focus group participants.

Table 1: Road Commission for Oakland County Program Activities

Road Commission Program Activity	Focus Group Comments	CSS potential
Maintenance Repair (no alteration to operational or physical infrastructure) – i.e., snow removal, pot holes, storm cleanup, mowing, tree trimming, brush clearing and swale cleaning.	Local government staff responds to citizen complaints over maintenance activities. For example, excessive tree trimming on local streets can destroy local road character. Limited opportunity for community input in maintenance and repair.	Limited Application of CSS principles
Minor alteration to operational or physical infrastructure – i.e., replacement of existing fixtures, road widening and major vegetation removal and control projects.	CSS education and training is needed for local officials in order to work with RCOC to develop local projects.	Evaluate for application of CSS Principles/Policies
Significant alteration to operational or physical infrastructure – i.e., including improvements and/or alterations that would be governed by National Environmental Policy Act (NEPA) processes.	Funding and incentives to incorporate CSS into projects with limited budgets. Changing the RCOC's point system for evaluating and prioritizing projects to award CSS planning.	Employ CSS principles

Overall, project stakeholders agreed that a "bottom up" approach would be required to build support for CSS-based planning and design in Oakland County. Focus group participants commented that there are many existing projects and programs that can be called "best practices" that embody different CSS-based principles. For example, since 1985, the Road Commission has met every two years individually with the leaders of the 61 communities in the county through a strategic planning process. These meetings facilitate a county-wide dialog on road maintenance and construction issues in the county. One of the hallmarks of the bi-annual meetings is the Oakland County "Roadshow." The roadshow is given by Road Commission staff with a PowerPoint presentation on local projects and community programs. Over 20+ years, the roadshow became a "best practices" catalogue highlighting the diverse natural environment and character of Oakland County. Together, these slide shows provided excellent examples of existing outreach activities to involve local communities in county-wide planning and decision making.

Some of the early project tasks with the steering committee were to review sample CSS policies and programs in other states and possibly develop an Oakland County policy statement. However, the steering committee cautioned that adoption of a county policy would not be as effective without either an educational program, funding or "cultural" change in county departments and agencies to support CSS planning.

The focus groups presented a unique opportunity for the project team (PB staff, county staff and project steering committee) to incorporate the focus group outcomes and specifically, the desire for an Oakland County CSS training program. In response, PB worked with the steering committee to develop an educational tool for CSS planning. The committee felt that an interactive CD and/or website would offer the best opportunity to begin the initial phases of a CSS educational effort in Oakland County. It is anticipated that future stages of Oakland County's CSS initiative will include the development of an Oakland County CSS policy statement for development and transportation projects.

Development of the Educational Tool for CSS

Several resources for the development of the tool included using photography, sketches and maps, and other resources developed by Oakland County and the Road Commission. Figure 1 illustrates one of a series of sketches as part of character guidebook for Oakland County.

In this way, the tool could build upon existing programs and potentially be used by county staff as part of the Road Commission road show or in other meetings with local governments and the public. In principle, the educational tool would focus on the different public values for Oakland County's diverse living environments, historical development patterns, and the county's vision for future development. CSS-based planning activities could potentially work towards helping to maintain and strengthen those values and diversity. As a result, the tool could also serve as an informational primer on CSS and be used to educate local government leaders and the public on tools to develop transportation projects that fit into the County's physical settings. However, this cultural change to CSS-based programs is a long term effort by County staff.

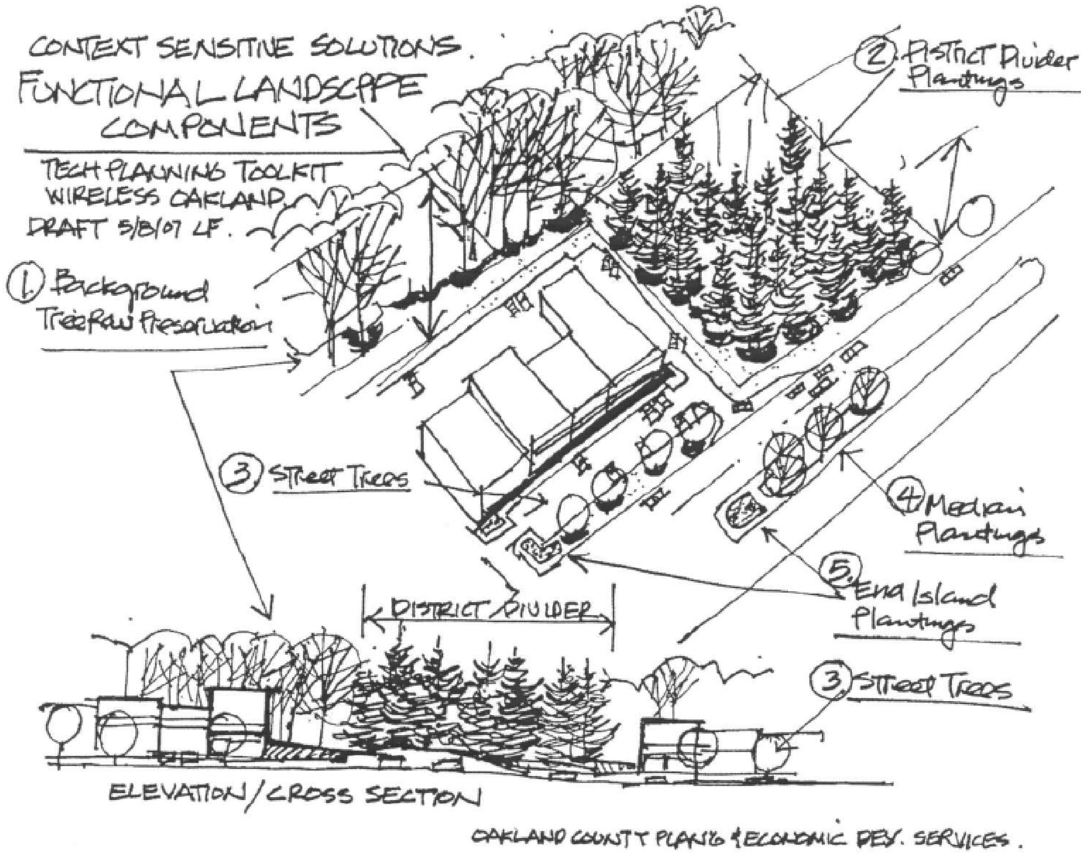

Figure 1. Example of a Sketch provided by the Oakland County Landscape Architect

Overview of the Educational Tool for CSS

The CSS tool presents six general land use themes, including: Back to Nature, Farm and Country, Lake Living, Suburban Style, Urban Neighborhood and Downtown/Town Center as shown in Figure 2. The user selects one of the six themes to display details on how each general land use theme relates to lifestyle and development patterns in Oakland County. Each theme or display screen contains an illustrative sketch linked with explanatory text, and local pictures in a digital photo viewer. The photos represent a variety of different locations in Oakland County and are included on the CD in a photo database. County staff can add additional photos to the database using commonly available software. In addition, before and after photos of Oakland County CSS projects can be incorporated as they are completed. For example, Figure 3 shows the opening display screen for the Downtown & Town Center theme.

Additional resources that compliment the land use themes are shown in Figure 4, Figure 5, and Figure 6. These resources include an interactive map linked to explanatory text and photos. Figure 4 includes an interactive graphic that displays the density and location of development in Oakland County across multiple decades between 1900 and 2008. Figure 5 shows the Oakland County Green Infrastructure Map and includes photos of natural features and environmental sensitive areas. A Lifestyles Map is shown in Figure 6 and represents the economic and geographic diversity of Oakland County. Additional display screens not described include a Base Map and 1966 and 2008 Land Use Maps. Figure 7, the tool exit screen, provides links and resources for further information on CSS planning.

The presenter or user can customize their self-directed tour to explore each of the land use themes. Each theme offers interactivity to engage and encourage users to learn about CSS, while providing relevant examples from Oakland County to illustrate the concepts being conveyed.

Practical Application of the Educational Tool for CSS

Released in February 2010, the tool can be used by Oakland County communities to prepare for a bi-annual strategic planning process conducted by the Road Commission. This process includes meetings with virtually all cities, villages and townships in the county. These meetings provide a unique opportunity for the leaders of 61 local governments in Oakland County to review needs and concerns and to share news on recent developments. The strategic planning process is an important tool for identifying the top road-related concerns of the communities.

The goal of the CSS education tool is to involve local leaders and the public in a discussion of physical features valued in Oakland County and to provide a resource for developing transportation projects that protect the diversity and quality of life in Oakland County. It is anticipated that future stages of the initiative will include the development of an Oakland County CSS policy statement for development and transportation projects. A web version of the CSS tool will also be made available on the Oakland County website in late 2010.

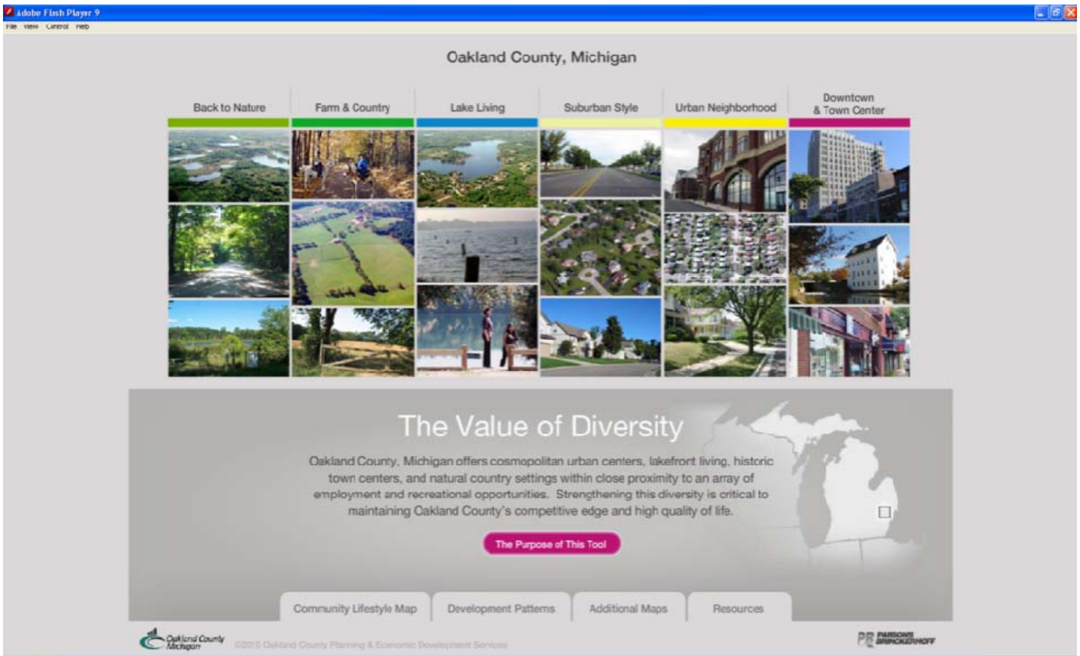

Figure 2. Introduction Screen

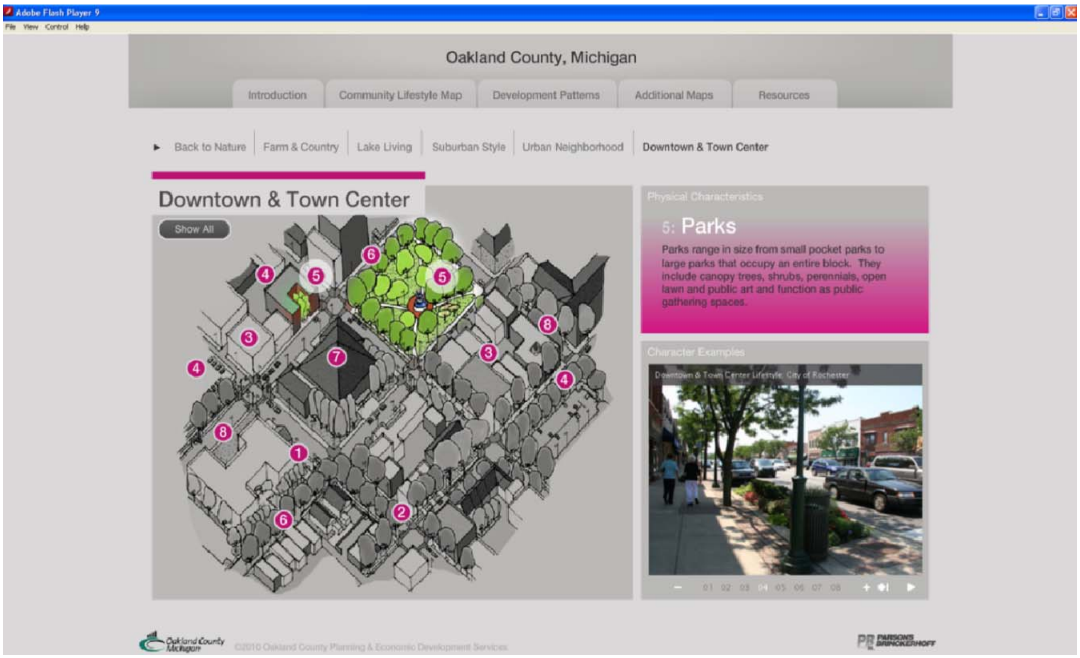

Figure 3. Downtown & Town Center

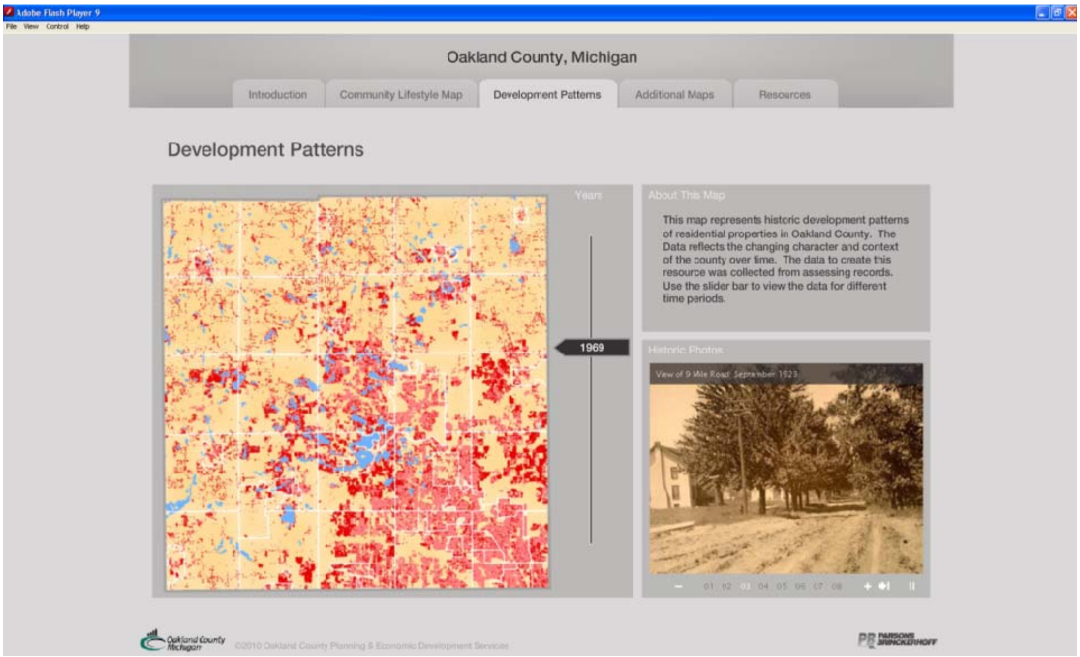

Figure 4. Development Patterns

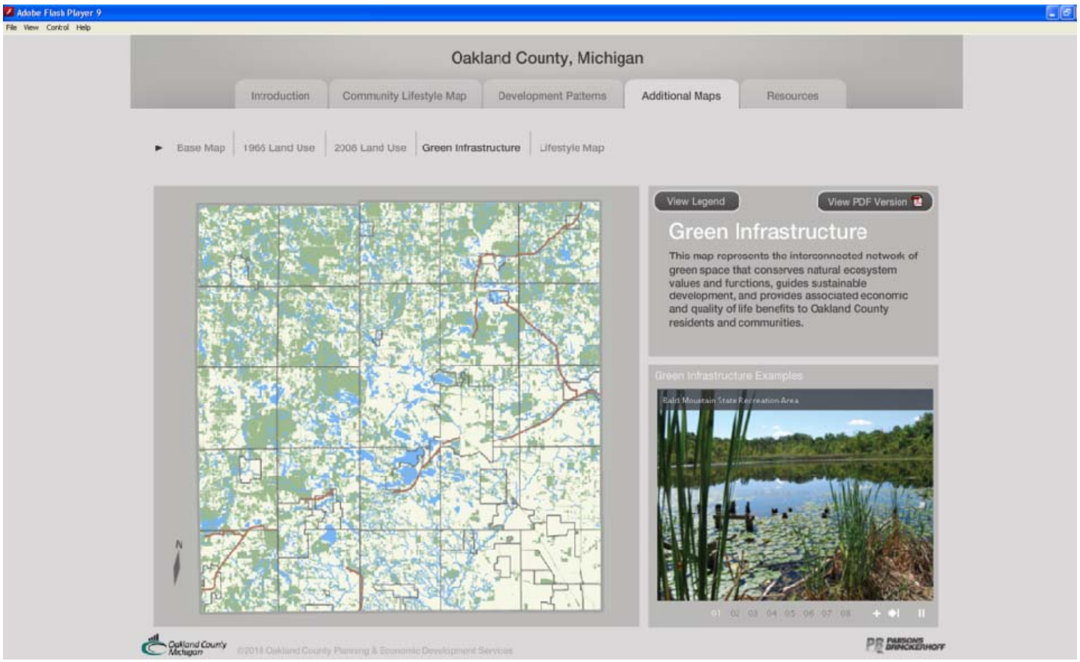

Figure 5. Green Infrastructure

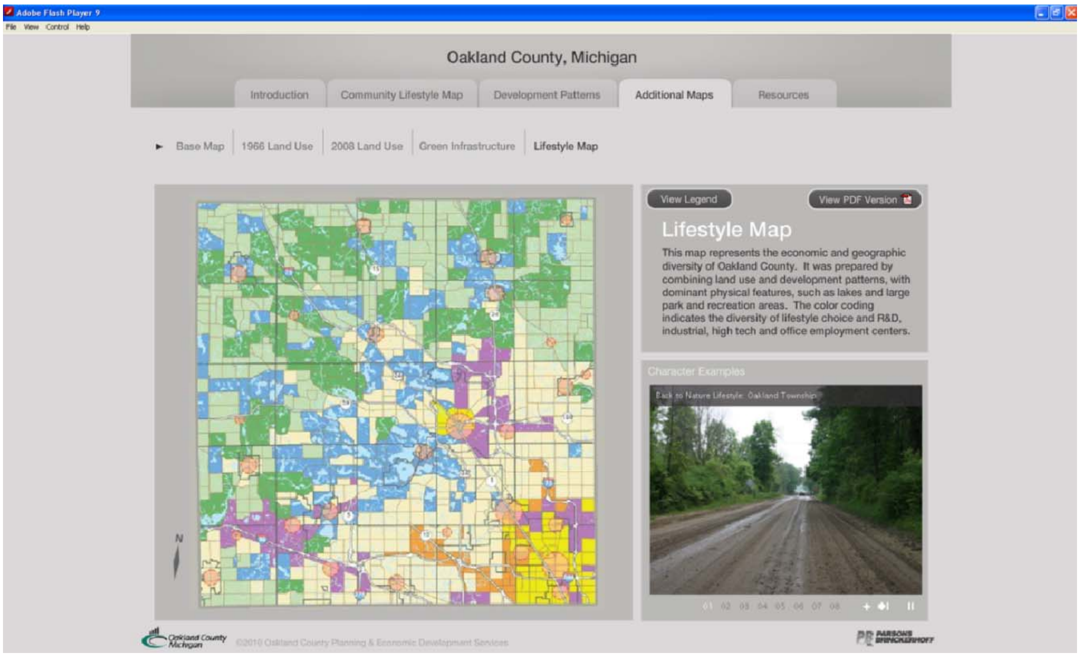

Figure 6. Lifestyle Map

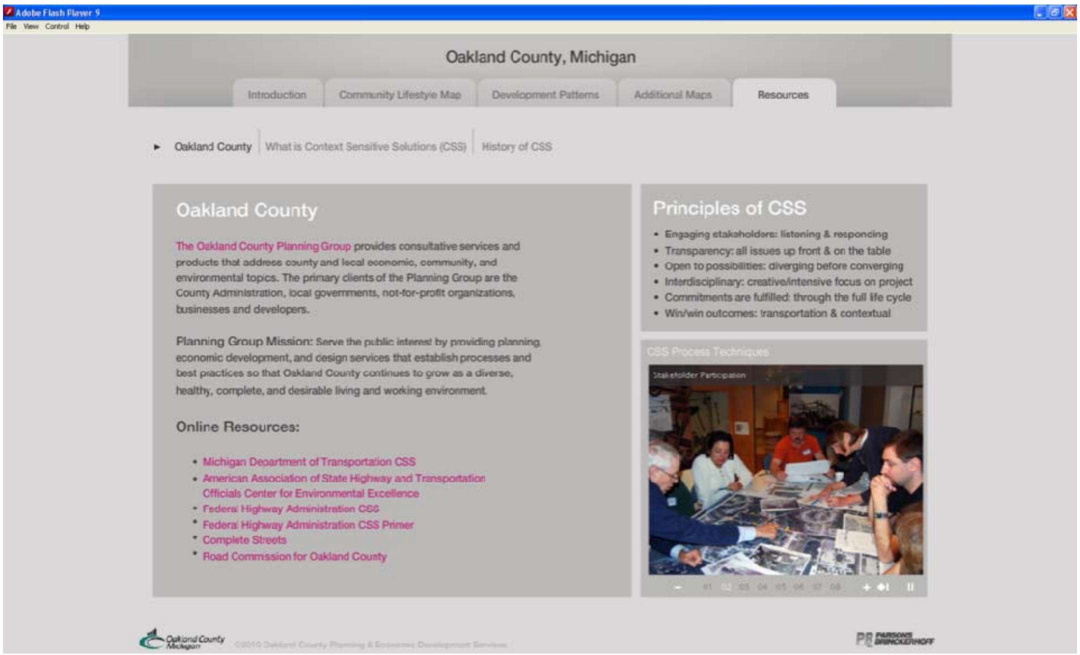

Figure 7. Exit Screen

Software Development Technology

The CSS tool was created using Adobe® Flash® CS3 software. Adobe® Flash® is a multimedia platform that allows for animation and interactivity while keeping the number of files and file sizes at a minimum, thus optimizing performance of the tool. All content is compiled and published into a single Flash® movie (.swf), which is generally supported by most computer operating systems and devices, thus allowing the tool to be easily distributed and viewed. The CD delivery format offers cost-effective reproduction and distribution. The Flash® tool may also be adapted for web and posted on the Internet to broaden outreach distribution.

Another Flash®-based application used within the CSS tool to display and navigate through photos was SlideShowPro™ (http://slideshowpro.net/). SlideShowPro™ is customizable and allows for easy updating of content. The user of the CSS tool benefits from a very usable slideshow navigation and nicely transitioning images.

Conclusion

The CSS tool does not focus on specific projects, programs or CSS activities in Oakland County; instead, the tool is intended to foster multiple levels of discussion among local government leaders, staff and the general public on what they value most about Oakland County. The history of this project's development and demonstration of the Educational Tool for CSS is intended to be a useful resource for future CSS planning efforts.

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A Process for Measuring Context Sensitive Solutions Benefits

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ABSTRACT

Context Sensitive Solutions (CSS) provides a systematic and comprehensive approach to project development from inception and planning through operations and maintenance. The ability to categorize and measure the benefits of CSS projects is vital to the long-term success of this approach. The paper presents a framework for transportation officials and professionals that allows for the comprehensive quantification of benefits resulting from CSS through all phases of project development. A fundamental aspect of this framework is the identification of CSS action principles and their potential benefits. A matrix that correlates benefits to specific CSS principles was generated to allow for the development of appropriate metric indicators for each benefit. Guidelines for benefit analysis have been developed to provide transportation agencies with a set of recommended practices for assessing benefits. The guidelines emphasize the fact that CSS is a principle-driven, benefit-justified effort that can enhance an agency's goals and interaction with stakeholders and the public. The need exists to analyze and measure the benefits of CSS and its impact on projects (e.g. cost and delay) in order to demonstrate a best use of agency resources.

INTRODUCTION

In recent years, Context Sensitive Solutions (CSS) has been promoted by both AASHTO and FHWA as a best practice, since it provides a systematic and comprehensive approach to project development from inception and planning through operations and maintenance. Its goal is to achieve an outcome harmonizing transportation requirements with community needs and values. The ability to categorize and measure the broad scope of benefits within projects is vital to the long-term success of CSS in meeting livability and mobility goals. Transportation agencies currently lack the capability and tools that allow them to accomplish this. The development of performance measures will enable evaluation of the benefits and allow state and local transportation agencies to gauge the value of employing CSS and measure the progress they are making to improve project development and delivery processes.

A key factor in developing benefit evaluation tools is the recognition that transportation projects are unique in terms of the nature, scope and importance of issues addressed. These factors impact project purpose and need, community and environmental concerns, topographic and geometric conditions, traffic, safety history, and other public priorities. There are guiding principles for CSS and a core of essential elements common to most projects. Those should be identified and considered when conducting project benefit evaluations, since such principles are the cornerstone of the unique project solutions to be developed. A range of measures must be examined to determine those most appropriate for assessing various types of project outcomes.

The objective of the work was to develop a framework for transportation officials and professionals that identifies a comprehensive set of performance measures of CSS principles and quantifies the resulting benefits through all project phases. This framework provides transportation agencies with tools for identifying and quantifying the benefits of applying CSS principles and to systematically collect needed data. This process is envisioned to be applied in all types and sizes of projects. This paper presents the framework for a continuous performance evaluation and opportunity for process improvement for transportation agencies using CSS.

PRINCIPLES AND BENEFITS

CSS has been a principle driven process aimed at increasing the quality and satisfaction of transportation projects. In order to fully implement the CSS approach it is evident that benefits associated with CSS must be identified and documented on all projects. Focusing only on project outcomes will allow for an analysis of benefits, but not for an understanding of how these outcomes were achieved. However, by applying the CSS principles on a project and identifying their potential benefits, a direct link between project actions and benefits can be readily identified. A proactive project approach uses this linkage by setting targets to be achieved for selected benefits and determining principle driven actions that must be made throughout the project development process to achieve these benefits. As a result the CSS principles provide the foundation for a systematic approach to project development and benefit analysis. This two prong effort allows CSS to be summarized as a "principle driven, benefit justified approach."

The project development/delivery process was examined to determine the discrete actions needed for a successful CSS project. These actions are stated as principles and they drive the activities and tasks needed to be completed during the project development process. It is these principles to which benefits can be associated and measured. The review of the project delivery process defined 15 principles to be used in the process as shown in Table 1.

Table 1 CSS Principles

1. Use interdisciplinary teams
2. Involve stakeholders
3. Seek broad-based public involvement
4. Use full range of communication methods
5. Achieve consensus on purpose and need
6. Address alternatives and all modes
7. Consider a safe facility for users and community
8. Maintain environmental harmony
9. Address community and social issues
10. Address aesthetic treatments and enhancements
11. Utilize full range of design choices
12. Document project decisions
13. Track and meet all commitments
14. Use agency resources effectively
15. Create a lasting value for the community

Some principles build on each other and have what appear to be hierarchal, cause-effect relationships. For example, principles 2 (involve stakeholders) and 3 (seek broad-based public involvement) will have a significant influence on principle 5 (achieve consensus on purpose and need) as well as shaping principle 4 (use full range of communication methods). Understanding the principles and their interaction promotes knowledge of CSS fundamentals and process relations and comprehension of how CSS projects are developed.

A good representation of these relationships is provided in Figure 1 showing the dependencies among principles as a building. The foundation of the building consists of the three Fundamental Principles of CSS. The floor is comprised of the four Basic Transportation Agency Principles that exist for every project. The six pillars of the CSS building are the six Agency Enabling Principles and Context-Sensitivity Enablers that provide for and ensure context-sensitivity:

Context-Sensitivity Enablers

- Maintain environmental harmony
- Address community and social issues
- Address aesthetic treatments and enhancements

Agency Action Enablers

- Utilize full range of design choices
- Document project decisions
- Track and meet all commitments

The lintel and roof of the building of CSS are the Long-Range Project Principles (Goals).

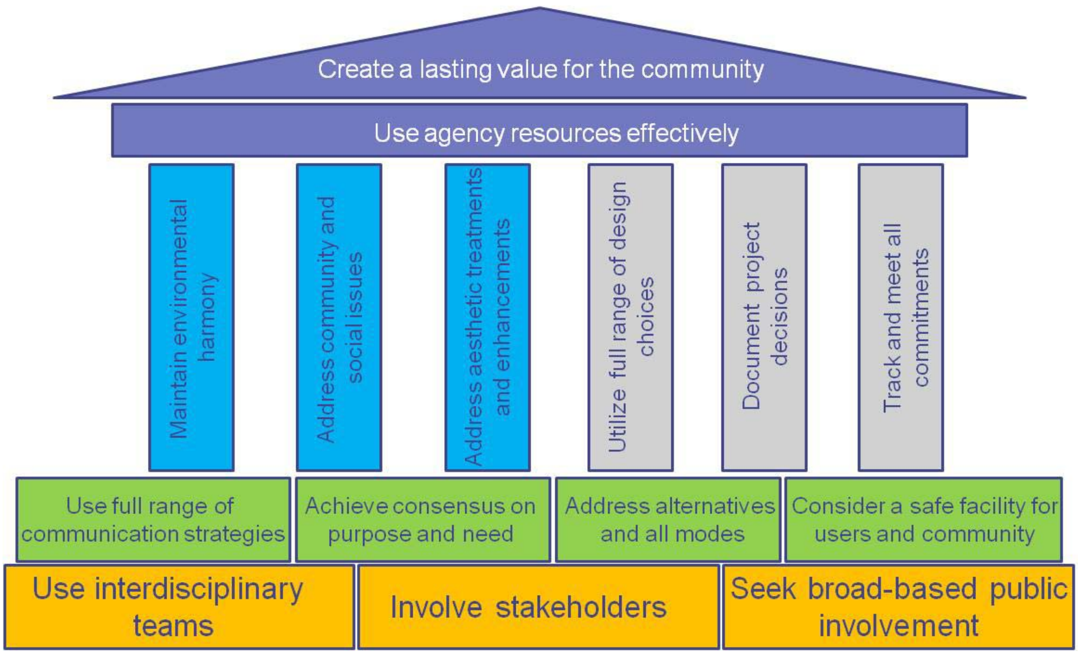

Figure 1 The building of CSS principles

The three Fundamental Principles must be applied to have a CSS project development process. The four Basic Transportation Agency Principles are present regardless of whether or not a project employs CSS. The six enabling principles are the tools that enable a project team to create a lasting value for the community and use agency resources effectively, which should be the aim of all projects. While all principles will be present on any project, their relative intensity (as applied) will vary between projects. Similarly all benefits will be present; however, resulting benefits will vary accordingly.

Projects vary and the intensity with which CSS principles are used will vary as well. The three Fundamental Principles must be applied to have a CSS project development process. The four Basic Transportation Agency Principles are present regardless of whether or not a project employs CSS. The six enabling principles are the tools that enable a project team to achieve both create a lasting value for the community and use agency resources effectively, which should be the aim of all projects. While all principles will be present on any project, their relative intensity (as applied) will vary between projects. The relative intensity of each principle should be examined, since the magnitude of benefits to be realized will be affected. This relative intensity is to be determined by the scope, scale, and context of the project. For example, for a small project, there may be a limited number of stakeholders involved, which will affect the extent and type of communication methods employed and the level of public involvement required. Extensive public involvement efforts may not be necessary to provide measurable benefits. On large, complex projects affecting many parties, greater stakeholder public involvement may be required to achieve an equivalent level of benefits.

A total of 22 specific potential benefits are identified as a result of applying the 15 CSS principles (Table 2). The benefits are grouped in two basic categories based on who accrues the benefits, i.e. the agency or the users. This is needed since some of the benefits are internal to the agency's operations and have no clearly understood benefit to the users. This differentiation provides the agency with the ability to determine those other benefits and that the users will best recognize and use to judge the agency's project development process performance.

Table 2 CSS potential benefits

1. Improved predictability of project delivery
2. Improved project scoping and budgeting
3. Improved long term decisions and investments
4. Improved environmental stewardship
5. Optimized maintenance and operations
6. Increased risk management and liability protection
7. Improved stakeholder/public feedback
8. Increased stakeholder/public participation, ownership, and trust
9. Decreased costs for overall project delivery
10. Decreased time for overall project delivery
11. Increased partnering opportunities
12. Minimized overall impact to human and natural environment
13. Improved mobility for users
14. Improved walkability and bikeability
15. Improved safety (vehicles, pedestrians, and bikes)
16. Improved multi-modal options (including transit)
17. Improved community satisfaction
18. Improved quality of life for community
19. Improved speed management
20. Design features appropriate to context
21. Minimized construction related disruption
22. Improved opportunities for economic development

Quantitative and semi-quantitative indicators were developed to capture and measure the impact of each benefit. Metrics have been developed for all benefits and therefore transportation agencies have the ability to customize the data collection and analysis.

PRINCIPLES AND BENEFITS RELATIONSHIPS

While it is reasonable to assume that the application of a principle could result in several benefits, performing such analyses may prove impractical due to the range and quantity of data required. To produce a useful and usable guide, it was deemed reasonable to identify those benefits that have a strong relationship to each principle, capturing the essence of each principle. However, some benefits may have multiple indicators or metrics that could be used to measure the entire breadth and depth of their impact and effectiveness. This approach allows for developing specific metrics for a smaller number of targeted benefits, limiting data collection and analysis requirements.

A matrix of principles and benefits was developed which identify benefits having a strong relationship to each principle. These relationships were based on the collective multi-disciplinary expertise of the team to identify the potential benefits for each principle using each team member's discipline-specific perspective. Those benefits identified as having the strongest relationship among the majority of the team were identified as primary benefits. Other benefit-principle relationships that had a lower level of agreement among team members were considered to have a moderate relationship to the principle and categorized as secondary benefits. Finally, all other benefits that could be realized from the application of the principle were considered as tertiary, i.e. having a weak relationship to the principle. These relationships were refined based on input received from the project panel, as well as data and knowledge from case studies. The matrix developed on these three levels of relationship between benefits and principles is provided in Table 3.

For each principle one primary benefit is designated fundamental providing a single indicator to capture the benefit of applying the principle. The fundamental benefit allows an agency to perform a focused evaluation of a CSS project in the event that resources are not available to complete a full-scale evaluation of all benefits.

An aspect of the matrix provided in Table 3 is its flexibility to be adjusted to an agency's needs and perspectives. The pairings provided here resulted from the input of the multi-disciplinary team members while considering the data obtained from the case studies. An agency can follow a similar approach to the one described above to determine their priorities and associations and therefore develop a different set of principle-benefit interactions. The metrics developed for each benefit are generic and thus could be used to measure the magnitude of the same benefit for each principle.

IMPLEMENTATION

As CSS has been defined as a principle driven benefit justified approach, any evaluation of CSS must consider both how the process should be applied (principles) and what the outcomes are (benefits). Several benefits and associated metrics can be used to measure project outcomes. Both the benefits and metrics vary in terms of data collection efforts and address various aspects of the project and project development process. Benefit analysis may be used for four distinct applications.

Table 3 Principles and associated benefits

Legend: F = Fundamental (◆); P = Primary; S = Secondary; T = Tertiary

Principles \ Benefits	1. Improved predictability of project delivery	2. Improved project scoping and budgeting	3. Improved long term decisions and investments	4. Improved environmental stewardship	5. Optimized maintenance and operations	6. Increased risk management and liability protection	7. Improved stakeholder/public feedback	8. Increased stakeholder/public participation, ownership, and trust	9. Decreased costs for overall project delivery	10. Decreased time for overall project delivery	11. Increased partnering opportunities	12. Minimized overall impact to human and natural environment	13. Improved mobility for users	14. Improved walkability and bikeability	15. Improved safety (vehicles, pedestrians, and bikes)	16. Improved multi-modal options (including transit)	17. Improved community satisfaction	18. Improved quality of life for community	19. Improved speed management	20. Design features appropriate to context	21. Minimized cosntruction related disruption	22. Improved opportunities for economic development
15. Create a lasting value for the community	T	S	P	S	S	T	T	P	T	T	T	S	S	S	S	S	P	F	S	S	T	T
14.Use agency resources effectively	S	P	P	S	S	T	T	S	F	P	S	T	T	T	T	T	T	S	T	T	T	S
13. Track and meet all commitments	S	T	T	S	T	P	T	F	S	S	T	S	S	S	S	S	P	T	T	T	S	T
12. Document project decisions	S	T	S	T	T	P	T	F	S	S	T	T	T	T	T	T	P	T	T	T	T	T
11. Utilize full range of design choices	T	T	S	T	S	S	T	S	S	T	T	P	S	S	S	P	S	S	P	F	T	T
10. Address aesthetic treatments & enhancements	S	S	S	S	S	T	T	P	T	T	S	T	T	T	T	T	F	P	T	P	T	S
9. Address community & social issues	S	S	S	S	T	S	S	P	T	S	S	P	S	S	S	S	F	P	S	P	S	S
8. Maintain environmental harmony	T	S	S	P	T	S	T	S	T	T	T	T	T	T	T	T	S	P	T	P	S	T
7. Consider a safe facility for users & community	T	S	S	T	T	P	T	S	T	T	T	S	S	P	F	S	S	P	P	S	S	T
6. Address alternatives and all modes	T	S	P	T	T	S	T	P	S	T	S	T	F	P	S	P	S	S	S	S	T	S
5. Achieve consensus on purpose and need	P	S	P	T	T	S	T	F	S	S	T	S	P	T	S	S	P	S	T	S	T	T
4. Use full range of communication strategies	T	S	T	T	T	T	P	F	T	T	S	S	T	T	T	T	S	T	T	T	S	S
3. Seek broad-based public involvement	P	S	S	S	T	T	S	S	T	S	S	S	S	S	S	S	F	T	T	S	S	S
2. Involve stakeholders	S	S	T	S	T	S	P	F	T	S	P	S	S	S	S	S	S	S	T	S	P	P
1. Use of interdisciplinary teams	S	P	S	S	P	S	T	S	S	P	S	P	S	S	S	S	S	S	T	F	T	S

1. **Justification of CSS Project/Project Elements.** Benefits are measured to allow for the project team to justify specific project elements (design or activities) throughout the project development process. Direct measuring and quantification of project benefits is used to address concerns about the project outcomes. These measured outcomes allow for greater acceptance of the project and can be used as an example in future projects.
2. **Continuous Improvement of the Project.** Benefits are measured in conjunction with the principles-benefit matrix as a tool for a continuous improvement of the project itself. Measured outcomes for benefits accruing throughout the project development process are monitored to identify problems in the project approach and/or outcome prior to completion of the project allowing for corrective actions before the completion of the project.
3. **Justification of Agency CSS Program.** Benefits are measured to allow for an agency to justify and evaluate the effectiveness of an agency wide CSS program or process. The use of agency-wide measured outcomes allows for determining the appropriateness of CSS in project development and demonstration of the benefits to the agency, the legislature and interested public parties.
4. **Continuous Improvement of Agency Process.** Benefits are measured in conjunction with the principle-benefit matrix as a tool for a continuous improvement of the agency's project development process. The benefit analysis can identify where improvements in project development have been made as well as identify opportunities for improvement. The measured outcomes are used to determine the benefits not accrued based on the agency's desires and to then initiate a review of the process to determine actions that directly produce those benefits.

Benefit analysis may be used by the project team to justify project actions or to improve processes for the project. Transportation agencies can use the same benefit analysis to justify the agency program or use it as part of a continuous improvement process. For successful benefit analysis, the evaluation approach should be established from the outset of the project so that principles are properly applied, data is timely collected, and benefits are systematically measured. This process is as follows:

1. Determine the application intensity of each principle using the project attributes.
2. Select the benefit(s) to be measured and the quantitative and/or semi-quantitative measures to be used.
3. Establish benchmarks for comparing measured outcomes for benefit accrual.
4. Collect data/information using a standardized format (forms and surveys), acquire the data/information in a timely manner and record it in an appropriate format.
5. Analyze (using comparison, benchmarks and dollar conversions) and evaluate benefit accrual, and report data/information.

The following sections identify key considerations in each of the above steps in the applications process.

Principle Intensity

All 15 CSS principles presented in Table 1 should be applied on all projects. However, unique project attributes (scope, scale and context) require that the application intensity of each principle should be determined to meet the unique characteristics of the project. Each of these can directly affect the intensity (depth and breadth) of the principle application. The effect of these attributes is demonstrated for principle 1 use an interdisciplinary team.

Scope: As the scope of the project increases, the number of involved disciplines expands, requiring increased members on the team. A resurfacing project may only involve a construction engineer and maintenance engineer in addition to the contractor. On the other hand a new construction project would require expertise in planning, highway design, construction, maintenance and other appropriate disciplines.

Scale: As the scale of the project increases, the demands on the project increase as well. This may require new expertise to coordinate the project, as well as require multiple persons to perform the work. A major new construction effort may require multiple highway design engineers, with individuals focused solely on specific project aspects. Conversely on a small project, a single engineer may be able to address all these issues at once.

Context: The varying context of the project has a direct impact on the project as well. As new constraints and resources are encountered or impacted the appropriate team members must be identified. This would include environmental specialists, historic preservationists, special user groups and others as needed.

For each of the 15 principles, a set of criteria for application are provided to assist the project team in the implementation of the principles within the project. These criteria guide the team in determining the appropriate intensity of the principle. As an example, one of the criteria of application for principle 6, address alternatives and all modes, is stated as *"Multiple alternatives including various modes, capable of addressing the issues in the purpose and need statement, are identified and developed."*

This criterion directly references the purpose and need statement and as such is limited by the defined scope of the project therein. As discussed above, the scale and context of the project should also be considered in its application. A resurfacing project applying this criterion may only examine the feasibility of alternative construction phasing alternatives to reduce construction impacts. If the roadway is heavily utilized by cyclists, i.e. it has a different context, the addition of a bicycle lane may be considered. The expanded scope of a corridor planning study, however, requires that many more alternatives be considered to address the full extent of such a project. This may include 1) the examination of multiple modal options along the corridor including transit, pedestrian and cycling 2) roadway alternatives such as two or four lanes, divided or undivided highways, 3) as well as construction phasing alternatives.

Benefit Selection

It is anticipated that not all benefits will be measured on all projects. Benefits to be measured should be selected based on the need to determine project or agency goals. Such a selective approach will allow for focusing on specific measured outcomes and limit unnecessary data collection. Benefits to be measured should be carefully selected based upon the purpose of the benefit analysis and the availability of data to measure project outcomes (and the commitment to collect and store the data). A focused evaluation plan enables the agency or project team to measure pertinent benefits, collect all necessary data and conduct the appropriate evaluation.

Benefit selection considerations for the four primary assessment methods are discussed here. For project related evaluations (justification or continuous improvement), benefits need to be specific and tailored to the project, element or activity to be measured. For the continuous improvement of the project, targeted benefits are those quickly accruing and those allowing monitoring of the application of principles in order to permit adjusting the principle intensity in real time. For agency related evaluations (justification of program or continuous improvement of process), benefit measures need to be standardized to allow for summarizing and comparing data for all projects. This can be achieved with data that is obtainable for all projects without extensive data collection and could be limited to measures of fundamental or primary benefits, since they capture the essence of CSS. For continuous improvement of agency processes, a broader range of benefits may be needed to capture the entire spectrum of project outcomes depending on the focus of the continuous improvement initiative. However, a wide range of benefit analysis will allow agency flexibility in dealing with future funding constraints and political realities.

Establish Benefit Benchmarks

The most critical element of the benefit analysis is the establishment of benchmarks for judging benefit accrual. Traditional analysis may use as benchmarks the difference in the measured outcome between before and after conditions or between CSS and non-CSS projects. However, such an analysis is often impractical due to lack of available data (before or non-CSS project). Benchmarks also vary greatly among agencies and projects, as well as, the purpose for which the benefit is being measured. For instance, if benefits are being measured for use in the continuous improvement of the agency process, the benchmark will be the measured outcome from the previous iteration. For benefits being measured to justify a CSS project, the benchmark is established relative to the project goals. It is therefore impractical to establish a single benchmark for each benefit metric to cover these benefit analysis options.

For benefit analysis on a single project, measures of effectiveness and their benchmarks should be explicitly stated in the purpose and need statement or in a memorandum of agreement or understanding (MOA/MOU). This approach allows for collecting only the required data for comparison and reduces data collection demands. These benchmarks should be both specific and tailored to the project and its context. Specificity is achieved by stating the desired benchmark to be targeted. For example, if the purpose and need statement calls for improved mobility, the specific target of decreased travel time by 20 percent compared to the existing conditions should be stated. Customization is achieved also this way, since benchmarking is specific to the project and agreed upon by team members and stakeholders. In the same example, an agency-wide goal of reducing travel time by 30 percent may be inappropriate for the context of this project.

As part of the continuous improvement of the agency process, a moving benchmark is established which is related to the measured outcomes of the previous round of projects. The evaluation is therefore established by determining the relative improvement of the process as it compared to the "benchmark" established by previous projects.

Data Collection, Maintenance and Accessibility

A data handling plan must be in place from the project outset. The plan identifies the data to be collected along with when is to be collected. In addition, how that data will be maintained and made accessible to users is also determined. Data needed to evaluate benefits is obtained throughout the project development process and often is available only for a short time. As an example, attendance level at stakeholder meetings is only available at the meeting. If pertinent data is not collected at that time, it may never again be obtainable. In addition, a system must be in place to maintain the data and make it accessible to those conducting the evaluation. For project specific benefit analysis, storage and accessibility may be less formal and available only to project team members. However, agency-wide efforts must have standardized data formats and provide a centrally located and catalogued data source so that others may access and analyze the data.

Evaluation

Once the data is collected it should then be analyzed by several methods depending on the nature of the metric and its intent:

- Quantitative data allows for establishing benchmarks and making direct ordinal comparison (using standard measures) and in some cases conversion to dollar amounts.
- Semi-quantitative data allows for making broad relational comparisons based on expert opinion and customer satisfaction. It can also be used to compare the views of the project team to the stakeholders/public. This information can be important as other data if, for instance, there is a goal to improve the public trust.

CONCLUSIONS

The primary outcome of this effort is a practical framework for transportation professionals to use for assessing benefits of a CSS project. To achieve this, a set of principles was identified with associated benefits to which metrics can be applied to measure the outcome of CSS projects.

The framework developed provides a methodology for completing a systematic quantification of benefits of using the CSS approach for project development. It is apparent that a systematic approach needs to be undertaken where data will be collected periodically in order to provide the basis for evaluating individual projects and identifying areas for agency CSS improvement. The benefit quantification is a process that any agency can undertake in order to determine the effectiveness of their efforts on a specific project, conduct a program evaluation, and use the lessons learned to improve specific actions for future projects. This allows for a continuous improvement effort that could be undertaken to positively impact project development and delivery operations using agency resources more effectively.

The framework has also been designed with the realities of project scope, size and extent. A project team has the ability to identify and customize the principle intensity applied in the project based on the specific needs of the project. This provides the ability to vary principles applications in terms of magnitude and allows for a flexible project development process that creates the capability for the agency and project team to achieve desired outcomes. Moreover, the project team can also select the anticipated benefits and determine those that are to be monitored and measured. This allows for an evaluation procedure that provides flexibility to the agency and project team to achieve desired outcomes. To determine whether a benefit accrued, the project team can develop benchmarks that would be specific for the project developed and customize data collection to determine them. The evaluation and comparison of the collected data to these benchmarks allows for identifying successful application of principles and improvement actions for future applications of principles that were not successfully employed. These efforts could then be used by the agency to improve the development process of other projects.

The principle-benefit matrix provides an agency with a linkage of direct actions to improve both project and program performance as well as to determine future process improvement opportunities. Once the agency targets benefits to be measured by all projects, associated metrics could be determined and the agency-wide target threshold values could be established. The collected data could then be used to identify the remedial actions required to meet or exceed the thresholds set through an identification of the appropriate actions for improving each principle by examining the corresponding application criteria. For example, if an agency is experiencing an extreme lack of trust, then it can identify several actions, using the associations established by the matrix that it might take to remedy that situation. The use of the matrix in this fashion will allow agencies to improve their overall performance and project development and delivery process.

The most important aspect proposed is that a systematic and well organized data collection effort should be undertaken from the outset of the project. The forensic approach often currently implemented makes it is almost impossible to identify and collect data after the completion of the project. Such data is likely to be incomplete, not adequately cover the required metrics, and not have the necessary statewide comparisons data available. The identification of the benefits to be monitored along with their metrics from the outset of the project is essential. This will allow for identifying the specific metrics to be monitored, allow for timely data collection, and the building of comparison data. It is important for an agency to identify data collection needs from the outset of the project and to include them in the project development process to ensure that critical windows of opportunity are not missed. Critical assessment data must be collected appropriately, maintained adequately, and be readily available.

Current procedures do not allow for the development of a systematic data collection effort across all projects for an agency nor for the establishment of a database that could be accessible to any interested party. Therefore, there is a need for commitment by agencies to systematically collect such data and maintain a database to allow for benefit assessment and/or establishing a continuous quality improvement effort.

URBAN GOODS MOVEMENT CASE STUDIES

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ABSTRACT

Urban goods movement is stimulated by the needs of business and commerce, but is also greatly influenced by growth in population. No city can function without the ability to efficiently move goods. Considering this fact and the growth that many regions are experiencing in population and goods movement, planners must place more emphasis on the freight-related needs of their transportation system. In order to maintain and enhance the economic vitality and quality of life of any thriving city, steps must be taken to manage the current level of freight activity and prepare for the increased activity that will result from sustained growth.

As stated in the 2003 Talking Freight Seminar Series Presentation, "Freight planning is somewhat different from passenger travel planning…Elected officials do not always give high priority to freight vehicles for planning."[1] Traditionally, planners have overlooked the freight component of the transportation system choosing, instead, to focus on the movement of people. Therefore, freight planning efforts have lagged behind other transportation initiatives. To ensure the economic sustainability of their region, planners must now find the best methods to seamlessly incorporate the growing volume of freight into their transportation network.

The goal of this project was to produce an informational package that would provide insight into previously implemented strategies in the field of urban goods movement. Through an extensive literature review, input from the Working Group consisting of freight professionals from both the private and public sector established for the project, and other data collections efforts, Street Smarts identified several specific projects that would most benefit others undertaking freight planning efforts. As a result, four case studies were prepared, documenting notable practices in urban goods movement: New York, Los Angeles, Orlando, and Washington, DC.

The case studies produced for this project provide information on freight-related initiatives that focus on mitigating congestion caused by, as well as improving the efficiency of, commercial vehicles in urban areas. By describing specific projects, offering the lessons learned during implementation, and providing insight on the transferability to different jurisdictions, the case studies will serve as a wonderful toolbox for planners everywhere.

1. Talking Freight Seminar Series (2003), "*Urban Goods Movement and Planning*", Transcript, FHWA, Accessible Via http://www.fhwa.dot.gov/freightplanning/nov19transcript.htm.

URBAN GOODS MOVEMENT CASE STUDIES

Urban goods movement is stimulated by the needs of business and commerce, but the magnitude is also greatly influenced by growth in population. No city can function without the ability to efficiently move goodsand planners must place more emphasis on the freight-related needs of their transportation system. In order to maintain and enhance the economic vitality and quality of life of any thriving city, steps must be taken to efficiently and effectively move both people and goods. Sustainable freight transportation supports business,commercial and community activities and mustenjoy the access and mobility required to function properly. This project serves as a resource for information covering previously implemented strategies which can be the basis for other communities to address their own issues.

The four case studies in New York, Los Angeles, Orlando and Washington DC, were selected by a steering committee after an extensive literature search was completed. The expert panel also identified candidate locations. Based on the existing application of urban area freight mobility management strategies as well as the transferability of implementation practices to urban areas throughout the country the list was narrowed to these four. It should be noted that the focus was strictly the uran part of the trip and not the over-the-road portion of the freight movement.

New York was deemed a viable case study based on its mitigation of extreme challenges in the area of curbside management. NYMTC's Regional Freight Plan, parking restriction enforcement has been enhanced throughout the city, especially in Manhattan. Though the magnitude of the parking problem another city might face may not be on the same scale as in New York, the general issues would be similar and, therefore, the solutions would be transferable. In Orlando, the establishment of "freight villages" as well as the use of its Truck Route Designation System have served as successful solutions to Orlando's high freight activity; it is located between two busy freight centers—Jacksonville and Miami. Washington, DC was selected due to its array of strategies including its curbside utilization management, truck activity management at the Convention Center and the relationship with the surrounding neighborhood as well as the development of a comprehensive motor carrier management program.

Some of the main goals were to find projects that had been implemented, were located in various geographic regions, and pertained to different categories of urban goods movements. These cities have a collection of freight mobility planning efforts which made them all strong case study candidates. The following are specific examples of sustainable freight planning efforts from each study area.

NEW YORK

As one of the nation's largest commercial centers, New York City moves more freight than any other metropolitan region in the United States. To move goods efficiently, the City makes improvements and adjustments to the management and operations of the transportation network on a continuous basis.

NOTABLE PRACTICES

Curbside Management

Midtown Manhattan is one of the nation's most active commercial centers. Many deliveries and pickups must be made to and from this thriving district by means of a physically constrained transportation system. To maintain the efficient flow of goods and services throughout this district, NYCDOT implemented several curbside management strategies indentified in its *Commercial Vehicle Parking Plan*. Commercial vehicles contribute to traffic congestion in Midtown Manhattan and are affected by it as well. The limited number of loading/unloading zones available, in addition to the number of vehicles using the spaces for long-term parking, has forced many trucks and other large vehicles to double-park, thereby reducing the capacity of the affected street by one lane of traffic.

To improve traffic flow, the Commercial Vehicle Parking Plan recommended providing additional curbside spaces for commercial vehicles, reducing the amount of time these spaces are occupied and increasing enforcement. By improving the management of loading/unloading zones in the Midtown area, NYCDOT decreased the number of double-parked vehicles, which resulted in a reduction in congestion. Initial implementation focused on the streets between 43rd and 59th and Fifth Avenue and Seventh Avenue. Because of the program's success, implementation was expanded to cover the streets between Second and Ninth Avenues.

In the newly designated commercial vehicle loading zones, New York City has replaced single-space parking meters with ticket dispensing "Muni-meters" (see Figure 1). These meters, located along each block of restricted curb space, allow commercial vehicle operators to purchase prepaid parking tickets for up to three hours. Payments can be made with quarter and dollar coins or NYC Parking Cards. Some machines now accept credit cards.

Figure 1. Muni-meter on New York City Street

***THRU* Streets Program**

Historically, midtown Manhattan has suffered from congestion. As a result, the City has developed strategies to improve traffic conditions. Average travel speeds of about four to five miles per hour along cross-town streets with little travel time reliability led to the implementation of a traffic operations improvement program called *THRU* Streets. The basic philosophy of this program, which was implemented in the Fall 2002, is to designate specific streets (*THRU* Streets) for cross-town travel and institute policies to facilitate cross town travel along these designated *THRU* Streets. Other streets were classified as "non-*THRU*" streets and policies including the designation of curbside areas for truck loading/unloading were instituted on these streets. Reducing the friction caused by turning movements and ensuring that effective moving lanes were provided on *THRU* Streets were important elements of this initiative. The *THRU* Streets initiative has helped New York City improve traffic flow within the Program area and has reduced conflicts between turning vehicles and pedestrians.

NYCDOT designated five one-way street pairs to serve as *THRU* Streets. These roads provide links between major Midtown destinations. The program restricts vehicles from turning off these sections of road between the hours of 10 a.m. and 6 p.m., which reduces congestion caused by motorists decelerating to make safe turns. It also reduces bottlenecks caused by the conflict between turning vehicles and pedestrians that often block through roads from proceeding. Vehicles may turn onto these streets from any intersection. Although the *THRU* Streets Program focused on moving all traffic through the area, several components of the plan directly affected commercial vehicle movement. Improved traffic flow on the *THRU* Streets caused a shift in volumes from several non-*THRU* Streets to the designated *THRU* Streets. Because of the reduced demand on non-*THRU* Streets, NYCDOT was able to add more commercial vehicle parking spaces. By adding Muni-Meters and parking restrictions to both sides of streets that previously had parking on one side, the City created 150 additional spaces for loading and unloading.

LOS ANGELES

As the region's largest city, Los Angeles plays an important role in developing and supporting business and trade. Because of its ideal location as a hub for global trade, its large manufacturing sector, and its massive size and population, the City of Los Angeles' transportation system carries a significant share of the nation's freight (Figure 2). Approximately 35 percent of the nation's waterborne freight travels through the gates of the Port of Los Angeles and the Port of Long Beach, also known collectively as the San Pedro Ports. The City's major airports also generate substantial amounts of truck traffic associated with the delivery of air cargo. Southern California residents and the rest of the nation depend on Los Angeles' transportation system to smoothly transport goods needed to support local, regional, and national economies.

Figure 2. City of Los Angeles Truck Traffic

NOTABLE PRACTICES

GIS Analysis

LADOT used GIS analysis to identify truck routes, truck circulation and access problems, hazardous locations, and corrective measures. LADOT undertook this project as part of the effort to develop the *Goods Movement Improvement Plan*. The first step was to identify the study areas. Phase 1 examined the industrialized area east of downtown Los Angeles. Phase 2 focused on City suburbs, including Northeast Los Angeles and the San Fernando Valley. Phase 3 covered areas not explored in the first two phases, including Hollywood, Mid-City, South Los Angeles, West Los Angeles, Los Angeles International Airport, and the Port of Los Angeles. Sub-areas were identified on an as-needed basis.

After the study area for each phase was defined, work began on the impediments to efficient goods movement. LADOT identified routes that trucks use to travel between Interstates and local freight attractors and generators by compiling truck count data and information from trucks studies from the City of Los Angeles. Truck count data were geocoded to illustrate areas experiencing high truck volumes. Using the data, LADOT calculated the truck share of all traffic on all roadways and designated de-facto truck routes. Truck routes were defined as roads that have existing truck volumes of 6 percent or greater for the downtown area and 3 percent or greater for suburban areas. These de-facto truck routes and those identified in previous studies were added to the City's GIS database. LADOT also added other information to the GIS database, such as truck-generated land uses, freeway entrances and exits, railroad grade crossings, and the percentage of trucks using specific roadway segments. Moreover, LADOT collected data on truck-related crashes that occurred over the previous five years and the Level of Service (LOS) at various intersections on designated truck routes. Locations with more than five crashes over a five-year period were geocoded.

After fully documenting the existing system in the GIS, LADOT gathered input through interviews with various stakeholders, including trucking companies, local businesses, other agencies, and elected officials. It gained input on issues that hinder efficient goods movement through and within the City. These issues were documented and, where applicable, included in the GIS database. LADOT then sent its engineers out to the field to observe problem locations identified by stakeholder input, truck-volume data, and crash data. By observing the circulation of trucks around specific locations throughout the City, LADOT engineers were able to better describe the real-world problems experienced by commercial vehicle operators. The documentation produced by LADOT engineers included the exact location, time of day, description of issues encountered, photographs, and videos.

The costs associated with the development of a GIS database will differ by agency and jurisdiction and depend on the availability of transportation-related data. Many agencies, including LADOT, maintain a database of roadways and other transportation facilities. In this case, the costs associated with the development of a freight-focused GIS database include the collection of truck-specific data, analysis, and report preparation. Although the initial cost of developing a similar database may be substantial for a smaller jurisdiction, the tool can be used by several agencies, updated easily, and tailored to meet the needs of other agencies. By creating this system of documentation and analysis, future planning efforts are enhanced.

ORLANDO

Orlando and the rest of Central Florida rely on tourism for much of its economic vitality, which in turn depends on trucks to deliver goods to a host of businesses that serve the tourist industry. Reliable and predictable travel times are especially important in a tourist-oriented economy like that of Central Florida. Over the past few decades, Central Florida has experienced heavy population growth and massive urban sprawl. As a result, traffic congestion and aging infrastructure are growing concerns (Figure 3).

NOTABLE PRACTICES

Freight Villages

The Freight Village concept regulates development in a defined area to provide sufficient infrastructure to facilitate the efficient movement of goods. Based on past and anticipated growth in Central Florida's population and economy, the number of warehousing and distribution facilities is likely to increase. Clustering warehousing and distribution facilities into a Freight Village would allow many shippers and carriers to benefit from the same infrastructure improvements.

Design Standards/Zoning Classifications

The *Mobility Strategy Plan* suggests that local jurisdictions develop a warehousing and logistics (WL) zoning category to ensure appropriate design standards for the development of Freight Villages or similar sites. Signal timing, geometric design standards, loading dock requirements, and other factors that affect goods movement also would be regulated in a WL zone.

Figure 3. City of Orlando Streetscape

METROPLAN has identified several ideal locations for a WL zoning designation in Central Florida. These areas have a concentration of industrial facilities, high volume of commercial vehicles, and excellent access to the existing transportation network. The City of Orlando has begun implementing new zoning classifications in the region south of the airport. For example, the City has developed an "airport support" zone as part of its *Southeast Sector Plan*. The airport support zone provides sufficient infrastructure to support activities vital to the operation of the airport and the efficient movement of goods.

Downtown Orlando Truck Route Designation System

Based on its *Downtown Orlando Transportation Master Plan*, the City of Orlando designated a system of truck and truck-restricted routes. The goal of the plan is to funnel truck traffic onto a few north-south facilities in order to minimize impacts on the downtown system and to better match infrastructure to freight transportation demand. The City designated four downtown roads as truck routes and required drivers to use one of the routes (SR 50, SR 408, US 441/Orange Blossom Trail, Rosalind/Magnolia Avenue) to reach the north-south road that is closest to their destination. Once on a designated downtown truck routes, trucks must travel as close to their delivery or pick-up location as possible before they may turn onto an east-west street, thus minimizing east-west travel (see Figure 2).

This system of truck routes also better matches infrastructure and traffic operations to commercial vehicle characteristics and infrastructure improvements such as larger turning radii and lane widths. Signal timing on these routes is designed to meet the needs of commercial vehicles by increasing the yellow and green signal phases to meet increased acceleration and deceleration requirements. Prior to Orlando's route designation, City roads accommodated trucks, passenger vehicles, pedestrians, and other modes of highway transportation. By restricting trucks from using several routes, the City can better meet the needs of other modes of travel in the downtown area.

WASHINGTON, DC

Washington, DC is home to a vibrant business district, a large tourist industry, important federal and local government agencies, world-renowned universities, dynamic entertainment centers, mixed-use commercial areas, and high-density residential neighborhoods. These conditions are unique do to the higher volume of federal agencies as well as the frequency of international visitors and representatives, thus the higher volume and frequency of road detours and security brigades in the area during various conferences, special dismissals, and closures. Additionally, the Washington metropolitan area, which includes the District of Columbia and Maryland and Virginia suburbs, has one of the worst traffic congestion problems in the country. Thus, the management of goods and services delivery is an important issue facing the area.

NOTABLE PRACTICES

Transportation Operations and Parking Plan

The District is home to the Washington Convention Center, a state-of-the-art facility that opened in 2003 in downtown Washington, DC. As described in the Transportation Operations and Parking Plan, the Center has a total floor area of approximately 2.3 million square feet, covering six city blocks on 17 acres, and is the largest building in Washington. Its size allows the simultaneous setup and breakdown of one convention while another one is being held. The Center can hold conventions on consecutive days, and thus produce steady transportation activity from week to week. Not surprisingly, the efficient management of truck activities such as loading, unloading, storage, and security, without negatively affecting neighboring streets, is critical to the successful operation of the Convention Center.

The Center has 72 truck loading docks, space to park up to 36 trucks along internal lay-by lanes and ramps, and capacity to store approximately 70 trucks in exhibit halls when not in use. Nearly 180 trucks can be stored within the building. The greatest truck activity, 100 to 140 trucks per day, occurs about 12 days per year. This level of truck activity can be accommodated within the Center by staging truck arrivals and departures throughout the day and utilizing the building's large storage capacity. The Convention Center also has an agreement with RFK Stadium to permit truck marshalling activities at the Stadium on an as-needed and pay-per-use basis. This allows for efficient management of truck traffic without negatively affecting surrounding streets.

Truck operations in and around the Convention Center typically are expected to occur between the hours of 7:00 a.m. and 8:00 p.m. on weekdays and are restricted to specific routes to prevent truck traffic in nearby residential neighborhoods (Figure 4). In addition, trucks are not permitted to park on surrounding streets, and all truck activity is expected to occur in the truck loading and unloading areas within the Convention Center itself. The Convention Center Transportation Manager provides this information to all contractors before an event. Convention Center public safety personnel enforce truck restrictions on surrounding streets and they monitor truck activity near the Center and report any restricted truck activity to the Metropolitan Police Department.

Figure 4. Truck Entering Convention Center

MAJOR FINDINGS AND CONCLUSION

The following are just a few of the observations regarding the sustainable strategies and practices that were identified in these case studies that can be implemented in other areas around the country. It should be noted that there were many other excellent studies identified which itemized additional strategies but there was no indication that they had been implemented. It was determined by direct contact with the authors that, in part, those responsible for implementation did so but did not document that work in any written form.

New York, Los Angeles, Orlando and Washington, DC have made great progress in improving the operation of their urban goods movement systems. However, to stay ahead of the demands placed on the system and, thereby, meet the needs of these thriving economic centers, freight planning, management and operations staff must continue to develop innovative solutions. The intent was to provide examples, a menu of possibilities, that could be applied in other communities, lessons learned and information regarding the benefits realized from implementation.

New York

- Enforced time restrictions can help clear spaces more quickly and provide more turnover in the use of limited curb space.
- Reserve spaces for commercial vehicles and concentrate the activity.
- Balance the benefits to commercial vehicles and communities.
- Understand how trucks are moving through an area and what can be done to improve the efficiency of truck movements while minimizing their impact on quality of life. Implement appropriate restrictions such as turns at limited intersections to improve overall system capacity.

Los Angeles

- Create a layer in the GIS database that defines the truck route network used to serve the area
- Use information to ensure connectivity, efficiency, adjacency, and the like
- Add additional information to the GIS database including the location of truck-generating land uses, freeway entrances and exits, railroad grade crossings, and data on truck related accidents.

Orlando

- Develop zoning classifications, such as a warehousing and logistics (WL) zoning category, to cover goods movement activities.
- Include in the zoning classification design standards such as signal timing, geometric design standards, loading dock requirements as well as other factors that affect goods movement.
- Differentiate between truck trips and vehicle trips in the development review process to determine the true impact that the development will have on the surrounding transportation network.
- Also identify and, where possible, designate key routes that will be impacted by the movement of goods to and from the proposed development.
- Focus improvements in the goods movement corridors to make them more attractive to truck drivers.

Washington, DC

- Get input from Stakeholder Workshops and/or Citizen Advisory Committees is essential to the implementation and continued success of initiatives described in this case study.

- The concept of Truck Marshalling can be used in other jurisdictions to regulate truck traffic produced by large events that would otherwise create significant congestion on surrounding roadways.
- Create a single office or single point of contact to simplify administration, which would allow parking policy to be adjusted more efficiently in response to observed changes on the streets, and reduce errors caused by miscommunication between agencies.
- Formally designate truck routes to address common concerns such as noise, vibration, and congestion. It will also remove trucks from side streets and other roadways with inadequate geometry or pavement quality for large trucks, and provide benefits to both truckers and residents.

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FM 518 Corridor Improvement Study and Implementation, Pearland, Texas

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Abstract

The City of Pearland (COP), located in Brazoria County, Texas, has witnessed an explosive population growth from 19,000 residents two decades ago to now over 92,000 residents. A critical link in COP's mobility is FM 518, a 4-lane roadway providing access and connectivity through COP and neighboring cities. The study corridor consists of a 2-mile segment of FM 518 with 11 signalized intersections providing access to a rapidly growing suburban commercial and residential district. FM 518 is among the heavily traveled arterial corridors within suburban Greater Houston Area with average peak hour flows over 3,600 vph and 4,200 vph on weekdays and Saturdays respectively. Prior to implementation of improvements, the corridor operated poorly with Level-of-Service E/F conditions, peak directional average travel time of 16 minutes, and 13 mph average speeds in the study area.

COP, in collective local agency partnership with the Texas Department of Transportation (TxDOT) and AECOM identified cost-effective traffic engineering strategies, and design and operational improvements. A phased implementation of strategies within a constrained budget and schedule resulted in optimal utilization and efficiency of infrastructure. Corridor operations significantly improved with 62 percent increase in average speeds and 55 percent reduction (8 minutes savings) in peak directional travel times. The project partnership and efforts successfully improved corridor mobility and access, enhanced business development, and has enriched resident quality of life.

Introduction

The City of Pearland (COP) is located in historic Brazoria County, Texas, and is one the fastest growing cities in the Greater Houston Area (GHA). COP is currently the third largest city in the GHA; the tenth fastest growing sub-urban area is the state of Texas; and the thirty fourth fastest growing city in the nation according to Forbes magazine, July 2007. The COP has witnessed an explosive growth in the last decade based on its geographic location; proximity to major commercial districts, facilities, and amenities in the cities of Houston, Sugarland, and Galveston; commercial and residential development opportunities and facilities; public safety and infrastructure; and a relaxing environment for residential community welfare and development. **Figure 1** illustrates the geographical location and boundaries of COP, Texas and the surrounding roadway network in the area.

The development opportunities and incentives offered in Pearland have triggered population growth in the COP, which has almost tripled in the last two decades from 19,000 to 92,600 residents as of July 2009. The rapid population growth is anticipated to continue driven by commercial, industrial, and residential developments within Pearland, Texas Medical Center (TMC), and Brazoria County. **Figure 2** illustrates the population growth trend and projections in Pearland, Texas.

A critical link in COP's mobility is Farm to Market (FM) 518, a 4-lane roadway providing access and connectivity through COP and neighboring cities. The study corridor consists of a 2-mile segment of FM 518 with 11 signalized intersections providing access to a rapidly growing suburban commercial and residential district. FM 518/Broadway Street provides the primary east-west access and connectivity through COP between Kingsley Drive and SH 35. **Figures 3 and 4** illustrate the dense commercial and residential developments, and the closely spaced 7 signalized intersections along the highly congested 1 mile segment of FM 518/Broadway Street. The COP is linked to other cities and counties within the GHA through a network of existing corridors including SH 288, Sam Houston Tollway, FM 518, SH 6, and SH 35 as shown in **Figure 1**. FM 2234 and County Road (CR) 59 are two alternate parallel relief routes to FM 518; however, currently they do not have sufficient capacity to relieve the traffic demand along FM 518. **Figure 4** illustrates the dense commercial developments and signalized intersections along the highly congested 1 mile segment along FM 518.

Corridor Needs, Issues, and Constraints

FM 518 is among the heavily traveled arterial corridors within suburban GHA with peak hour flows over 3,600 vph and 4,200 vph on weekdays and Saturdays respectively. The corridor serves as a vital route for major businesses, residential, and commercial developments in the area and is critical to the vitality, prosperity, and overall resident quality of life in Pearland. Recent large-scale multi-use developments including Shadow Creek Ranch, a 3500 acre lake themed master planned community; and Pearland Town Center, a 167-acre multi-use development with retail, restaurants, and apartments have opened on the west section of the corridor, which attract heavy traffic volumes during weekday evenings and weekends.

FM 518 has experienced severe congestion, traffic flow, mobility, and safety issues during the weekday specifically the PM peak and weekend peak periods. The weekday and weekend peak period traffic patterns along the corridor vary greatly based on trip attraction and production zones, and origins and destination locations. FM 518 and SH 288 diamond interchange is a critical point along the corridor with geometric and lane constraints, and heavy approach volumes. In the evening peak periods, the interchange experiences heavy southbound left (SBL) volumes from the SH 288 southbound (SB) exit ramp to major residential and commercial destinations east of SH 288; heavy eastbound through (EBT) volumes to major residential and commercial destinations east of SH 288; high westbound through (WBT) volumes to the Pearland Town Center, commercial developments, and Shadow Creek Ranch; and high westbound right (WBR) volumes to SH 288 NB. The long traffic queue on the SH 288 SB ramp spilled over into the SH 288 mainlanes resulting in major safety issues and concerns for TxDOT. During the weekends the interchange experiences high EBT and WBT volumes to/from the Pearland Town Center, Shadow Creek Ranch and WBR volumes to SH 288. Thus, to maintain traffic flow and progression along the corridor it was critical to coordinate traffic signals to progress EBT and

WBT traffic as well as the heavy SBL movement at the SH 288 SB Frontage Road. The study corridor continually operated poorly with Level-of-Service E/F conditions at most intersections. The prevailing poor peak hour corridor operations resulted in restricted access and connectivity to residential and commercial developments; business loss; commuter frustration; resident and employer access and mobility complaints; and recurring heavy congestion, poor air quality, and safety concerns for the COP. FM 518 peak period congestion, mobility, and safety concerns were determined to be a result of a combination of linked issues including capacity constraints, uncoordinated signal timings, lane use conditions, surrounding land use, driver origin and destination, and a lack of alternate relief routes to/from major freeways in the vicinity. **Table 1** shows the pre-improvement delay and LOS conditions at the signalized intersections along the study corridor for the weekday evening peak and Saturday peak hour conditions.

Travel time (TT) runs along the study corridor were conducted for the weekday evening and Saturday peak critical conditions. The study corridor continually operated poorly with an average weekend peak hour travel time of 16 minutes WB and 11 minutes EB over its 2-mile length. The corridor segment between Kirby Drive and CR 94/Home Depot was observed as the most congested with average speeds ranging between 5 to 10 miles per hour (mph) WB, and 15 to 20 mph EB. Weekday evening peak period travel times of 7 minutes WB and 6 minutes EB were observed along the 2-mile corridor. **Figures 4 and 5** illustrate the pre-improvement average TT and speed results along FM 518 EB and WB directions for the weekday evening and Saturday peak conditions.

Several studies and signal re-timing projects were previously conducted to improve traffic flow and operations along FM 518. TxDOT and Houston-Galveston Area Council (H-GAC) commissioned a study (by others) in year 2004 to identify transportation measures that would improve public safety and traffic flow, reduce motorist delay, and enhance air quality along FM 518 between SH 288 to SH 146. Several access management strategies identified as part of the study were implemented by TxDOT, and corridor signal timings plans were also updated along FM 518 (by others). However, due to the rapid growth and development in the area; increasing vehicular demand; and lack of alternate parallel relief routes, the corridor peak period congestion worsened with several intersections along the study corridor continually operating poorly at unacceptable LOS E or F conditions.

Project Goals, Approach, and Successful Implementation

AECOM was requested by HEB and AmREIT developments in May 2008 to perform a study to improve traffic flow and operations at the Broadway Street and Business Center Drive intersection especially the southbound left (SBL) egress traffic flow from the Shadow Creek Ranch Town Center located north of Broadway Street. As part of the study, AECOM identified several interlinked issues along the FM 518 corridor, and discussed the needs and potential relief approach with COP and the client. The COP maintained a proactive approach to develop cost-effective strategies to solve transportation issues along the FM 518 corridor as they envisioned further reduction in operational LOS due to the additional vehicular demand, land use and socio-economic conditions, and population forecasts. Based on follow-up discussions with AECOM, the COP in partnership with TxDOT commissioned a traffic engineering and operations study with a mission to optimally utilize the existing infrastructure; identify cost-efficient techniques to improve roadway geometrics and lane configurations within existing right of way (ROW); access management; and operational measures to provide immediate congestion relief and to improve traffic flow, operations, and safety along the corridor. The study approach required a collective local agency partnership and technical expertise and support from AECOM to identify critical constraints, develop strategies, design plans, and provide field implementation support within a constrained budget and schedule. The project tasks required effective communication, coordination, and teamwork between local agencies and AECOM throughout the project. Based on the COP mission and corridor requirements identified by AECOM staff during field visits and discussions with the local agencies, a phased approach was developed and selected for the corridor improvements as described below:

- **Phase I** - Develop and implement signal timing plans to improve traffic progression and coordination at the new COP signalized intersections along Broadway Street between Business Center Drive and Kirby Drive (west of SH 288) to the existing signalized intersections along the TxDOT corridor (east of SH 288) prior to opening of Pearland Town Center Mall in August 2008.

    - AECOM developed and implemented signal re-timing plans to provide traffic congestion relief.

- **Phase II** - Develop and perform traffic signal retiming for 11 signalized intersections along the congested 2 mile study corridor to improve the east-west traffic flow, progression, and coordination based on additional vehicular demand during the weekday and weekend after the opening of Pearland Town Center Mall and new residential sub-divisions in the Shadow Creek Ranch master-planned community.

    - AECOM developed and implemented signal retiming plans with critical support from COP and TxDOT to provide traffic congestion relief and improve vehicle throughput and travel times along the entire corridor. The COP and the TxDOT signal system are currently non-NTCIP compliant proprietary systems from different controller manufacturers, thus, direct field communication between TxDOT intersection signal controllers (east side) and the COP intersection signal controllers (west side) was not possible which made timing adjustments challenging. Intersections east of SH 288 were previously interconnected by TxDOT via twisted pair communication, and local controller clocks were checked to determine synchronization and communication. GPS units were installed at critical intersections along the COP and TxDOT intersections to maintain controller clock synchronization and provide a secondary closed loop system network. Based on data collected along the corridor previously by

TxDOT new timing plans were developed based on time of the day traffic patterns to optimize traffic flow, progression, and bandwidths under over saturated conditions. In addition to using common traffic signal optimization programs, bandwidth optimization methodology along with advanced controller features in the EPAC and NAZTEC controllers were used to ensure optimal cycle lengths, splits, green time distribution and utilization, and offsets.

- **Phase III** - Identify corridor improvement strategies, develop design plans, perform field construction and implementation within a constrained budget and schedule to maximize traffic flow and efficiency with minimal costs.

    - AECOM performed a traffic engineering and feasibility study to identify geometric and operational constraints, develop and analyze mitigation alternatives, and recommend feasible short-term cost-effective strategies. The objective of the study was to analyze and recommend improvements within the existing ROW and the project length threshold to avoid an environmental phase process to save valuable time and cost while providing immediate congestion relief along the FM 518 study corridor. Figure 3 graphically illustrates some of the improvements implemented by the COP.

        - **Cost-effective Construction, Striping, and Signing Recommendations**
            - Widen FM 518 corridor between Town Center and CR 94/Home Depot from a four lane thoroughfare to a six lane thoroughfare by adjusting striping and adding minimal pavement to significantly increase through capacity (based on delays, v/c ratios, and queue lengths)
            - Add a dedicated WBR turn lane from FM 518 to SH 288 NBFR (based on delay, lane utilization, queuing, and v/c ratio)
            - At FM 518 and SH 288 intersection reconfigure the eastbound left (EBL) from a dedicated left turn configuration to a shared thru-left, and the WBL from dual left (a dedicated left and shared through-left lane) configuration to a single shared thru-left lane configuration to increase EBT and WBT capacity and traffic progression (based on traffic patterns, lane utilization and operational needs)
            - Add a southbound right turn lane (SBR) on the SH 288 Southbound Frontage Road (SBFR) at FM 518 (based on delays, v/c ratios, and queue lengths)
            - Try to eliminate the cross-street split phasing along Broadway Street in favor of lead-lead or lead-lag phasing. (based on operational constraints)

    - TxDOT provided professional engineering design services and developed detailed roadway design improvement plans in-house based on AECOM feasibility report recommendations and follow-up discussions with COP to expedite the design and implementation on a constrained schedule and budget.

    - COP Public Works Department coordinated with AECOM and TxDOT to administer in-house roadway construction, signing and striping, and other local recommended cost-effective solutions with critical assistance from Brazoria County. COP saved valuable time and budget in the construction effort as it eliminated the bid phase and associated administrative costs. AECOM performed interim construction phase timing updates along FM 518 between Town Center Drive and CR 94/Home Depot to ensure mobility, traffic flow, and progression during the one month construction phase.

- After construction completion, striping and signage improvements, and signal configuration improvements completed by COP and TxDOT, AECOM performed the final Phase III timing updates along FM 518/Broadway Street study corridor to maximize vehicular throughput, flow, progression, and speeds along the corridor and minimize congestion, delay, and queuing.

- AECOM used average TT and speeds along FM 518 EB and WB as measures of effectiveness (MOE's) to determine improvements in traffic flow and progression along the corridor. In addition vehicular stopped delay was used to determine signalized intersection performance. **Figures 6 and 7** illustrate pre and post improvement TT comparisons along the FM 518 corridor during weekday evening peak and Saturday peak conditions (worst case).

- The coordinated efforts by COP, TxDOT, and AECOM helped reduce the corridor travel time during Saturday peak conditions (worst case) by 55 percent in the WB direction and 7 percent in the EB direction. Travel times along FM 518 WB and EB have improved significantly by over 8 minutes and around 1 minute respectively on a 2 mile study corridor. **Figures 8 and 9** illustrate pre and post improvement speed comparisons along the FM 518 corridor during weekday evening peak and Saturday peak conditions (worst case). Average peak hour speeds along FM 518WB have increased around 7 mph and around 3 mph along FM 518 EB during the Saturday peak conditions. A similar pattern was determined along FM 518 WB during the evening peak conditions.

Project Success and Future Steps

FM 518 corridor improvement project including study, design, construction, and implementation were completed within a highly constrained schedule and budget. With the chronic heavy congestion, poor air quality, and safety concerns associated with the rapid growth, COP worked with state and local agencies to promptly find cost-effective solutions to restore the quality of service that drivers and businesses needed. The mission was achievable due to cohesive teamwork, proactive approach, collective local agency partnership, and technical expertise to implement quality solutions within a short schedule which was critical due to the urgent need for traffic relief in the area.

The project MOE's indicated significant improvements in mobility and vehicular throughput along the FM 518/Broadway Street corridor; significant reduction in congestion and delay; and substantial improvement in the quality of service for drivers. COP has received positive feedback and response from commuters, commercial developments, residents, and officials which is an indicative measure of commuter satisfaction, improvement in residential and commercial connectivity, and overall business development. The collective agency and consultant coordination and efforts have successfully improved traffic mobility, access to residents and visitors to key destinations including employment, business, and entertainment which had enriched the overall quality of life in Pearland, Texas.

The COP is currently in the planning process to determine other candidate corridors for improving mobility, access, and connectivity in the region. COP is also coordinating with TxDOT, Brazoria County and other neighboring cities and counties to develop a local Intelligent Transportation System plan to monitor real-time traffic conditions on its roadways, improve information sharing, and coordinate activities with other public agencies.

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Table 1: FM 518 Corridor Pre-Improvement Delay and LOS at Signalized Intersections

Study Intersection along Broadway/FM 518	Weekday PM Peak		Saturday Noon Peak Hour	
	Delay (sec/veh)	LOS	Delay (sec/veh)	LOS
Kirby Drive	38.2	D	36.4	D
Town Center Drive	**79.2**	**E**	**81.1**	**F**
Business Center Drive	**79.1**	**E**	**86.5**	**F**
SH 288 SB Frontage Road	**119.8**	**F**	**248.5**	**F**
SH 288 NB Frontage Road	**110.9**	**F**	**118.6**	**F**
Silverlake Village/Smith Ranch Drive	**170.4**	**F**	**380.5**	**F**
Walmart Drive	**56.8**	**E**	**82.6**	**F**
County Road 94/Home Depot	42.4	D	**59.8**	**E**
County Road 93/Miller Ranch Road	20.7	C	**106.9**	**F**
County Road 90/Southwyk Road	25.8	C	**55.3**	**E**
Sunrise Lake Boulevard	11.2	B	35.6	D

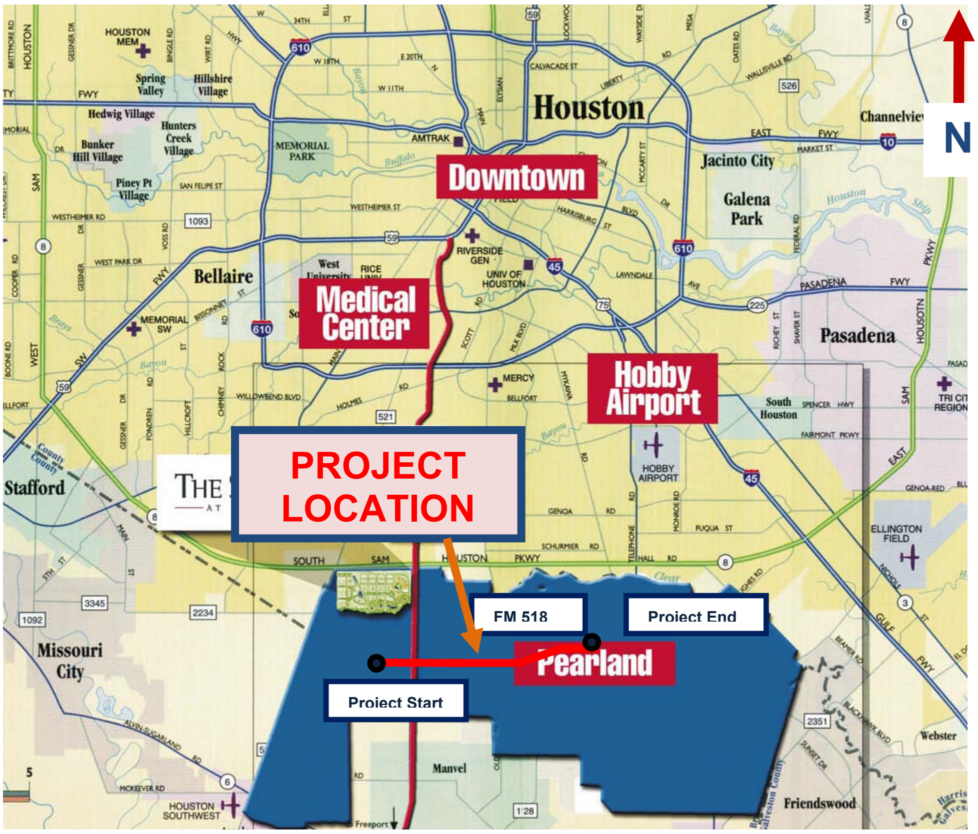

Figure 1: City of Pearland Project Location Map in the Greater Houston Area (City of Pearland, with Permission from City of Pearland)

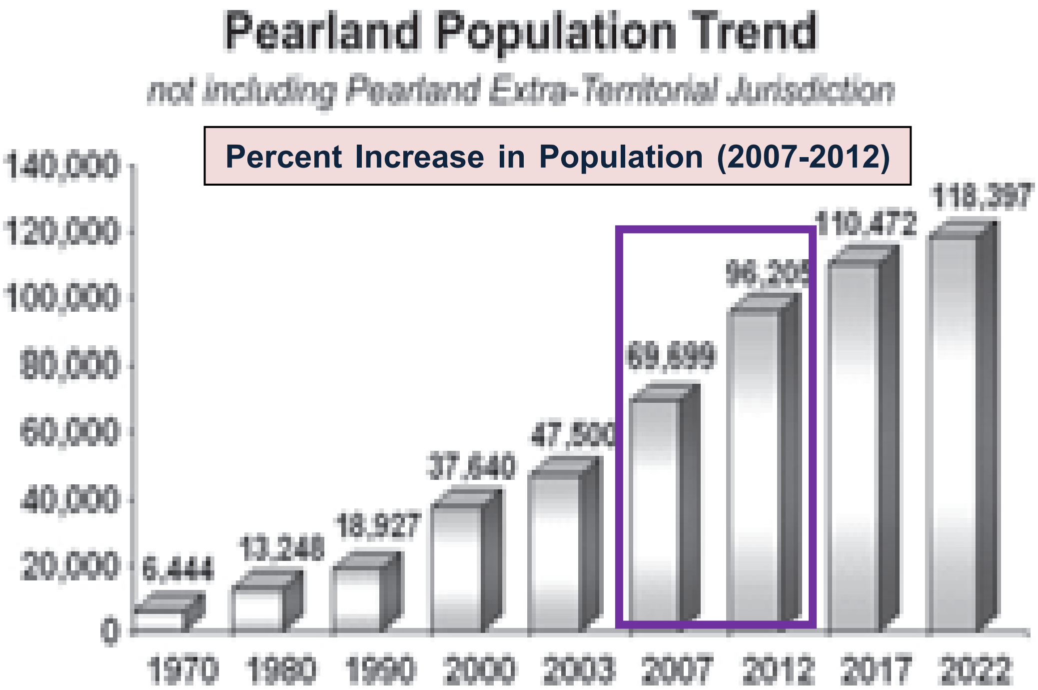

Figure 2: City of Pearland Population Growth and Forecast (City of Pearland, with permission from City of Pearland)

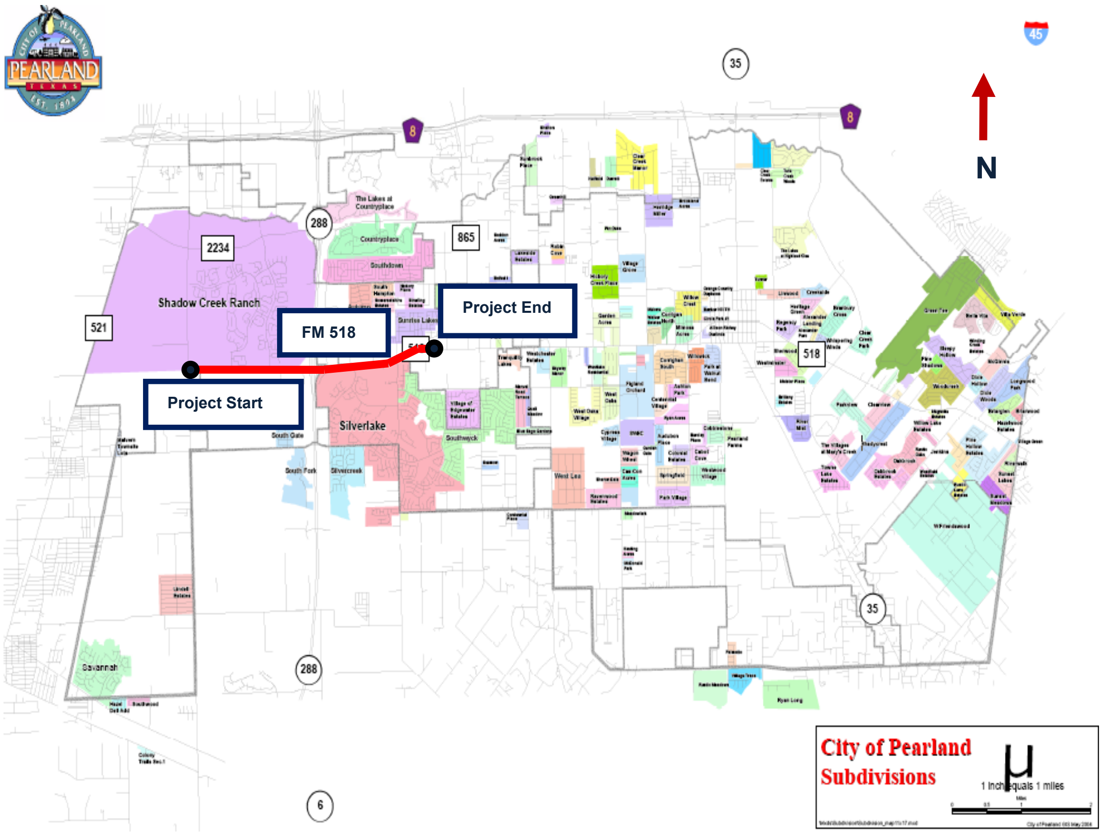

Figure 3: Residential Developments along FM 518 Study Corridor (City of Pearland, with permission from City of Pearland)

Figure 3: Large Commercial Developments along the FM 518 Study Corridor

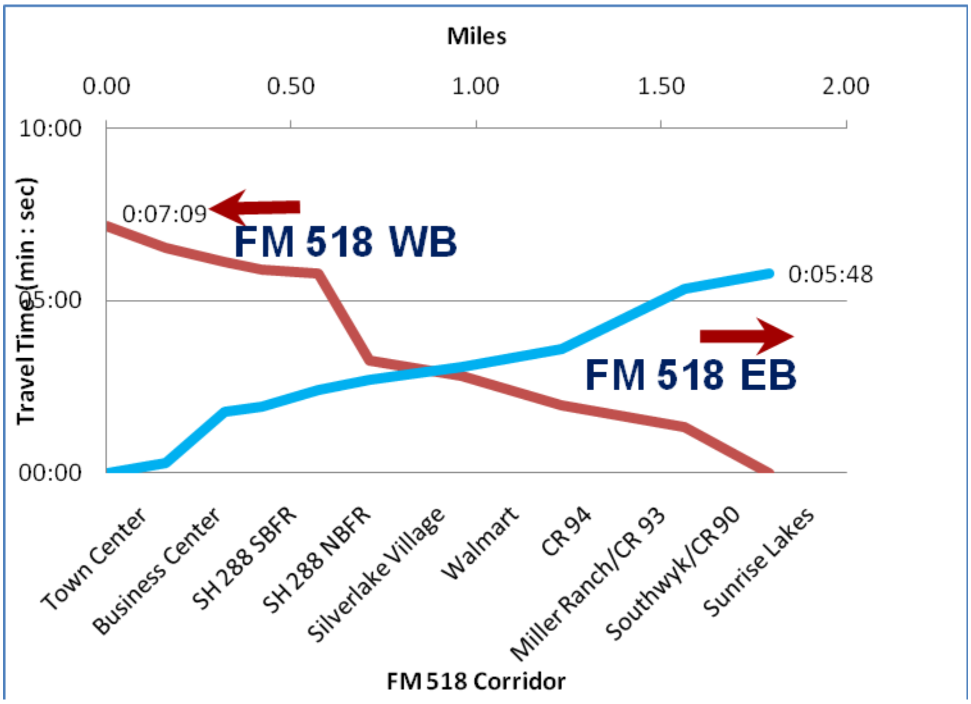

Figure 4: FM 518 Study Corridor Pre-improvement Weekday Average PM Peak hour TT

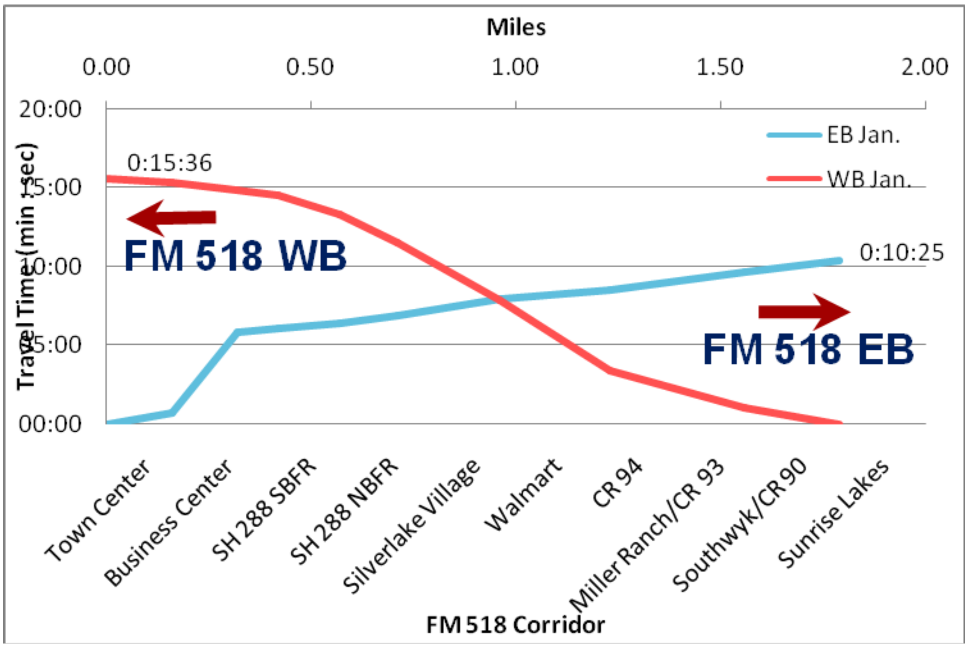

Figure 5: FM 518 Study Corridor Pre-improvement Saturday Average Peak Hour TT

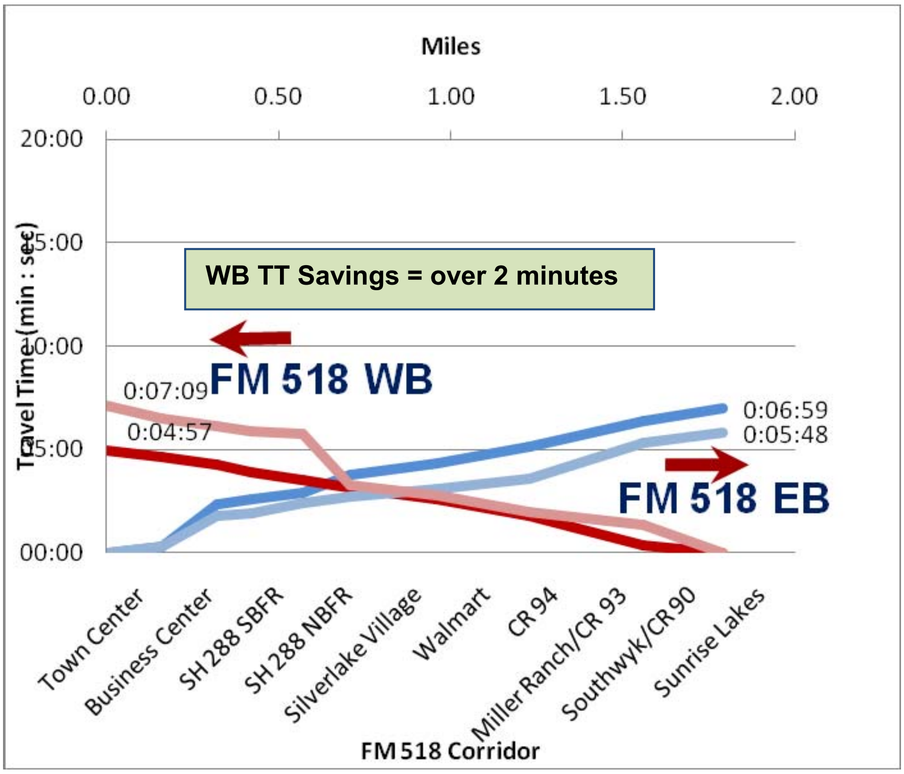

Figure 6: FM 518 Study Corridor Pre and Post-improvement Weekday Average PM Peak Hour TT Comparison

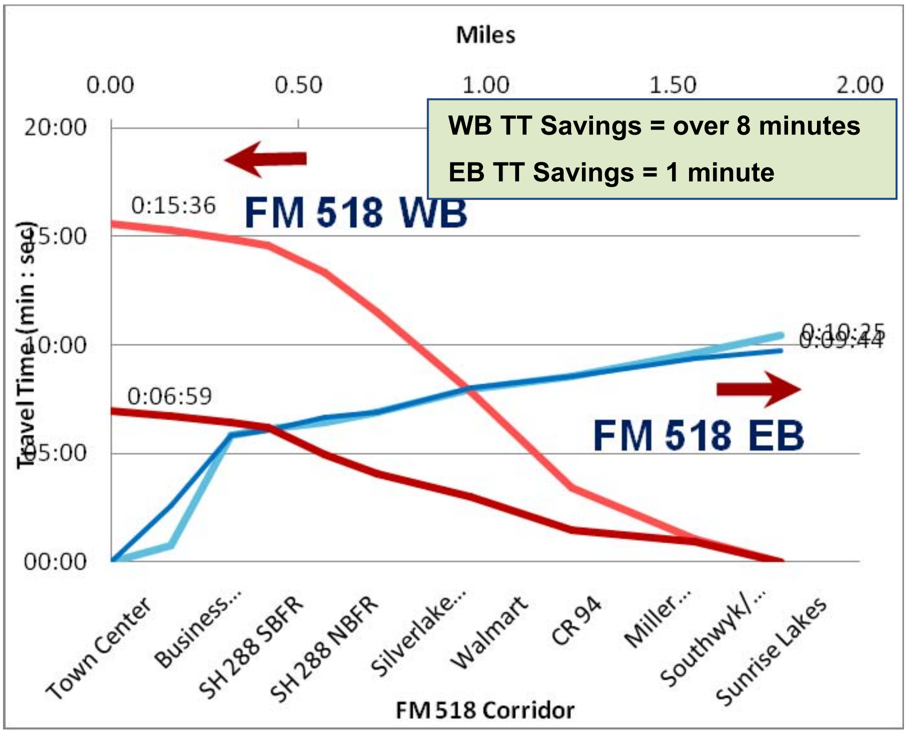

Figure 7: FM 518 Study Corridor Pre and Post-improvement Saturday Average Peak Hour TT Comparison

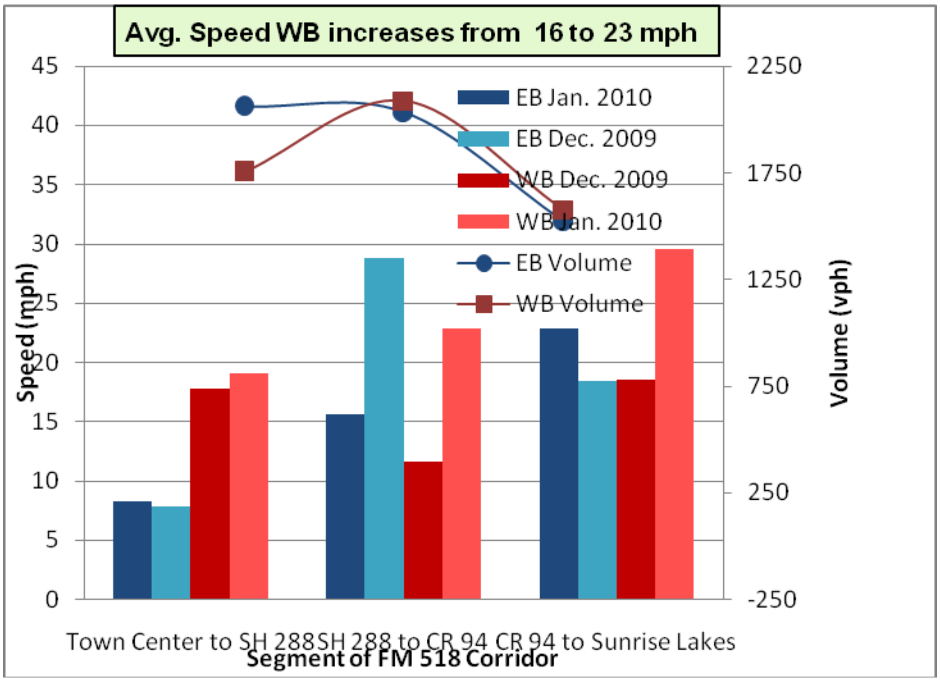

Figure 8: FM 518 Study Corridor Pre-and Post- improvement Weekday PM and Post- Average Peak Hour Speed Comparison

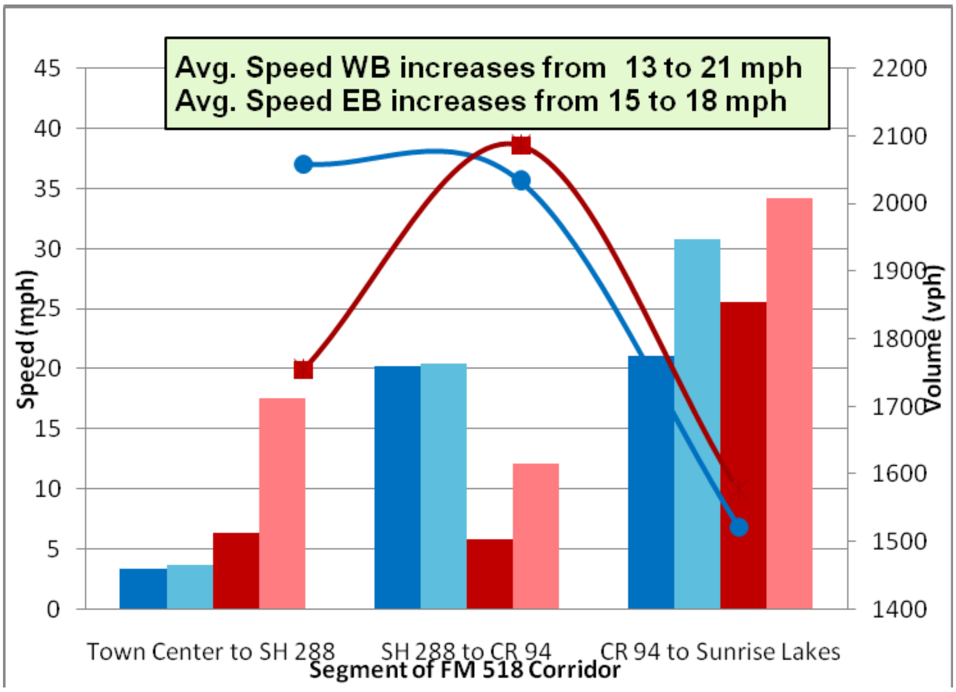

Figure 9: FM 518 Study Corridor Pre and Post-improvement Average Saturday Peak Hour Speed Comparison

Roundabouts and Sustainable Design

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Abstract

Roundabouts exhibit many of the characteristics of sustainable design: no power consumption by signal indicators; less pavement devoted to roadways; and lower vehicle energy use and emissions. Moreover, they result in lower delay and fewer crashes. Yet many states and local communities are reluctant to use this method of traffic control. The objective of this paper is to evaluate the use of roundabouts as a tool for reducing energy consumption and greenhouse gas emissions. This paper will quantify several sustainable performance measures for roundabouts used in typical applications (in lieu of traffic signals and all-way stop control). Using the City of Boulder as an example, aggregation of sustainable performance measures for a reasonable level of roundabout implementation will be evaluated to quantify the impact of large-scale use of roundabouts on emissions and energy consumption.

Sustainable Transportation Design

What is sustainable transportation? There is no one definition but a good description of the term might be "meeting our present mobility needs without compromising the needs of future generations." The goal of sustainable transportation is to protect the environment and conserve resources while taking into consideration societal needs as well as benefits and costs.[1] The modern roundabout, in contrast to other forms of traffic control, can achieve these sustainability goals. Two key characteristics of the modern roundabout include (1) a requirement for entering traffic to yield to circulating traffic and (2) geometric constraints that slow entering vehicles. Many studies have shown that modern roundabouts (hereafter referred to simply as roundabouts) can be safe and efficient, and they are now widely used internationally.

In general, roundabouts have improved both overall crash rates and, particularly, injury crash rates in a wide range of settings (urban, suburban, and rural) for all previous forms of traffic control except for all-way stop control, for which no statistically significant difference could be found.[2]

Roundabout Characteristics

Circular intersection forms have been part of the transportation system in the United States for over a century. Their widespread usage decreased after the mid-1950s, as rotary intersections began experiencing problems with congestion and safety. However, the advantages of the modern roundabout, including modified and improved design features, have now been recognized and put to the test in the United States. There are now estimated to be well over a thousand roundabouts in the United States and tens of thousands worldwide, with the number estimated to be increasing in the United States each year.[3] A modern roundabout has the following distinguishing characteristics and design features:

- Channelized approaches;
- Yield control on all entries;
- Counterclockwise circulation of all vehicles around the central island; and,
- Appropriate geometric curvature to encourage slow travel speeds through the intersection.

Figures 1 illustrates these characteristics and design features.

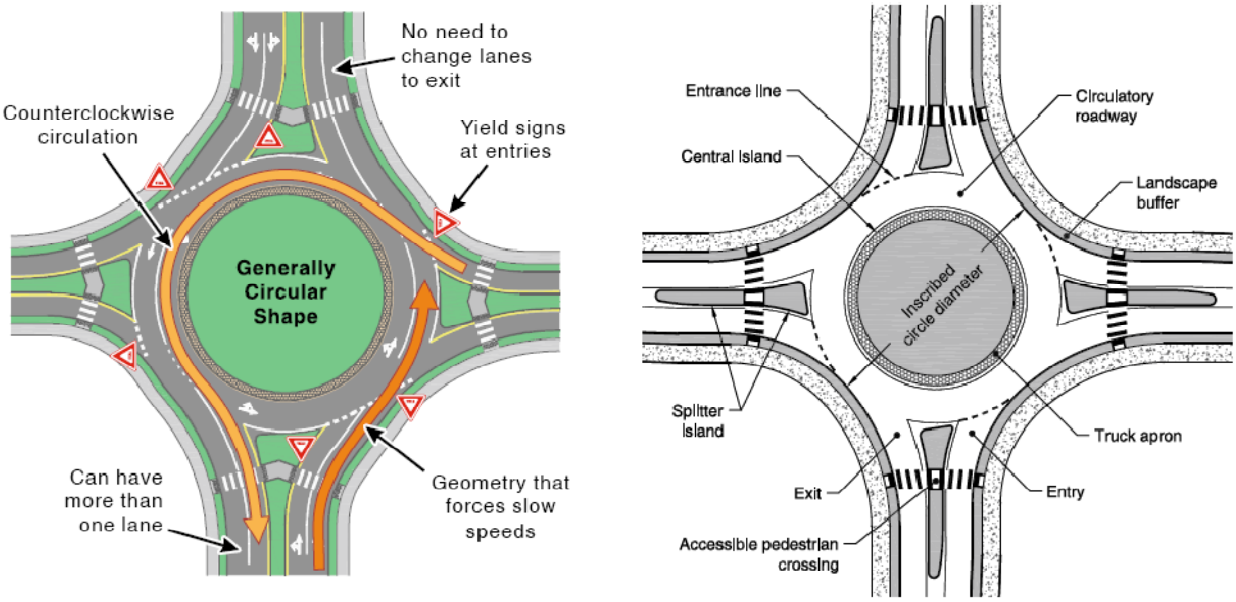


Figure 1
Key Roundabout Characteristics and Design Features

Figure 2 shows an aerial view of the roundabouts along the South Golden Road corridor in Golden, Colorado. In this case, roundabouts, in combination with access management, have reduced injury crash rates by 93 percent and reduced 85th-percentile speeds from 47 miles per hour (mph) to 33 mph while also reducing corridor travel times.[4]

Figure 2
South Golden Road Corridor, Golden, Colorado

Benefits of Roundabouts

Roundabouts are becoming more popular based on the multiple opportunities to improve safety and operational efficiency, and provide other benefits. Of course, roundabouts are not always feasible and do not always provide the optimal solution for every problem. The benefits of roundabout intersections, and some constraining factors, are described below.

- Traffic Safety – Numerous studies have shown significant safety improvements at intersections converted from conventional forms to roundabouts. The physical shape of roundabouts eliminate crossing conflicts that are present at conventional intersections, thus reducing the total number of potential conflict points and the most severe of those conflict points. The most comprehensive and recent study showed overall reductions of 48 percent in total crashes and 78 percent in injury crashes.[3]

- Operational Performance – When operating within their capacity, roundabouts typically have lower overall delay than signalized and all-way stop-controlled intersections. The delay reduction is often most significant during non-peak traffic periods. These performance benefits can often result in reduced lane requirements between intersections. When used at the terminals of freeway interchanges, roundabouts can often reduce lane requirements for bridges over or under the freeway, thus substantially reducing construction costs. However, as yield-controlled intersections, roundabouts do not provide priority to specific users such as trains, transit, or emergency vehicles.

- Environmental Factors – Roundabouts often provide environmental benefits by reducing vehicle delay and the number and duration of stops compared with signalized or all-way stop-controlled alternatives. Even when there are heavy volumes, vehicles continue to advance slowly in moving queues rather than coming to a complete stop. This can reduce noise and air quality impacts and fuel consumption significantly by reducing the number of acceleration/deceleration cycles and the time spent idling.

- Pedestrian Safety – Due to the reduction of vehicle speeds in and around the intersection, roundabouts can improve pedestrian crossing opportunities. Additionally, the splitter island refuge area provides the ability for pedestrians to focus on one traffic stream at a time while crossing. However, pedestrians with visual impairments may not receive the same level of information at a roundabout as at a typical signalized intersection, and they may require additional treatments, such as pedestrian signalization. Specific design treatments for enhancing accessibility for visually impaired pedestrians are receiving continued study.[5]

- Aesthetics – The central island and splitter islands offer the opportunity to provide attractive entries or centerpieces to communities through use of landscaping, monuments, and art, provided that they are appropriate for the speed environment in which the roundabout is located.

- Ongoing Operations and Maintenance – A roundabout typically has lower operating and maintenance costs than a traffic signal due to the lack of technical hardware, signal timing equipment, and electricity needs. Roundabouts also provide substantial cost savings to society due to the reduction in crashes, particularly fatal and injury crashes, over their service life. As a result, the overall life cycle costs of a roundabout can be significantly less than that of a signalized intersection.

- Approach Roadway Width – A roundabout may reduce the amount of widening needed on the approach roadways in comparison to alternative intersection forms. While signalized or stop-controlled intersections can require adding lengthy left-turn and/or right-turn lanes, a roundabout may enable maintaining a narrower cross section in advance of the intersection. However, roundabouts usually require more space for the circulatory roadway, central island, and sidewalks than the typically rectangular space inside traditional intersections. Therefore, roundabouts often have greater right-of-way needs at the intersection quadrants compared with other intersection forms.

Strategies to Reduce Transportation Greenhouse Gas Emissions

In a recent report to Congress, the US Department of Transportation[6] identified four groups of strategies to reduce transportation GHG emissions:

- Introduce low-carbon fuels;
- Increase vehicle fuel economy;
- Improve transportation system efficiency; and
- Reduce carbon-intensive travel activity.

The use of roundabouts would fall under the third strategy – improving transportation efficiency. However, this strategy has drawbacks due to potential induced demand effects. In fact, in its report to Congress, the US DOT did not attempt to quantify the GHG reductions due to transportation system efficiency because of the offsets of induced travel demand.

While employing roundabouts on a widespread basis could lead to some induced demand, there are compelling reasons why the overall GHG reductions would be positive:

- Roundabouts have significant benefits during off-peak periods, when induced travel would be minimal since the roadway network is generally under capacity.
- Unlike traffic signals, roundabouts react instantaneously to changing vehicle demand. If there are few conflicting vehicles present, entering vehicles can enter with minimal delay. In contrast, traffic signal systems often operate more inefficiently during off-peak periods.
- Roundabouts require all vehicles to slow down, so induced travel will be much less than a high speed synchronized traffic signal corridor or a freeway system.

Quantifying Roundabout Emissions and Energy Consumption

There have been several studies comparing the emissions and energy consumption of roundabouts to alternative forms of traffic control. Since modern roundabouts are relatively new in the United States, analytical tools are evolving. Most common traffic engineering analysis packages, such as Synchro or the Highway Capacity Software, have limited capacity to analyze roundabouts. The Australian traffic model, SIDRA Intersection (signalized and unsignalized intersection design and research aid), is capable of modeling stop and signal controlled intersections as well as roundabouts. The SIDRA Intersection model does have the capability to model vehicle emissions based on vehicle mode including cruise, deceleration, idle, and acceleration.[7] The software produces many Measures of Effectiveness (MOEs) including kg/h of CO_2 and gallons of gasoline consumed. However, the emission factors are not based on EPA's MOBILE, which is the EPA approved emission factor model. MOBILE6 is an emission factor model for predicting gram per mile emissions of HC, CO, NOx, CO_2, PM, and toxics from cars, trucks, and motorcycles under various conditions. This is EPA's most up-to-date MOBILE model and is recommended for all new modeling efforts. Since MOBILE6 is essentially a line source model, its use in comparing intersection traffic control is limited. Recent research[8] at Iowa State University used MOBILE 6 defaults in comparing an intersection with signalized vs. roundabout control and found significant reductions in emissions with the roundabout scenario. Notwithstanding the technical issues with the use of SIDRA Intersection, the use of one software package with roundabout analysis capabilities and energy and emissions MOEs led to its use in this study.

The focus of this study is to evaluate the use of roundabouts as a sustainable transportation measure. Traffic volume data from 15 existing intersections is used to compare unsignalized and signalized traffic control with roundabout control. Low, moderate, and high volume intersections are examined for both peak-hour and off-peak periods. Extrapolations of emissions and energy reductions to an annual basis are presented and compared with other sustainable transportation measures.

Study Methodology

A total of 15 Colorado intersections were selected for evaluation, five from three volume groups. The lowest volume group contains intersections with total peak-hour entering volumes between 500 and 1,000. The moderate volume group contains intersections with total peak-hour entering volumes between 1,000 and 2,000, while the highest volume group contains intersections with total peak-hour entering volumes in excess of 2,000 vehicles per hour. Table 1 shows the intersections that were evaluated and their total peak-hour entering volume.

Table 1 - Study Intersections by Group

Low Volume		Moderate Volume		High Volume	
Intersection	Total PM Peak Entering Volume	Intersection	Total PM Peak Entering Volume	Intersection	Total PM Peak Entering Volume
Ursula/16th	816	Commerce/Town Center	1,114	Sable/120th	2,266
Montbello/51st	561	Factory Shops/Memphis	1,066	Baseline/95th	2,813
Shaffer/Shaffer	558	Twenty Mile/Pony	1,077	US 6/19th	3,883
Heritage/Eagle	984	Wagon Box/Valleybrook	1,661	Old Wads/Ralston	2,518
Oberon/66th	987	Ford Street/13th	1,661	US 85/166th	2,752

Weekday evening peak-hour data for each intersection was obtained from recent traffic counts. Hourly volumes were calculated for the remaining 23 hours by using the hourly distribution data found in Table 41 of *NCHRP 365 – Travel Estimation Techniques for Urban Planning*[9], published by the Transportation Research Board (TRB) in 1998. Once a full weekday of volume data was calculated for each intersection, all 15 intersections were evaluated as a roundabout and an unsignalized or signalized intersection using the SIDRA Intersection, version 3.2, capacity analysis software. Each intersection in the low volume group was evaluated as a one-lane roundabout and an all-way stop controlled intersection with single-lane approaches. For the moderate group, each intersection was evaluated as a one-lane roundabout and a traffic signal. Finally, for the high volume group, each intersection was evaluated as a two-lane roundabout and a traffic signal. The lane geometry used for the traffic signal analysis was based on the actual existing lane geometry found at the study intersections. Existing phasing was also used, while the timings for each phase were optimized within the SIDRA Intersection software.

The SIDRA Intersection analyses provide various MOEs relating to operational efficiency, energy use, and emissions. However, this study will focus on two in particular, fuel consumption and CO_2 emissions. Both were calculated for each of the 15 intersections assuming roundabout and unsignalized or signalized control. The results for each group were averaged and compared to determine the reduction in both fuel consumption and CO_2 emissions when comparing roundabout to stop control and traffic signals. The daily results were then extrapolated to an annual quantity.

Reduction in Fuel Consumption and CO_2 Emissions

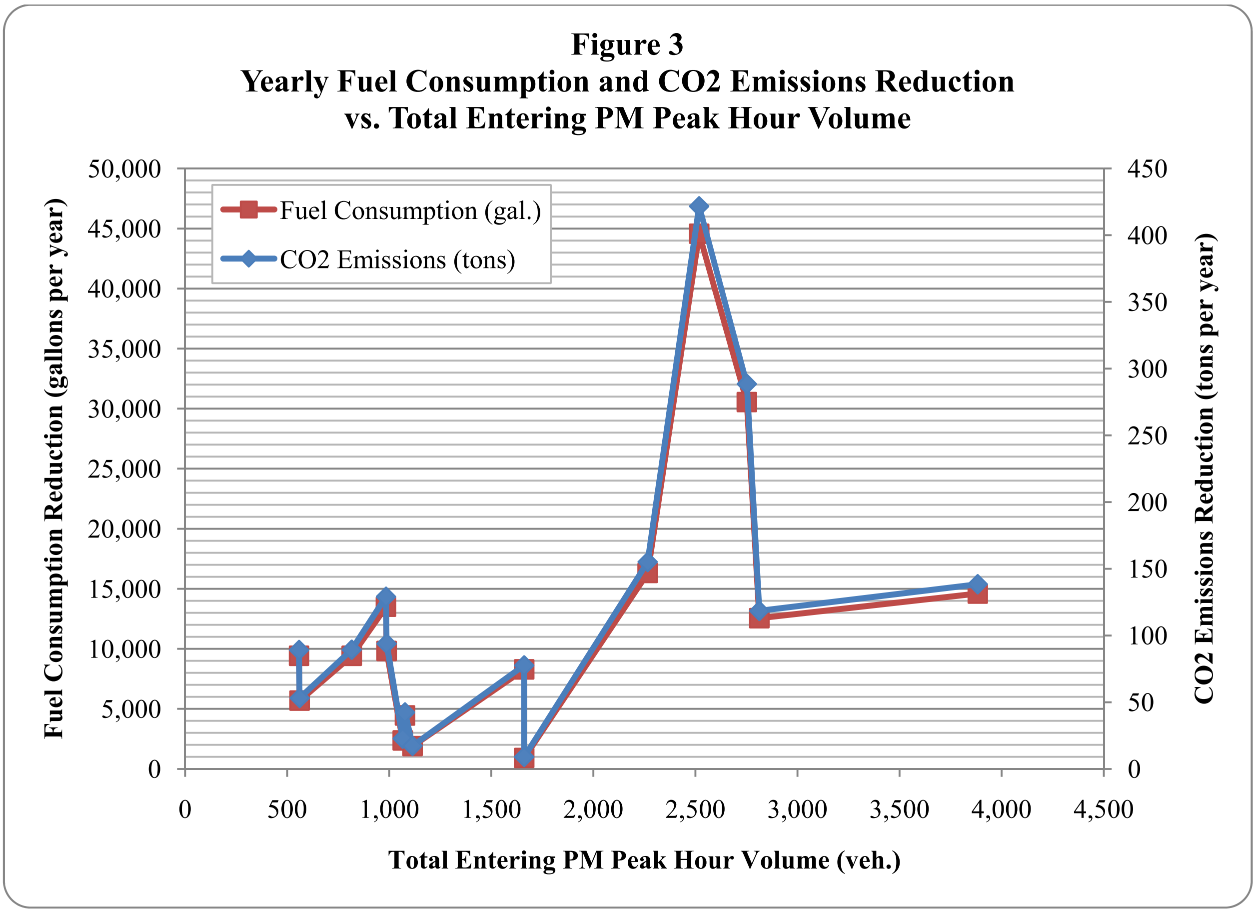
Table 2 shows the reduction in fuel consumption and CO_2 emissions when comparing roundabouts to unsignalized and signalized traffic control for each of the three volume groups.

Table 2 - Fuel Consumption and CO_2 Emission Reductions by Group

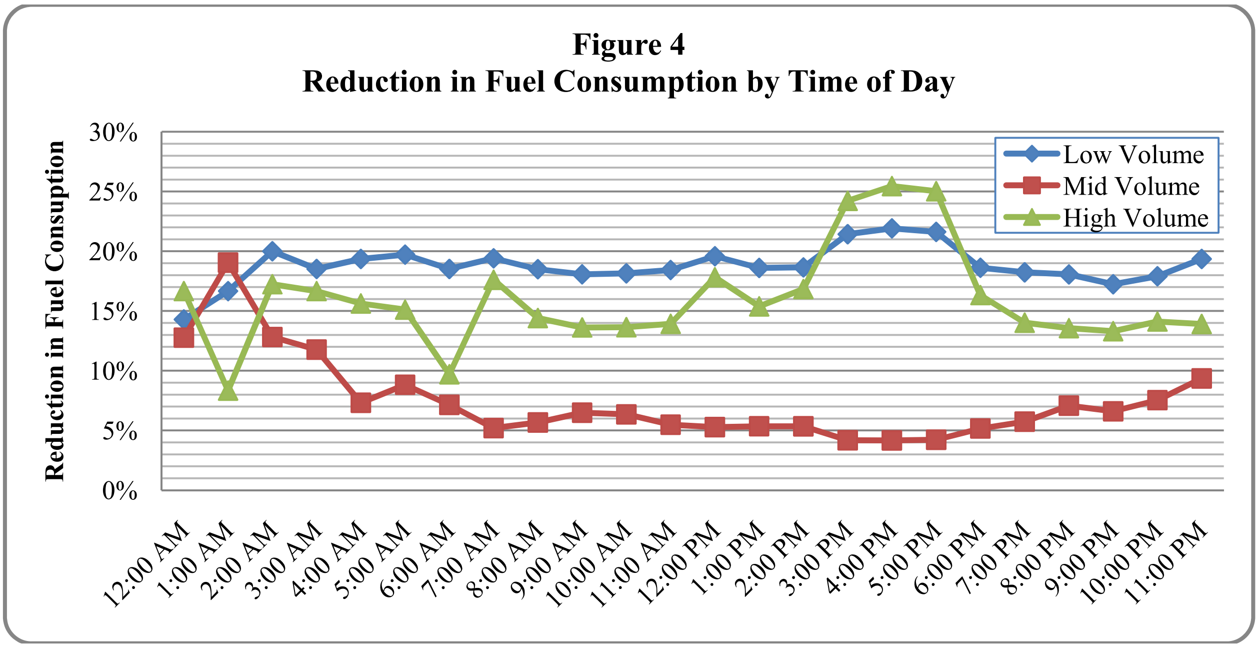
		Fuel Consumption		CO_2 Emissions	
Group	Comparison	Reduction (gal. per year)	Percent Reduction	Reduction (metric tons per year)	Percent Reduction
Low	All-Way vs. One-Lane	9,570	19.4%	90.9	19.5%
Moderate	Signal vs. One-Lane	4,000	5.6%	37.7	5.5%
High	Signal vs. Two-Lane	23,718	13.3%	224.5	13.3%

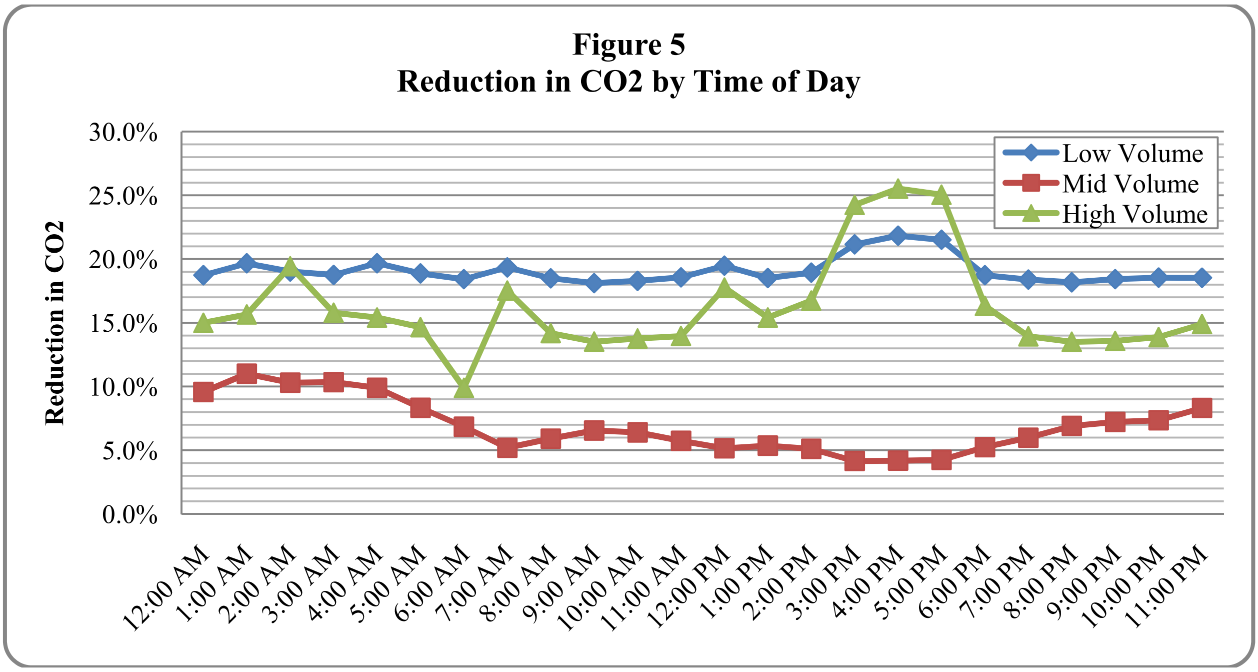
As shown, roundabout control provides significant reductions in both fuel consumption and CO_2 emissions. Reductions of fuel consumption of approximately 6 to 20 percent can be expected when roundabouts are installed instead of stop control or traffic signals. Similar benefits can be expected when comparing the CO_2 emissions of each type of traffic control. As shown in Table 2, the benefits are highest for low volume intersections where one-lane roundabouts can be installed in place of all-way stop control and those with higher traffic volumes where two-lane roundabouts can be constructed in place of large signalized intersections.

Utilizing data from all 15 intersections, a relationship between total peak-hour entering volume and the reduction in fuel consumption and CO_2 emissions can be established, and is shown in Figure 3. As shown, reductions in both fuel consumption and CO_2 emissions increase proportionally with increases in the total evening peak-hour entering volume. For low volume intersections with entering volumes of around 500 vehicles per hour, annual reductions of approximately 8,000 gallons and 75 metric tons of CO_2 emissions can be expected. For high volume intersections with total evening peak-hour entering volumes of 2,500 to 4,000 vehicles, annual reductions of 15,000 to 45,000 gallons and 150 to 400 tons of CO_2 emissions can be expected.



Finally, the reduction in fuel consumption and CO_2 emissions by time of day was also calculated. Figures 4 and 5 show these relationships for fuel consumption and CO_2 emissions, respectively. As shown, the reduction is highest during the peak-hour for intersections with low traffic volumes where all-way stop control is less efficient than a one-lane roundabout during periods of high activity. For intersection with moderate traffic volumes where a one-lane roundabout might be considered in place of a traffic signal, the benefits are highest during the off-peak when drivers are able to navigate the roundabout with minimal delay. For the high volume group, the highest reductions were once again found during the peak-hour, where a two-lane roundabout was able to better handle the large traffic volumes.





Additional Benefits due to Roundabouts

In addition to the emissions reductions associated with the operations of a roundabout, there are additional benefits that roundabouts bring when compared to a traffic signal. The power consumption that a typical moderate volume traffic signal produces results in the production of approximately 3 metric tons of CO_2 emissions per year, while a larger high volume traffic signal will produce approximately 5 metric tons of CO_2 emissions per year. If these reductions are added to those shown in Table 2, the total CO_2 emissions reduction for moderate intersections increases to 40.7 metric tons per year while the total reduction for high volume intersections increases to 227.5 metric tons per year.

As previously mentioned, roundabouts also provide significant safety benefits. Based on research found in *NCHRP 572 – Roundabouts in the United States*[3], roundabouts result in a 48 percent reduction in total crashes when compared to an urban traffic signal with a 78 percent reduction in injury crashes. All-way stop controlled intersections have similar crash rates to roundabouts. Based on crash research at by the Colorado Department of Transportation[10], a traffic signal experiences approximately 4.41 injury crashes and 10.84 property damage crashes per year. Assuming the reduction percentages in the NCHRP report, a roundabout intersection would result in approximately 3.4 less injury crashes and 5.2 less property damage crashes. Based on data compiled by the Federal Highway Administration (FHWA)[11], a minor injury crash costs approximately $54,800 while a property damage crash costs $2,740. As a result, the safety benefits of a roundabout would result in approximately $200,570 of savings per year. This is a significant cost savings when compared to the approximately $84,000 of fuel cost savings associated with a high volume intersection (30,441 gallons of fuel multiplied by a cost per gallon of $2.75).

Roundabouts as a Climate Change Strategy – Case Study

To put the emissions reduction benefits of roundabouts in perspective, the City of Boulder, Colorado, was selected for a case study. Boulder has adapted a *Climate Action Plan* and vehicle transportation was identified as the second largest sector of Boulder's GHG emissions, producing 514,000 metric tons of CO_2 in 2004, or 28% of total emissions. The City has set an emissions reduction goal of 157,000 tons of CO_2 by 2012. One strategy identified is to improve overall fuel economy of passenger vehicles by 5% which would reduce the City's GHG emissions by 28,700 tons of CO_2 in 2012, or about one-sixth of its transportation goal.

Another strategy could be converting existing intersections to roundabouts. The City has 125 traffic signals and converting 10% or 12 intersections may be feasible. Converting another 13 unsignalized intersections to roundabouts may also be conceivable. Table 3 shows a potential breakdown of these roundabouts by low, moderate, and high volume along with CO_2 emission reductions. The conversion of 25 intersections to roundabouts could achieve 2.0% of Boulder's transportation sector emissions reduction goal.

Table 3 - Reductions in CO_2 in the City of Boulder

Group	No. of Locations	Annual CO_2 Emissions Reduction per Location (mt. ton)	Total CO_2 Emissions Reduction per Year (mt. ton)	Percent of City of Boulder 157,000 Ton Goal
Low	8	90.9	727.2	0.5%
Moderate	8	40.7	325.6	0.2%
High	9	227.5	2,047.5	1.3%
Total	**25**		**3,100.3**	**2.0%**

The potential benefits to the City of Boulder could also be evaluated in terms of cost, where several of the benefits of roundabouts could be combined. Table 4 shows a summary of the annual and 20-year cost benefits if the City converted 25 intersections to roundabouts.

Table 4 - Cost Benefits in the City of Boulder

Group	No. of Locations	Total Reduction in Fuel Consumption (gal.)	Total Reduction in Injury Crashes	Total Reduction in PDO Crashes	Total Annual Cost Savings	Total 20-Year Cost Savings	Total Cost to Construct
Low	8	76,560	0.0	0.0	$210,540	$4,210,800	$4,000,000
Moderate	8	32,000	27.2	41.6	$1,692,544	$33,850,880	$6,400,000
High	9	213,462	30.6	46.8	$2,392,133	$47,842,660	$10,800,000
Total	**25**	**322,022**	**57.8**	**88.4**	**$4,295,217**	**$85,904,340**	**$21,200,000**

As shown, the annual savings for all 25 intersections would be approximately $4.3 million dollars. This is based on the reduction in fuel consumption (at $2.75 per gallon), injury crashes (at $54,800 per injury crash), and property damage crashes (at $2,740 per property damage crash). Over 20 years, the cost savings would equal almost 86 million dollars, or more than 4 times the initial 21.2 million dollar construction cost. As a result, roundabouts not only provide environmental benefits, but are also very cost effective.

Conclusions

As the Boulder cast study suggests, roundabouts can achieve sustainable transportation goals of protecting the environment and conserving resources while taking into consideration societal needs as well as benefits and costs. High volume roundabouts can reduce CO_2 emissions by up to 400 metric tons per year, reduce energy consumption by up to 45,000 gallons of gasoline per year and reduce crashes by 8.6 per year. Roundabouts should be considered an important climate change strategy and in the case of Boulder, construction of 25 roundabouts could achieve 2 percent of its transportation section emissions reduction goal. While the emissions reduction benefits of roundabout are considerable, the safety benefits are significant and combined make roundabouts an important sustainable transportation traffic control measure.

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Contextually Complete Streets

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ABSTRACT

Throughout the US and worldwide, great places can be defined as attractive, active, open, walkable, entertaining and full of people. Great places have great streets and great streets have a "place" function. Great streets are accessible, livable, safe, comfortable, and interactive. Over 130 municipalities across the US have complete streets policies. A Contextually Complete Street is a multi-modal complete street reflecting the principles of context sensitivity and sustainability. In a Contextually Complete Street, the stakeholders and context define what is meant by "complete."

This paper describes Contextually Complete Street principles and provides examples of these complete street solutions. Common themes of Contextually Complete Streets are explored and tools that can be used in achieving a Contextually Complete Street are highlighted. These tools include road diets, traffic calming, intersection design, designing for pedestrians and bicyclists, transit design features, lane restrictions, and green street options.

DEFINITION OF CONTEXTUALLY COMPLETE STREETS

A contextually complete street is a function of both the outcome of the process and the process itself. Contextually complete streets are different from complete streets in that the context and stakeholders define what is meant by "Complete." In a contextually complete street, the stakeholders define the transportation modes and facilities that need to be accommodated, which may vary from street to street (ie bus-only street, bicycle/pedestrian crossings at key locations, etc). The street solution is not a "one size fits all" and the street may not require every mode. Contextually complete streets require proactive stakeholder involvement, an inter-disciplinary team, collaboration and commitment from all stakeholders. Figure 1 illustrates the process of applying contextually complete streets.

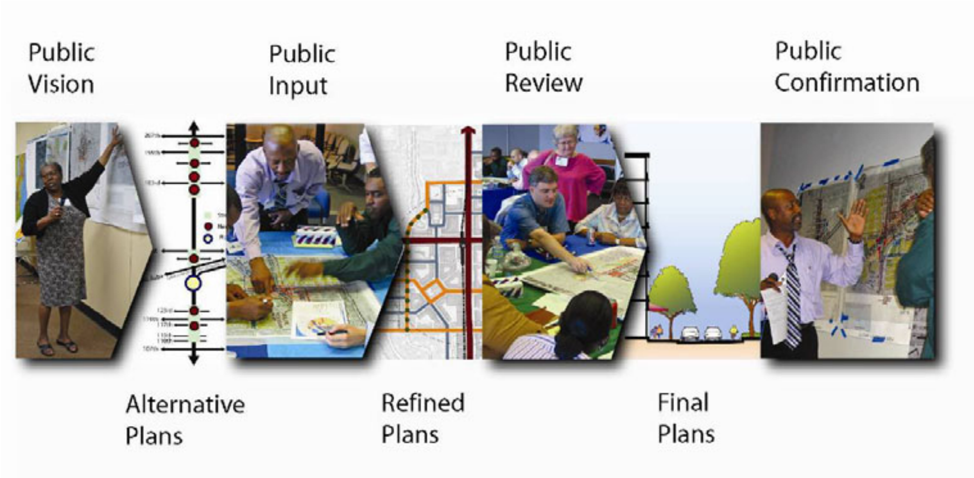

Figure 1: Proactive Stakeholder Involvement through the Project Process

CONTEXTUALLY COMPLETE STREETS PRINCIPLES

As defined above, the context and stakeholders define what is meant by a complete street. A number of principles unique to Contextually Complete Streets are identified as follows. These principles are not specific to Complete Streets alone; instead, they reflect a need to integrate stakeholder input to help shape the transportation planning process. General principles of Contextually Complete Streets include:

- Understanding and application of context
- Flexibility and creativity to shape transportation solutions
- Preserve and enhance community and natural environments
- Consideration of multiple modes
- Creation of street that is safe, accessible, and livable
- Humanize the street; transform into a destination
- Proactive stakeholder involvement and interdisciplinary team
- Development of a unique solution

There are several benefits to planning, designing and implementing Contextually Complete Streets. These benefits include:

- Public acceptance
- Humanizing the street
- Transforming to a destination
- Safety
- Revitalization
- Pedestrian activity
- Multi-modal transportation options
- Reducing greenhouse gas emissions

Figure 2 provides an illustration showing different streets in a sample transportation network and how each one is contextually unique. Each has its own function and purpose, and all work together to form a cohesive network of streets.

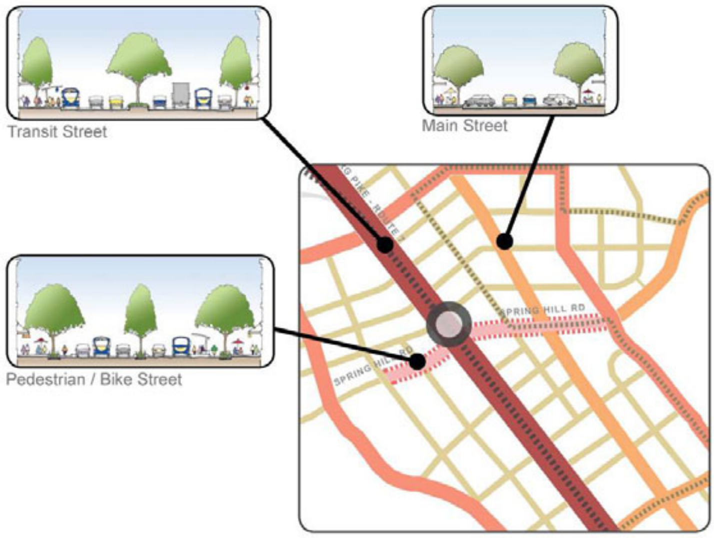

Figure 2: Context and Stakeholders Define "Complete"

CONTEXTUALLY COMPLETE STREETS EXAMPLES

Examples of Contextually Complete Streets in the United States and Australia are described in this section including the process, context and unique design features for each of the streets. The examples include Stone Avenue (Tucson, Arizona), Franklin Corridor (Eugene, Oregon), Mooloolaba Esplanade (Sunshine Coast, Australia) and 14th Street (Denver, Colorado).

The projects described below represent Parsons Brinckerhoff project examples that the authors of this paper were involved with. The projects were selected based on their representation of the principles embodied in Contextually Complete Streets, as well as their diversity in transportation components and context. Stone Avenue is a large-scale suburban example while 14th Street is a smaller-scale urban example in a downtown environment. The Franklin EmX corridor provides a transit example in street right-of-way while Mooloolaba provides an example of roadway transformation (narrowing) to create an oceanfront destination. These examples best reflect the principles of Contextually Complete Streets as defined above.

Stone Avenue, Tucson, Arizona

Stone Avenue is a north/south urban corridor that was formerly a "main drag" through Tucson, Arizona. A four-mile stretch of this street was proposed to be widened to accommodate suburban commuters. The corridor had experienced deterioration, and business owners and residents sought to revitalize the street.

A group of 18 neighborhood associations collaborated with the City of Tucson to define key issues and goals for the street which included accommodation of future travel without widening, reinvigoration of businesses and residences, and improved pedestrian safety. To improve traffic flow without widening, this corridor was modified by improving key intersections and geometrics, upgrading of traffic signals, reducing access points to minimize conflicts, and consolidating off-street parking (Parsons Brinckerhoff, 2001).

The unique design features included:

- No widening of the street
- Addition of center turn lane or landscape islands
- "Greening" of the corridor
- Integration of public art
- Improved pedestrian and bicycle crossings
- Prohibition of cross-traffic on side streets (right turns only)

Figure 3 shows side street (cross traffic) to Stone Avenue with rights only for vehicles and improved bicycle and pedestrian crossings. The Stone Avenue project has been successful with incremental improvements making a big difference. The economic assistance and incentives from the City are spurring higher density mixed-use development. The Contextually Complete Street examples exemplified through this project include flexibility and creativity to shape transportation solutions, as well as development of a street that is safe, accessible and livable. The street improvements led to a street that is more inviting, and that is safer for all users.

Franklin Corridor – Bus Rapid Transit, Eugene, Oregon

The Franklin EmX Corridor consists of 4 miles of the larger bus rapid transit (BRT) system in Eugene, Oregon. The corridor has eight stations including stops at major regional facilities (University of Oregon and the Sacred Heart medical center). The system opened in January 2007 as one of ten FTA demonstration projects for BRT. The route has experienced an 80% increase in first year ridership over the fixed route service. Twenty-five percent of riders are new transit users.

Figure 4: Franklin Corridor, *Photo courtesy of Kari Turner, Pivot Architecture*

An important part of this project was developing solutions that would reduce the overall footprint of the BRT transit way to minimize impacts on the street and surrounding uses. Key components of the Franklin EmX corridor included signal priority, queue jumping, dedicated transit-ways, median stations, public art, and sustainable features. Additionally, trees older than 50-years, classified as heritage trees by the City of Eugene, needed to be protected. By City ordinance, these trees could not be damaged or removed without a public vote.

Development of the design included investigation of the true functional minimums of lane widths on both tangent and curved transit ways, vehicle approach and departure angles from stations to assure adequate docking for near level boarding, and reversing curve radii at various speeds to allow for lane shifts across intersections. These minimums were tested through a combination of computer modeling, customized with BRT vehicles and field testing of the designed configuration to validate the model results.

The designed transit ways incorporated key innovations which include:

- Bi-Directional Lanes (shown in Figure 4) - Implementation was critical to the success of the project using a block control concept and detection system of loops and onboard transponders.
- Tree Protection – Use of reinforced grade beams for vehicle support to distribute live loads and minimize the compaction of the subsurface soils around the deeper tree root system.
- Integrated Water Quality - For portions of the corridor with separated right-of-way, the design integrated water quality strips between track like ribbons of concrete. The concept of the water quality strip provided water quality treatment before stormwater flow concentrated.

Specific Contextually Complete Streets principles embodied in the Franklin Corridor example include preservation and enhancement of the natural environment and creation of a unique transportation solution. A key to the introduction of the BRT involved minimization of the footprint and protection of the surrounding street environment. Through tree protection and integrated water quality solutions, the BRT exemplified sustainable solutions to minimize the project's impact. In addition, the project required a solution for BRT which was unique to the Franklin Corridor. Constraints in the existing street, paired with the community's vision for the project, led to this unique solution.

Mooloolaba Esplanade, Sunshine Coast, Australia

As a recreational corridor parallel to the ocean, the Mooloolaba Esplanade was experiencing increased traffic congestion and acting as a barrier between shops/restaurants and the ocean. Poor pedestrian and bicycle connections further limited access and connectivity. In addition, traffic on Mooloolaba Esplanade was creating significant noise that became disruptive to restaurant, shop and beach visitors. The solution for Mooloolaba Esplanade was to apply a road diet to reduce the number of lanes. The street was converted from a four-lane two-way street to a one-lane one-way street with short term parking, landscaping, street lighting, islands, and bulb-outs at intersections (See Figure 5).

Figure 5: Mooloolaba Esplanade, Sunshine Coast, Australia, *Photos courtesy of Steven Burgess, PB*

The results of the Mooloolaba Esplanade project include:

- Designed to fit the context and shaped by the community
- Attractive and vibrant street
- Safe and comfortable for all users
- Gathering place for pedestrians
- Retail and restaurants with outdoor seating line the street with ocean on other side

The Contextually Complete Streets principles exemplified in this project included the need to understand the area's unique oceanfront context, and the transformation of the street into a destination. The project was successful in that it lessoned the importance of the street as a through-corridor and instead allowed for outdoor dining, recreation and access to the ocean. The transportation improvements helped create a destination within the larger context, and provided greater connections to nearby destinations. In addition, by implementing a more walkable, human-scaled street environment, pedestrian activity was encouraged.

14th Street Project, Denver, Colorado

Denver's 14th Street project was initiated in 2005 to create a new identity for the corridor. This 12-mile stretch of Downtown Denver is home to a number of visitor-oriented uses including the Colorado Convention Center, the Denver Performing Arts Complex, the Hyatt Regency at Colorado Convention Center, and four other new or recently-constructed hotels. The City of Denver, the Downtown Denver Partnership and the Downtown Denver Business Improvement District came together to plan for new street improvements that would improve the multi-modal capacity of the street, create a pleasant walking environment and capture the street's entertainment context. As the project evolved, the street became known as the "Ambassador Street" of Denver, and the transportation plan needed to respond to this unique context.

The 14th Street example is a notable example of two principles in Contextually Complete Streets: consideration of multiple modes and utilizing proactive stakeholder involvement. In terms of consideration of multiple modes, it was important in this example to link decisions to the surrounding roadway network function. It was not feasible to place every mode on 14th Street (particularly buses) due to the physical constraints that exist. However, since users have access to an interwoven network of facilities downtown, they can easily connect to the surrounding streets with transit. This concept of connecting to the network is explained in detail in a number of literature sources, most recently in *Complete Streets: Best Policy and Implementation Practices* and *Designing Walkable Urban Thoroughfares: a Context-Sensitive Approach*.

In terms of stakeholder outreach, the corridor has a number of large landowners and thus the discussion on street improvements and funding for those improvements focused on the landowners. Multiple workshops were held to focus on the project vision and transportation solutions, sustainability, General Improvement District formation, urban elements, conceptual streetscape alternatives and maintenance priorities and assessment methodologies. In addition, multiple meetings were held with City Council to provide updates and gather feedback.

In the proposed plan, the one-way street configuration will be transformed from three through-lanes to two lanes with a flex lane. The flex lane will be used as a through lane in peak hours and a parking lane in off-peak hours to provide only enough capacity to adequately serve anticipated vehicle traffic. In addition, sidewalks will be expanded to 16 feet on one side and 19 feet on the other to facilitate outdoor seating and ground floor shopping. A dedicated 5-foot bicycle lane will be added in the street to attract bicyclists. Additional streetscape elements along the corridor include:

- Approximately 200 new trees,
- New flower planters,
- Better "wayfinding" signage,
- Crosswalk bulb-outs,
- Improved pedestrian lighting,
- Decorative street corner monuments, and
- Bike racks.

Figure 6 displays visualizations developed to show the future cross-section and streetscape environment on the corridor.

Figure 6: 14th Street Visualizations, *Photos courtesy of PB*

CONTEXTUALLY COMPLETE STREETS TOOLS

Tools that can be used in achieving a Contextually Complete Street include road diets, traffic calming, intersection design, designing for pedestrians and bicyclists, transit design features, lane restrictions, and green street options.

Road Diets

A road diet entails removing travel lanes from a roadway and utilizing the space for other uses and travel modes such as bike lanes, on-street parking, transit, wider sidewalks, and landscaping. The technique is commonly used to convert four-lane undivided roadways into streets with two travel lanes and a center turn lane or raised median. Resulting benefits include reduced vehicle speeds; improved mobility and access; reduced collisions and injuries; and improved livability and quality of life.

The Road Diet Handbook: Setting Trends for Livable Streets authored by Jennifer Rosales (2007) is a comprehensive guide for practitioners on the decision-making of the applicability of road diets. The handbook explains that for cost-effectiveness and natural resource conservation, road diet projects can be designed and constructed by simply re-striping the roadway and re-using the existing pavement width and curbs.

It is important to recognize that every project is unique. Design solutions for road diet project alternatives need to:

- Provide a safe and efficient transportation corridor for vehicles, buses, bicycles and pedestrians.
- Balance the needs of the transportation system with the interests of the surrounding community and the environment
- Create a transportation facility that is an asset to the community

The road diet design concept of the conversion of a four-lane undivided roadway to a two-lane roadway is shown in Figure 7. A center turn lane is recommended when driveways are present, and a landscaped center median in areas where driveways are uncommon or absent. The remaining roadway width can be converted to bike lanes, on-street parking, landscaping, sidewalks, and/or turned back to the property owners.

BEFORE **AFTER**

Figure 7: Road Diet Illustration *Photos courtesy of Todd Boulanger, City of Vancouver, Washington*

Traffic Calming

Traffic calming measures can be implemented as part of road diet projects. The *Traffic Calming State of the Practice* (ITE, 1999) provides traffic calming options that can be considered. The handbook presents examples of traffic calming measures. Traffic calming measures include:

- Narrow streets
- Pavement texturing/coloring
- Curb extensions
- Medians
- Landscaping
- Street trees
- On-street parking
- Chicanes
- Chokers
- Raised crosswalks
- Raised intersections
- Diagonal diverters
- Selective enforcement

In addition to the above traffic calming examples, roundabouts can be used for intersection traffic control to both slow traffic speeds and keep traffic moving. *Roundabouts: An Information Guide* (FHWA, 2000) is an important resource to use when considering the implementation of a roundabout.

Designing for Pedestrians

Streets have multiple uses and appropriate solutions should be selected to improve pedestrian safety and access. When designing for pedestrians, the following are key issues/actions to be addressed and/or undertaken:

- Identification of pedestrian crossing locations and exposure to potential hazards.
- Identification of missing sidewalks or pathways.
- Identification of transit zones and stop locations and provision of adequate pedestrian access.
- Both pedestrian and bicycle facilities need to be designed to be compatible with and facilitate transit use.
- Design and maintenance of landscaping to provide good visibility between pedestrians and approaching vehicles.
- Provision of adequate lighting for pedestrian safety at night.
- Comfortable sidewalks for pedestrians, with a minimum width of 5 feet, and maintained routinely.

Other sources for effective design of pedestrian facilities include: *Alternative Treatments for At-Grade Pedestrian Crossings* (ITE 2001), *Safety Effects of Marked vs. Unmarked Crosswalks at Uncontrolled Locations* (FHWA, 2002), *Design and Safety of Pedestrian Facilities* (ITE, 1998), and the *Guide for Planning, Design and Operation of Pedestrian Facilities* (AASHTO, 2004). Pedestrian facilities need to be accessible to all users, and in the U.S. meet the requirements of the Americans with Disabilities Act (ADA), and an additional resource is the *Draft Guidelines for Accessible Public Rights-of-Way* (U.S. Access Board, 2005).

Figure 8: Curb Extension
Photo courtesy of Jennifer Rosales, PB

Guidelines for installing marked crosswalks and other needed pedestrian improvements at uncontrolled (unsignalized) locations are provided in the Road Diet Handbook. To reduce the effective street crossing distance for pedestrians, the following design options can be considered:

- Narrow the street width
- Provide curb extensions (Figure 8)
- Add raised pedestrian refuge islands at intersections
- Pedestrian refuge islands as raised medians between center left turn lanes, if designed appropriately.

Designing for Bicyclists

Bicycle travel is an important element of multimodal, livable streets. Bike lanes not only improve the bicycling environment, but also provide a buffer to pedestrians. In addition, bike lanes allow space for vehicles to temporarily stop while emergency vehicles pass. They add to turning radii and improve sight lines. Important sources for bicycle facility design and treatments are the *AASHTO Guide for the Development of Bicycle Facilities* (AAHSTO, 1999), *Innovative Bicycle Treatments* (ITE, 2002), and the *MUTCD* (FHWA, 2003).

Figure 9: Bicycle lane in Portland, Oregon *Photo courtesy of Jim Hencke, PB*

Bicycle facilities may come in a number of forms, including:

- Bicycle lanes (Figure 9)
- Multi-use paths
- Sharrow - shared facilities (wider curb lane)
- Bicycle Racks

General considerations for bicycle facilities are:

- Smooth surfaces are needed for safety and comfort of bicyclists.
- Regular maintenance and street sweeping are required and pavement should be free of large cracks and potholes.
- Curb inlets for drainage or bicycle-safe inlet grates should be provided.

Designing for Transit

Transit-friendly streets need to address all of the functions of a street, including adequate space for pedestrians. Every street is unique, and thus requires a different solution. The right balance is required, since some transit modes may have the tendency to overwhelm other street activities. The integration of various modes at intersections is important, particularly at busy downtown intersections with substantial pedestrian traffic. In Figure 10, a Denver Regional Transportation District (RTD) light rail line intersects with the 16th Street Mall Shuttle in the center of downtown. Safety and visibility are key factors to maintaining separation of modes and efficient travel movements.

There are many examples of successful integration of transit with streets. The Melbourne Tram system, one of the most extensive of its kind in the world, runs in a loop through downtown in the center of the street. Pedestrians access the Tram stations via crosswalks that link them to stations in the center. The streets maintain wide sidewalks for pedestrians, with bi-directional vehicular flow.

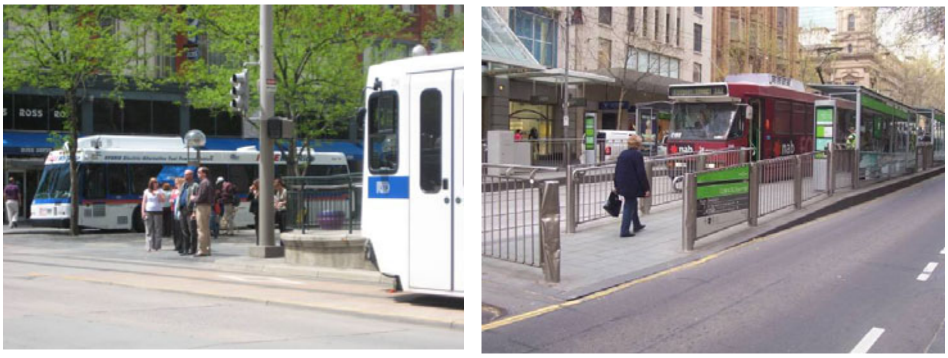

Figure 10: Transit Streets in Denver, CO and Melbourne, Australia
Photos courtesy of Lindsey Sousa, PB

On-Street Parking
On-street parking provides a buffer to pedestrians from traffic and is found to decrease traffic speeds. In addition, on-street parking meets the needs of adjacent land uses and stimulates street activity. On-street parking should be implemented based on project context, traffic volume and speed, adjacent land uses, and local parking management plans and policies.

General considerations for on-street parking are (Rosales, 2007):

- Parallel parking should be considered on urban arterials and collectors.
- Angled parking may be considered on low-speed and low-volume commercial collectors and main streets.
- On-street parking should not be considered on major streets with speeds greater than 35 miles per hour due to potential maneuvering conflicts.
- Consider the use of a curb lane for on-street parking during off-peak hours.
- Provide a minimum of 1.5-foot offset between face of curb and edge of potential obstructions such as poles and trees.
- Parking should be prohibited within 20 feet of fire hydrants or per local codes.
- Parking should be at least 20 feet to 50 feet from midblock crosswalks and at least 20 feet from the curb return of intersections (30 feet for signalized intersections). Curb extensions can be used to reduce this distance.

Lane Restrictions
Lane restrictions are one tool available to improve the function of different modes together along one corridor. Lane restrictions may isolate modes, such as bus lanes, from free flowing traffic to improve the operational capacity and efficiency of travel

(See Figure 11). The intent of implementing lane restrictions is to improve the operations of each travel mode while maintaining a safe environment for all street users. Bicyclists may be separated from vehicular traffic through colored bicycle lanes, or trucks may be restricted to certain lanes. Lane restrictions should be implemented in the context of the street, based on existing and future traffic volumes, bicycle and pedestrian traffic and transit mode share. Enforcement and signage are important elements to lane restrictions.

Figure 11: Transit Only Lanes with Bicycle Sharrows

Green Streets

A green street should both meet transportation need and apply environmental stewardship to improve the natural, built and social environments. As identified in Metro's (regional government agency for Portland Metro, Oregon) *Green Streets Handbook* (Metro, 2002), the appropriate green street design solutions and/or combination of solutions depend on the desired functions (e.g., runoff reduction, detention, retention, conveyance and water quality mitigation) and site/watershed conditions. One example of a green street treatment is shown in Figure 12. An important consideration with green streets is the need to reduce impervious surface area. However, reducing impervious surface area should not occur at the expense of accommodating multiple modes of travel (McCann and Rynne, 2010). Green streets and complete streets can be mutually beneficial, and each should consider the larger context in coming to a solution.

Figure 12: Green Street with Bio-Swale and Unit Pavers, *Photo courtesy of Jennifer Rosales, PB*

IMPLICATIONS

The principles and tools described in this paper have implications for the roadway planning and design profession as a whole. Oftentimes, the solution to a street may be predetermined prior to beginning a project. In a contextually complete street, the key is to work with stakeholders and the existing context to help define the project outcome. The sampling of techniques listed above may not apply to every project; however, these techniques should be considered by agencies in the project design process. Many of them may be new concepts that have not been tried before (ie the road diet); however, by using these tools, agencies may have greater flexibility in accommodating multiple modes in corridors with limited right-of-way.

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Quantifying Non-Motorized Demand - A New Way of Understanding Walking and Biking Demand

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ABSTRACT

Many factors influence one's decision to walk or bike when making a trip. Currently there are limited models available to quantify the demand for walking and biking. This paper describes the basic concepts to estimating non-motorized demand and introduces a new paradigm to quantifying walking and biking trip demand at a parcel level. Looking at non-motorized trips at the parcel level represents a shift towards analyzing activity at a true pedestrian and bike scale. This robust modeling approach is the first of its kind and provides a powerful tool for communities to quantify and compare actual walking and biking demand so that future transportation investments can be evaluated and prioritized. This modeling approach also serves as a tool in conveying how certain land use patterns and infrastructure investments can and do influence the way we travel. The components of the parcel-level, non-motorized model and its application are discussed.

INTRODUCTION

Throughout the United States over the last two decades there has been an ever growing movement to increase walking and biking opportunities within our communities. This movement has been spawned by a desire to make our communities more livable, to reduce our dependence on the automobile and limited energy resources, to increase mobility options, and to live healthier lives through active transportation.

The Non-Motorized Demand Model (Trip Model) is a procedure developed to estimate daily walking and biking trip demand at a parcel scale. The first of its kind nationally, the Trip Model has been used to estimate demand spatially for up to eight types of walking trips and five types of bicycle trips in two urban areas in Tennessee. It provides a powerful tool for communities to quantify and compare actual walking and biking demand so that future transportation investments can be evaluated and prioritized. It also helps convey how certain land use patterns and infrastructure investments can and do influence the way we travel.

This research paper summarizes the travel estimating process, explores how non-motorized travel estimating techniques differ from traditional auto-oriented approaches, and discusses the new approach of the Trip Model in estimating demand for walking and biking trip making.

BACKGROUND

Since the 1950s, regional transportation forecast modeling has played an important role in transportation planning in urban areas. The use and formation of transportation modeling at the regional level is firmly linked to the passage of the Federal-Aid Highway Act of 1962 which set in place the requirement of urbanized areas of 50,000 or more in population to have a continuing, comprehensive urban transportation planning process carried out cooperatively by states and local governments in order for a region to receive federal transportation funding (Weiner, 1997).

The use of regional transportation models has been an integral part of urban transportation planning since that time and has evolved over the years in response to the need to address a broader range of policy, project, and investment options. A primary objective of the travel demand model is to predict changes in travel behavior and transportation conditions as a result of proposed transportation projects, policies, and future changes in socioeconomic and land use patterns. While advancements in travel demand modeling for motorized modes (i.e. auto, transit, and freight) have been made over the years travel demand modeling for non-motorized modes (i.e. walking and biking) have seen relatively limited advancements in comparison.

This section briefly discusses the general framework of methods used to quantify travel demand specifically non-motorized demand, the factors that are largely attributed to affecting demand for non-motorized transportation, and how the parcel-level, non-motorized model fits within these current approaches.

Modeling Travel Behavior

A variety of forecasting methods has been developed to predict changes in travel behavior. Forecasting methods are generally founded on theoretical models and then verified by empirical studies, which describe how people change their behavior in response to changes in conditions which influence these behaviors. The two quantitative methods that are often used for analyzing and forecasting non-motorized behavior include:

- Aggregate Methods - Aggregate methods look at travel from an areawide perspective. They attempt to relate characteristics of an area (e.g., population, employment, or average income) to travel characteristics of that area (e.g., average number of trips per household, or the number or percent of trips made by foot or bicycle). In the context of non-motorized travel, these studies may also look at characteristics of specific facilities (e.g., roadway and sidewalk width or type) in conjunction with characteristics of the surrounding area (e.g., population density, or number of students) to predict the number of people using the facility.

- Disaggregate Methods - Disaggregate methods look at travel decisions from the perspective of the individual. The individual's personal characteristics (e.g., age, gender, attitudes, beliefs) interact with the travel options available to them (e.g., time, cost, comfort of competing modes). To predict overall demand, models of individual behavior are applied across a population with known characteristics.

Each approach has its advantages and disadvantages. Aggregate-level methods tend to be relatively easy to apply, with readily available data sources and computational methods, and can be useful for sketch-planning purposes. Disaggregate-level methods are more complicated to develop but can be much more effective at predicting behavior changes. This is because they explain individual choices rather than making generalizations based on overall population characteristics (FHWA, 1999).

Variations on both the aggregate and disaggregate approaches can be developed and applied as stand-alone travel demand forecasting methods, appropriate for specific purposes. Alternatively, a set of methods can be applied in conjunction with each other to create a larger modeling framework.

Traditional Four-Step Modeling Process

The four-step urban transportation modeling system (UTMS), first developed in the 1950s to forecast automobile travel and now applied in urban areas throughout the world is an example of such a framework. To predict how travel patterns will change as a result of future changes in land use patterns and the transportation system, this framework integrates models of various aspects of travel behavior (e.g., trip-making or mode choice) with spatial information on land use patterns and the transportation network (Weiner, 1997).

The traditional four-step travel demand model includes trip generation, trip distribution, mode choice, and trip assignment. These four stages address the corresponding questions: how many trips will be made (generation), where are trips coming from and going to (distribution), what mode will they use (mode choice), and what route will they choose (assignment). The UTMS uses traffic analysis zones (TAZs), which typically correspond to census boundaries (e.g. block, block group, or tract) and a network of transportation facilities (e.g. roadways, transit routes) connecting the zones.

While the traditional four-step travel demand model is the most universally accepted modeling process used throughout the world very few urban areas actually use or have the capabilities to forecast non-motorized demand using these models. This is largely because factors that could influence the decision to walk or bike are not usually included in the traditional four-step model process. Standard travel demand modeling procedures generally predict total trip-making and mode choice based on a limited number of variables, such as household characteristics and the time and cost of competing modes. However, these factors only partially explain the decision to walk or bicycle (FHWA, 1999).

Factors Influencing Non-Motorized Travel

Development of non-motorized travel forecasting methods requires consideration of a range of factors specific to non-motorized modes. From an individual perspective, personal factors, environmental factors, and trip characteristics interact to determine whether a trip is made by foot, bike, or other mode. The specific factors are unique to walking and to bicycling (Weiner, 1997).

Past studies of non-motorized transportation collectively identify a broad range of factors that influence the level of non-motorized travel. These factors include:

- Perceptions and Attitudes - safety, convenience, time, cost, and cultural awareness/support
- Socioeconomic and Demographic Characteristics - age, sex, race, and income
- Trip Characteristics – trip distance, travel conditions, presence and quality of sidewalk and bikeway facilities
- Environment – land use and land use patterns, connectivity, attractions, street layout and design features, weather, and topography

A common theme that runs through each of these factors and is continually mentioned in research is distance. Distance is identified by both walkers and cyclists as the major disincentive to walk or bicycle more frequently (FHWA, 1992). Despite this understanding, little actual advancement has been made in refining non-motorized demand modeling approaches to better account for factors associated with distance.

Methods for Modeling Non-Motorized Demand

The *Guidebook on Methods to Estimate Non-Motorized Travel* published in 1999 is widely referenced when it comes to understanding methods of quantifying and forecasting non-motorized travel demand. The *Guidebook* presents eleven types of quantitative methods that can be used to forecast non-motorized travel demand or that otherwise support the prioritization and analysis of non-motorized projects. Table 1 describes those methods that derive quantitative estimates of demand:

Method	Description
Comparison Studies	Methods that predict non-motorized travel on a facility by comparing it to usage and to surrounding population and land use characteristics of other similar facilities.
Aggregate Behavior Studies	Methods that relate non-motorized travel in an area to its local population, land use, and other characteristics, usually through regression analysis.
Sketch Plan Methods	Methods that predict non-motorized travel on a facility or in an area based on simple calculations and rules of thumb about trip lengths, mode shares, and other aspects of travel behavior.
Discrete Choice Models	Models that predict an individual's travel decisions based on characteristics of the alternatives available to them.
Regional Travel Models	Models that predict total trips by trip purpose, mode, and origin/destination and distribute these trips across a network of transportation facilities, based on land use characteristics such as population and employment and on characteristics of the transportation network.

Table 1 - General Types of Quantitative Estimations of Demand (FHWA, 1999)

The Trip Model includes both aggregate behavior and sketch plan methods. Portions of this can be seen in the Trip Model through its use of population, household, and land use data as well as its use of calculations associated with trip lengths, and travel behavior. The Trip Model also emulates aspects of a regional travel model in the sense that total trips by trip purpose and mode are derived and the fact that origins and destinations are a major driver in the probability of a trip. The only aspect the Trip Model does not achieve at this time is assignment in the context of a four-step modeling process.

THE PARCEL-BASED APPROACH

Current practice generally makes trip predictions over a relatively large area, the TAZ being typical. Since most bicycle trips are less than three miles and most walking trips are less than one-quarter mile, the accuracy of even homogenous TAZ-based estimation may be compromised where TAZs are any larger than approximately one-quarter square mile (160 acres). Conducting analysis at the smallest possible land unit, the individual parcel, represents a major step forward in demand estimating because it most closely approximates an individual's decision in making a non-motorized trip.

The Trip Model was developed to use each parcel's demographic information and proximity to other land uses to predict how many walking and/or cycling trips a parcel will likely generate. The generation rate takes the general form of the equation:

$$T_A = \sum_{p=1}^{n} H_P \times \left(\sum_{t=1}^{k} F_t \times I_t \right)$$

Where T_A = Number of non-motorized trips within study area
H_p = Number of households in the parcel[1]
F_t = Unique function multiplier by trip type
I_t = Distance impedance multiplier by trip type
n = Number of parcels in the study area
k = Number of trip types analyzed

The estimated number of daily trips in this procedure, then, depends on the number of households within the parcel, the type of trip being made, and the distance from the origin to the destination land use.

IMPACTS OF TRIP TYPES AND DISTANCES

The National Household Travel Survey (NHTS) provides the most comprehensive national-scale, non-motorized trip data. This data set is the basis for much of the trip type and distance impedance factoring used by the Trip Model. The Trip Model analyzes eight different walk trip types and five different bike trip types based on NHTS data and other sources (US Census, ITE, etc.) to establish total walking and biking trip demand. A unique function multiplier was developed from these data sources for each trip type to describe the trip making characteristics of each. For example, the employment density within a walkable area surrounding a parcel is used to estimate the likelihood of walk to work trips from that parcel. The trip types are: walk to school, walk to work, walk to recreation, walk to shop, walk to errand, walk to transit, walk from transit, walk from parking, bike to school, bike to work, bike to recreation, bike to shop, and bike to errand.

In addition to the propensity of different trip types to generate varying numbers of non-motorized trips, the inverse relationship between the distance separating the origin and destination and the probability of making a non-motorized trip is critical. The distance impedance factor is determined as a polynomial function describing the decreasing probability of making a walk or bike trip as the distance of the desired trip increases. Walking trips have different impedance factors than biking trips and both are shown for selected trip types in Figure 1.

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[1] Generally households are used, but some trip types, such as walk to errand, do not consider households as the trip origin. Other factors are used as trip origins for these trip types.

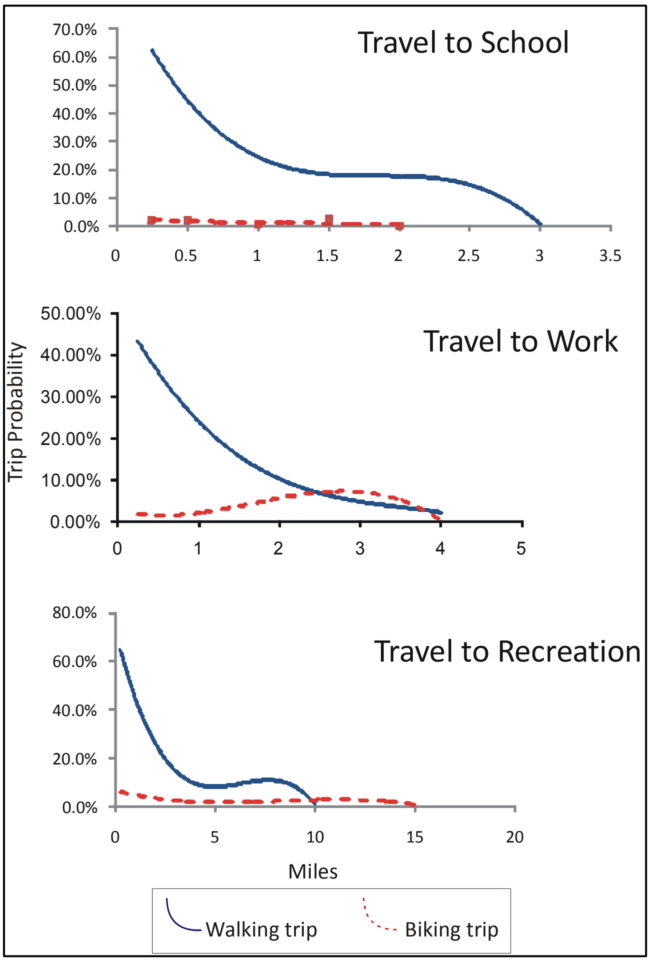

Figure 1 - Distance-Impedance Curves for Selected Trip Types

A characteristic to note is that no trip type was found to have zero impedance (the trendline does not intersect the y-axis at 1.0) no matter how close the origin and destination. Also of interest is the fact that only under rare conditions was the impedance of a trip by bicycle lower than that of a trip by walking. This corresponds to research explaining the significant level of complexity in choosing to bicycle over that of choosing to walk (FHWA, 1992).

APPLICATIONS AND LIMITATIONS

Data Requirements

Analyzing non-motorized trip demand on the parcel level presents new data requirements, though none are exceptionally specialized. Having the per-parcel data shown in Table 2 allows estimation of all 13 trip types. Most urban area planning departments will already have these data, or they can be produced relatively easily. A standard GIS platform will produce the Trip Model, though computing times for larger data sets (>250,000 parcels) may be slower than desirable. The computing time limitation was found to currently restrict non-motorized travel as an effective MOE in large-area land use scenario planning.

Data Required for 8 Walking Trip Types	Data Required for 5 Bicycle Trip Types
No. of households per parcel	No. of households per parcel
No. of employees per parcel	No. of employees per parcel
No. of employees within 1.5 miles of parcel	No. of employees within 3 miles of parcel
No. of parking spaces (major lots or garages)	Distance to the nearest recreational space
Distance to the nearest recreational space	Distance to the nearest retail area
Distance to the nearest retail area	Distance to the nearest school
Distance to the nearest school	
Distance to the nearest transit stop	

Table 2 - Data Requirements of the Trip Model

Trip Model Assumptions

Perhaps the most significant assumption of the Trip Model is that the quality and presence of the facilities required to make the walking or biking trip are assumed to be ideal. This includes uninterrupted connectivity of facilities at regular intervals that are in good condition. This assumption may be close to the actual conditions in urban downtown settings, but is far from the reality in many suburban and rural areas. This is not necessarily problematic, however, once it is understood that this method assumes perfect non-motorized travel conditions and connectivity. In fact, idealizing all networks can be an advantage to practitioners analyzing the potential use of new facilities that are to be provided.

The Trip Model assumes that all trip type land uses are equivalent as is the travel population. The accuracy of the Trip Model, however, can increase with the quality of the land use and demographic data available. For instance, research relating pedestrian rates to low-income areas could be used to better predict non-motorized travel demand in specific low-income neighborhoods.

Variable Reporting

Aside from an increased level of detail, estimating generated trips at a parcel level allows flexibility in reporting walking and cycling trips. Trips can be reported on the parcel level, but were found to be more useful and meaningful when reported by larger areas such as blocks or neighborhoods. Trips can also be aggregated to a street network to allow a roadway segment analysis of non-motorized trips.

SUMMARY

The desire for non-motorized travel facilities continues to increase, though, in all but the most major urban areas, bicycle and pedestrian travel is not having an appreciable effect on congestion levels or other traditional measures of transportation efficiency. An incrementally adjusted UTMS process which was developed in the 1950s for vehicular travel has severe limitations when used to estimate walking and biking demand. While more work is needed, the development and use of the Trip Model procedure has shown that a fine-grained, parcel-based analysis of non-motorized trips is possible and such an approach represents improvements to the demand modeling practice.

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'Regional Trail Spines and Bikeway Networks

A Priority Strategy for Greening Streets and Highways'

By Spencer Finch, Director, Pennsylvania Environmental Council; Marc Morfei, Pennoni Associates

Introduction

Transportation investments in America throughout history have come at many different scales and from varying funding sources. Over time, investments have varied from public to private sources and back: From the private investments in construction of tolled "turnpikes" to connect the original 13 colonies; to a shift to public investment in the mid-19th century, best exemplified by Abraham Lincoln's support for "internal Improvements" early in his political career and for railroad construction subsidies later[1]; from private investments in streetcars and streetcar suburbs in the turn of the 20th century; to the Eisenhower-era public investment in the national interstate highway system.

Today, America is again trying to decide how best to fund repairs to its aging transportation infrastructure and what kinds of innovations will be needed in the 21st Century. The American Society of Civil Engineers reports every year on the state of American infrastructure. The assessment is poor. In 2009, America's best ranking stood at a "C plus" for Solid Waste facilities, while Drinking Water, Inland Waterways, Levees, Roads, and Wastewater infrastructure all stood at the opposite end, each with a "D minus"[2].

The State of Our Roadways

What these grades reflect is the sorry state of repair and maintenance of critical pieces of public infrastructure. For America's roadways, for example, the ASCE (and many other professionals in the field) sees safety, congestion and wear and tear on the infrastructure as the major issues that need to be addressed. On safety, the latest statistics (from 2007) showed that over 41,000 people died and nearly 2.5 million were injured that year, costing the US over $230 billion, or $819 per taxpayer in medical costs, lost productivity, travel delays, workplace costs, insurance costs, and legal costs[3].

On congestion, the average daily percentage of vehicle miles traveled (VMT) under congested conditions rose from 25.9% in 1995 to 31.6% in 2004, with congestion in large urban areas exceeding 40%. Americans spent 4.2 billion hours a year stuck in traffic at a cost of $78.2 billion a year in wasted time and fuel costs--$710 per motorist. And as a result

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[1] Emerson, Jason. "Abraham Lincoln as a Defender of Improved Transportation", Defense Transportation Journal, Feb 1, 2009. http://www.allbusiness.com/government/government-bodies-offices-regional-local/11808853-1.html

[2] ASCE 2009 Report Card for America's Infrastructure, http://www.infrastructurereportcard.org

[3] Same as above, Roadways section. http://www.infrastructurereportcard.org/fact-sheet/roads

of increased congestion, total fuel wasted climbed from 1.7 billion gallons in 1995 to 2.9 billion gallons in 2005.

On state of good repair, while percentage of VMT occurring on roads classified as having "good" ride quality has steadily improved, the percentage of "acceptable" ride quality steadily declined from 86.6% in 1995 to 84.9% in 2004, with the lowest acceptable ride quality found among urbanized roads at 72.4%. The 2007 I-35 Mississippi River Bridge collapse in Minneapolis was just an indicator of what can happen when investments in monitoring and maintenance of infrastructure do not occur.

Though the NTSB investigation[4] of this collapse eventually concluded that a combination of design flaws (design of gusset plates) and construction flaws (possible mistakes in constructing these plates) had probably been major contributors to the disaster, the lack of a maintenance program that "saw the big picture" was one also of the lessons learned during the investigation. In other words, the gusset plates were undersized for the structural requirements the bridge was going to see throughout its design life (a design or construction flaw), but the maintenance procedures also missed these major issues that added to the level of risk and eventually led to the collapse:

- Regular maintenance and repaving of the bridge roadway added at least 20 percent additional dead load on the structure, and the long time span of these additions were not flagged by the regular maintenance and management procedures for the structure
- The bridge was being repaved again during the collapse, and significant amounts of heavy construction equipment and materials were on the bridge, increasing the dead loads even more, probably beyond design capacity
- No regular inspections of the bridge safety features were performed, beyond periodic corrosion analysis

Approximately 75,000 other bridges in America had the same classification as the I-35 bridge at the time of the collapse, "Structurally Deficient". The ASCE estimated that $930 billion per year would be required to keep America's roads and bridges in a state of good repair. With current estimated expenditures of $380.5 billion, a $549.5 billion gap remains between what is needed and what might be available at current spending levels[5].

State of Our Funding

Pennsylvania is known as the "Keystone State", and in transportation that designation carries even more weight. As an example, approximately ten percent of national rail freight

[4] National Transportation Safety Board, Collapse of I-35W Bridge, Minneapolis, Minnesota, August 1, 2007-Accident Report. http://www.ntsb.gov/publictn/2008/HAR0803.pdf
[5] Same as footnote 3.

traffic passes thru the state every year, and its fifth-largest network is an indispensable link between the Northeast, the South, and the Midwest of the country[6].

Being a keystone does not in itself guarantee the quality and permanence of the network. In 2005, Governor Rendell created a Transportation Reform Commission specifically to address the then-latest crisis in state transportation funding[7].

For highways and bridges, the state's dedicated funding sources were not keeping pace with construction cost increases, and the Federal funding formulas were not being as beneficial to the state as they had been in the past. Pennsylvania had more than twice the percentage of structurally deficient bridges than the national average, and more than a third of the 21,000 miles of state-owned secondary roads were rated "poor." Pennsylvania's state-owned bridges were on average 50 years old. Some preventive maintenance was being deferred, and much of the network infrastructure was approaching an age that would require more significant rehabilitation or replacement.

On the operating transit side, four major items created an even more acute crisis that reached a crescendo at the end of December 2006. These factors included the loss of federal operating funding, the reliance on limited state revenue sources, and the impact of inflation (which resulted in operating shortfalls). In addition, the effects of these revenue shortfalls were exacerbated by the long-term dramatic growth in costs for items such as fuel and healthcare, and financial market conditions that reduced interest income and increased pension costs.

On the transit capital improvement funding side, a chronic investment backlog was the norm. Federal and state capital funding were insufficient to maintain a state-of-good-repair for transportation assets and to invest in technology and other high return-on-investment projects. This led to less reliable, less attractive and less efficient service, with potential results including lower ridership, lower revenues, and higher operating costs.

The Reform Commission recommended the creation of more dedicated funding sources ($960 million per year for highways and bridges, $576 million for transit) and the implementation of cost saving measures at the tune of $120 million per year (including streamlined project delivery, better asset management strategies, implementation of intelligent transportation and transportation management strategies, public-private partnerships, and right-sizing initiatives).

The Commission's report led to the passage by the PA Legislature of Act 44 of 2007, which found $750 million in annual dedicated funding for the state's transportation system. Yet the stability that Act 44 initially provided was short-lived. One of its main sources of funding was to have been additional toll revenues on the state's Federal Interstate highways. After much wrangling, the state's latest proposal to fill the toll revenue stream was rejected by

[6] American Association of Railroads, Class I Railroad Statistics.
http://www.aar.org/~/media/AAR/Industry%20Info/Statistics%202010%2004%2012.ashx
[7] Pennsylvania Transportation Funding and Reform Commission, Final Report, November 2006.
ftp://ftp.dot.state.pa.us/public/pdf/TFRCReport/04FinalReportExec%20Summary.pdf

the FHWA multiple times in 2009 and 2010, and thus the state saw itself in the grip of a new annual gap of $472 million[8].

In addition, the world continued to change in the five years between 2005 and 2010. Current revenue sources are being quickly outmoded by changes in technology, vehicle efficiency, and soaring construction material costs. At the Federal level, SAFETEA-LU (the latest Transportation authorization bill) ran out at the end of 2009, and 2010 has seen Federal transportation funds being allocated once again on temporary extensions of the Transportation bill.

Finally, the world economic crisis has deeply impacted the state and Federal economies, creating additional revenue gaps. Pennsylvania sees itself again in crisis mode, and Governor Rendell, in his last year in office, has called up again an extraordinary Summer Legislative Session to attempt to address the transportation funding issues, and "leave the house at least partly in order" for his successor.

Prioritization Strategies

With the world economy still facing the effects of the global financial meltdown, engineering professionals and policymakers must be pragmatic and face the fact that funding will continue to be a challenge for a long time to come. Accordingly, new prioritization strategies and innovative infrastructure funding and maintenance strategies must be tried out. For that to happen, the current state of infrastructure planning in America must be analyzed.

Current practice in transportation planning and management is basically guided by two main factors – first, the long-static Federal funding formulas for transportation projects; and second, the fragmented and mode-focused interaction of local, state and Federal transportation officials that Metropolitan Planning Organizations (and state DOTs) across the nation manage. Countless individual decisions from these actors concerning the allocation of resources, such as money, road space, parking spaces, and priority in traffic end up influencing what a typical transportation user ends up having at his/her disposal.

Current planning practices often allocate these resources inefficiently, such as devoting a relatively small portion of transportation funds to non-motorized modes, allocating parking on a first-come basis, and giving no priority to space-efficient modes (carpools, vanpools and buses) in congested traffic.

Similar issues exist for other types of infrastructure – for example, water and sewage infrastructure investments are also fragmented and do not currently have enough federal, state and local dedicated sources of funding (in 2002, the EPA issued a report identifying a potential 20-year funding gap for drinking water capital expenditures as well as operations

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[8] Pennsylvania State Transportation Advisory Committee, Transportation Funding Study, May 2010. ftp://ftp.dot.state.pa.us/public/Bureaus/Cpdm/TAC/Transportation_Funding_Study_May_2010_Executive_Summary.pdf

and maintenance, ranging from $45 billion to $263 billion[9] – Congress has still not addressed this gap). At an even more dire state, stormwater infrastructure implementation is even more fragmented (and in some cases, nearly non-existent) and has even fewer sources of funding.

One solution to the question of prioritization is the use of new Transportation Demand Management strategies. Transportation prioritization explicitly allocates resources to favor *higher value trips and lower cost modes priority over lower value, higher cost trips* in order to improve overall transportation system efficiency and support strategic planning objectives[10]. Some of the strategies used in TDM and TP include:

- Road Space Reallocation (such as Complete Streets, HOV lanes and creation of bike lanes, trails, cycletracks, bikeways, and even just sidewalks – where they do not exist)
- Design for Mobility and Accessibility (including strategies such as mobility services, universal ADA-compliant design, and location-efficient development)
- Parking Management
- Traffic Calming
- Bus-Rapid Transit
- Pricing Strategies (Congestion Pricing, Parking Pricing, and VMT Taxes)

Another solution to the question of prioritization is to focus limited funds into projects that will have multiple benefits in a wide range of infrastructure types. For example, the construction of a "Complete Street" at a specific location can be prioritized if the construction of the transportation infrastructure at that location will also address a critical piece of recreational and/or stormwater retention infrastructure for a given community.

In the Philadelphia area, he Pennsylvania Environmental Council (PEC), the City of Philadelphia's Mayor's Office of Transportation (MOT), the Philadelphia Water Department (PWD), and Pennoni Associates have collaborated since 2006 in several projects and initiatives that attempt to bring together these two prioritization strategies.

The Philadelphia Example – The Major Actors

Until the election of Mayor Nutter in 2008, the City of Philadelphia had for many years lacked a dedicated focus on transportation planning. Once elected, Mayor Nutter created a position for a Deputy Mayor for Transportation and Utilities with a dedicated staff that would start coordinating efforts with the City Planning Commission, the City Streets

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[9] ASCE 2009 Report Card for America's Infrastructure, Drinking Water Section. http://www.infrastructurereportcard.org/fact-sheet/drinking-water

[10] Vancouver Transport Policy Institute, TDM Encyclopedia, Prioritizing Transportation, January 26, 2010. http://www.vtpi.org/tdm/tdm110.htm

Department, SEPTA (the regional transit agency), and other stakeholders at the local, regional, state and federal levels.

Around the same time, the Philadelphia Water Department started research and pilot projects that would implement a new strategy for meeting EPA and Clean Water Act compliance requirements. The PWD is one of the nation's oldest water and sewage authorities, and is notable for being one of the few utilities in the nation that combine in one entity the elements of water, sewage, and stormwater control.

The sewer system within the City is currently being utilized far beyond its capacity. Sixty percent of the City's land area has combined stormwater/sanitary sewers, and there are a total of 164 combined sewer outfalls in the City of Philadelphia. These outfalls can discharge millions of gallons of stormwater into the rivers during a rain event.

In Washington D.C., a CSO area of nearly twenty square miles and an overflow volume of 2.5 billion gallons per year, compliance costs reached $2.65 billion. In Pittsburgh, with a CSO area of sixty square miles and an overflow volume of fourteen billion gallons per year cost about $3 billion. In Philadelphia, where the CSO area is sixty-four square miles, and overflow volume reaches sixteen billion gallons per year, the cost of traditional sewage and stormwater infrastructure investments of types similar to Washington and Pittsburgh would likely surpass that of the other two cities.

Instead, the PWD has proposed to implement its "Clean Water, Green City" plan, with two main strategies:

1) Shifting some of the investment onto the private sector. By properly adjusting the stormwater billing rate and creating new infiltration requirements, the PWD has created a financial incentive for large generators of stormwater (such as shopping center parking lots) to invest in on-site stormwater management.
2) Leveraging PWD investments with other types of infrastructure investments – the PWD has started coordinating its water and stormwater infrastructure investments with multiple other agencies and stakeholders, thus hoping to leverage limited dollars into more "bang for the buck". For example, it is collaborating with the Philadelphia School District in removing pavement and creating new green infiltration areas in Philadelphia schools; and is collaborating with the MOT in developing a new "Complete Streets Guidance Manual" that will set a new standard for future design and maintenance of Philadelphia city streets.

The PEC is a widely-respected statewide non-profit organization that was created on the vanguard of the creation of the EPA in 1970. It is unique because it works on both the policy arena and in project implementation, and thus is able to utilize lessons learned in one sphere to inform the other. The PEC works closely with the PWD in the policy arena, and with the MOT in implementing a regional trail and bikeway network.

Finally, Pennoni Associates is one of the leading engineering firms in the Mid-Atlantic, and has done multiple transportation and infrastructure planning and engineering design projects for the PEC, the PWD, and the City of Philadelphia.

The Philadelphia Example – Prioritization Strategies

On the funding side, the City of Philadelphia has little leeway. Hemmed in by the typical Federal funding streams and by limited discretionary budgets typical of older urban centers, the City usually has scarce funds available to match Federal funds. The PWD has an advantage, since its water fees and independent bonding authority give them some additional leeway in finding and allocating funding for infrastructure. Yet, coordination of even basic infrastructure investments can be difficult. For example, timelines for street repavement and for water and sewage pipe reconstruction rarely coincide.

Some might think that a third actor would just complicate coordination even more. However, the PEC played an interesting role that has helped advance both the MOT's and the PWD's goals.

The PEC's Southeast Regional Office in Philadelphia has hosted two separate major programs since 2005, the *Urban Stormwater Program*, which provides support to PWD policy and stakeholder and public outreach initiatives; and the *Tidal Delaware Program*, which focuses on building new recreational infrastructure along the Delaware River, including the completion of a new "Delaware River Trail" that will become a 67-mile long link in the national East Coast Greenway. To build this trail in Philadelphia, one of the three counties it will traverse in PA, the PEC closely collaborates with the MOT.

One of the seeds of the outside collaboration amongst the PEC, MOT, and PWD started with conversations within the PEC on how to integrate Urban Stormwater programs goals into the trail construction projects, and vice-versa. From that point on, PEC staff worked closely together and with outside stakeholders to coordinate efforts.

This collaboration resulted in the completion of multiple feasibility studies for Delaware Trail segments; preparation of multiple conceptual design studies for these segments, incorporating innovative stormwater management structures; and finally, design and construction of some of these segments.

From this collaboration three basic prioritization strategies were utilized:

1) First, the completion of the **major spines of the regional trail network** dictated the location of the corridors where investments would take place.

2) Second, a "**Complete Streets" TDM strategy** was utilized to limit the costs of construction of trail and bikeway segments. In other words, the PEC and the MOT prioritized selection of existing public street rights-of-way over acquisition of private

right-of-way, where feasible; thus also expediting project completion and leveraging existing street repavement budgets.

3) Finally, the potential contribution of trail and bikeway rights-of-way to wider City **stormwater management priorities** was considered at every step. In other words, in some cases the particular location of a bikeway alignment was selected due its potential contribution to managing stormwater for a given neighborhood; and in every case, trail and bikeway designs incorporated innovative stormwater control structures.

These strategies are further examined in the following three case studies.

The Philadelphia Example – Case Study: Center City Greenway Feasibility

The Center City Greenway feasibility study analyzed more than 20 potential alignments for connecting the growing trail networks on the east and west sides of Philadelphia (respectively, on the Delaware and Schuylkill riverfronts), across Center City Philadelphia. The PEC retained Pennoni Associates Inc. to conduct the study, and the MOT was an active participant in the process. Three final alignments were recommended for implementation, one each for short-term, medium-term and long-term implementation.

Short-Term: The installation of new dedicated and buffered bike lanes on Spruce and Pine Streets would provide a 1.5-mile long connection from river to river on the southern edge of Center City. Implemented in the fall of 2009, these new bike lanes were implemented at negligible cost (they used existing City repaving and restriping funds), have proven to have little negative impact on vehicular traffic, and have proven to be a wild success for recreational users.

Figure 1 – Installation of Spruce and Pine bike lanes, Fall 2009.

Medium-Term: This option proposes the upgrading of existing bike lanes on Spring Garden Street, on the northern edge of Center City, to create a linear park and greenway. While skirting the commercial and cultural core of the downtown, this alignment benefits from a generously wide right-of-way that permits full-fledged separated pathways for bicycles, pedestrians, and cars, along with the possibility of ambitious sustainable storm water practices. (For more details, see "The Next Step", below)

Long-Term: The final and most complex suggestion was for the transformation of Market Street, the major east-west thoroughfare along the core of Center City, into a true multi-modal transit artery, connecting commercial, cultural, and institutional centers with a continuous bicycle greenway serving a wide range of potential users. With this alignment, bicycle circulation is fully woven into the fabric of the downtown, allowing maximum connection with all other modes of circulation in the downtown.

The street is already served by subway, regional commuter rail, and local city and national (i.e., Greyhound) bus routes. Serving the major retail and employment center of the city, the Market Street alignment does the most to promote bicycles as a viable means of *transportation* (not just *recreation*). Furthermore, this alignment has the potential to tap the city's substantial tourist market. A greenway along Market Street would connect virtually all the major destination points in Center City, including Independence National Historical Park and Independence Visitor's Center, the Convention Center, and connections beyond to the cultural attractions of the Parkway. Such an alignment would maximize the economic development potential of the greenway, and present the City in the best possible light to visitors and greenway users.

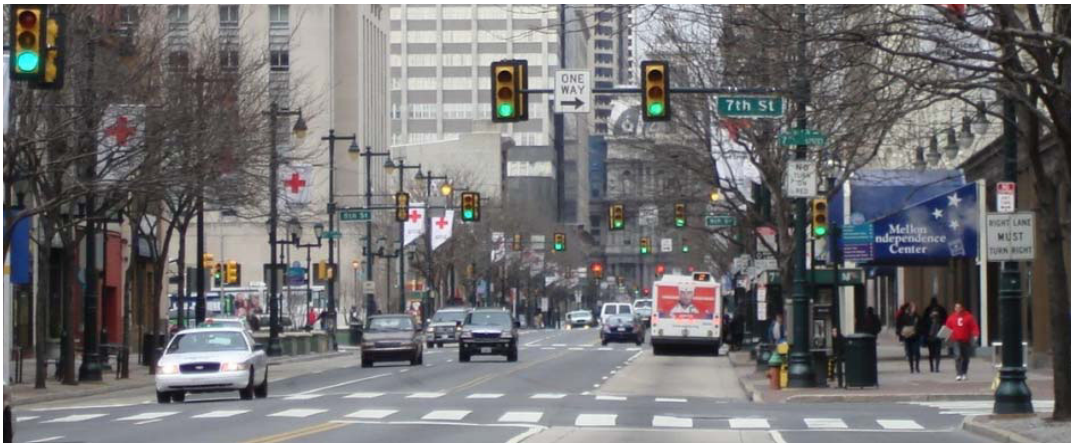


Figure 2 - Current Market Street configuration (3 lanes eastbound, 2 lanes westbound), with City Hall at center in background.

Since Market Street sits atop a subway line and other occupied "concourse-level" spaces, the potential to infiltrate storm water is limited compared to other options. However, the potential appeal to the widest possible range of bicycle users makes this a highly intriguing option.

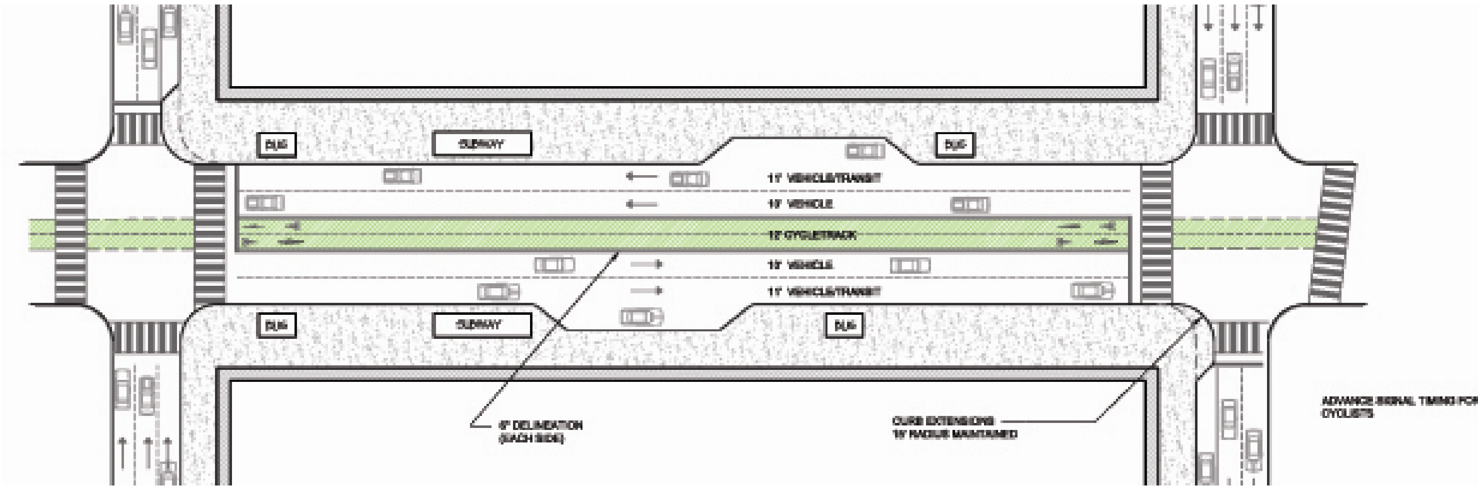


Figure 3 - Plan view of proposed Market Street reconfiguration.

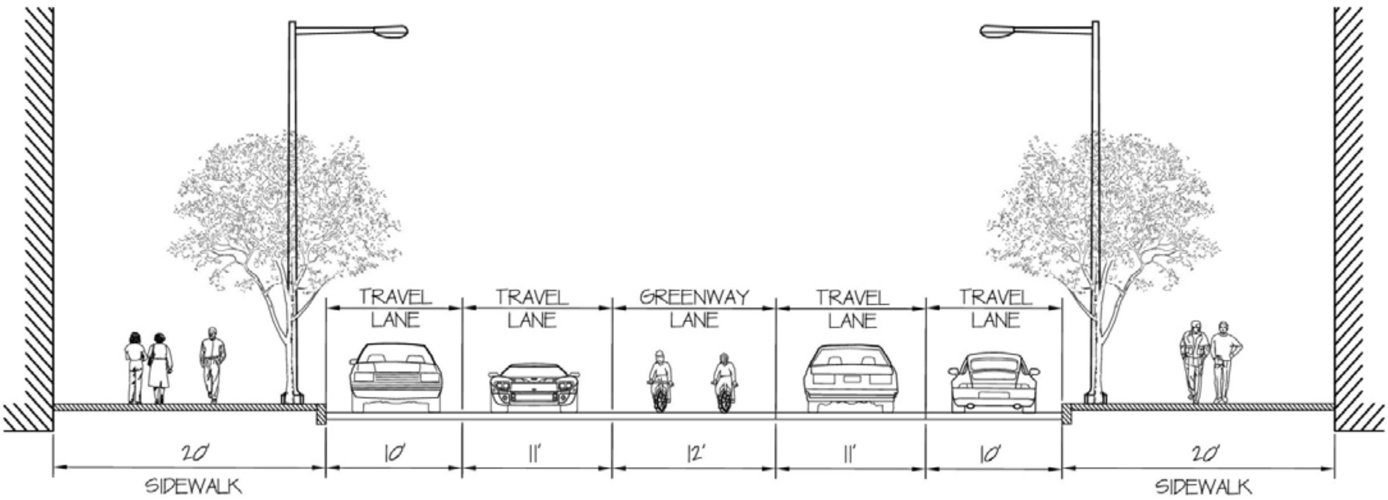


Figure 4 - Cross-section of proposed Market Street reconfiguration.

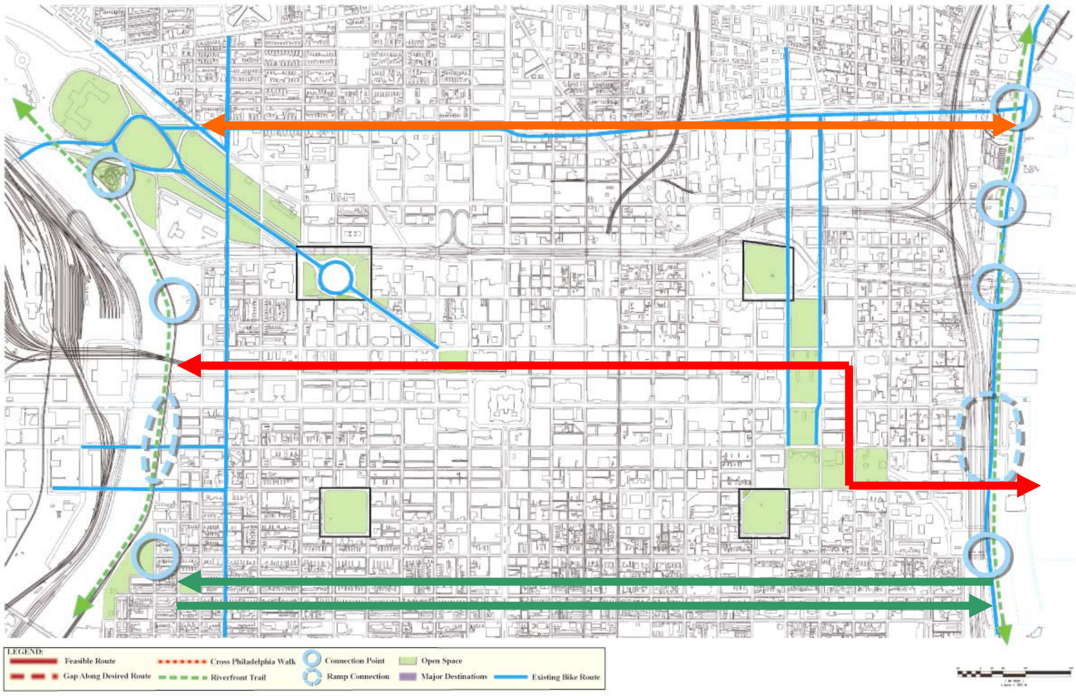


Figure 5 – Short-, Middle-, and Long-Term Proposals for Center City Greenway

Blue Lines – Current City of Philadelphia bike lane system (note that most existing lanes are on the perimeter of the downtown business district and thus provide little connectivity)

Blue Circles – At-grade connections with Schuylkill River Trail (on west side of Center City) and Delaware River Trail (on east side of Center City)

Blue Dashed Ovals – Ramp / graded connections with Schuylkill River Trail (on west side of Center City) and Delaware River Trail (on east side of Center City)

Green Lines – Newly-installed (2009) Spruce and Pine Buffered Bike Lanes

Orange Line – Proposed upgrade of Spring Garden Street bike lanes

Red Line – Long Term proposed improvement of Market St and Ben Franklin Parkway

The Philadelphia Example – Case Study: 58th Street Greenway Construction

Currently, the City of Philadelphia has one major, nearly complete trail / greenway corridor, the Schuylkill River Trail. From its current terminus at Locust Street in Center City Philadelphia, a recreational user can bike or hike up the Schuylkill River into the Valley Forge National Park (20 miles to the northwest of the downtown), with only a few sub-mile segments still located on interim on-street alignments. In other words, most of the trail up to the northwest edge of the metropolitan region is already complete.

Yet, the plan is to extend the Schuylkill River Trail south as well, changing its terminus from Locust Street to the confluence with the Delaware River (near the Philadelphia International Airport), and connecting with the growing network of trail along the Delaware River and the national East Coast Greenway alignment.

A "straight shot" alignment, following the bends of the Schuylkill River down to the confluence to the Delaware (an approximately 9-mile stretch) is the long-term goal. However, this alignment would cross lands that are still heavily and actively used in industry (multiple refineries and tank farms are present there, for example; as is the Philadelphia International Airport). Acquisition and environmental concerns will push the completion of this alignment back decades, and a less complex solution was sought to complete the connection sooner.

The PEC completed a feasibility study[11] which identified an ingenious solution to this problem. Just a mile or two to the west of the Schuylkill basin, a smaller basin, the Darby and Cobbs Creeks watershed, also has a confluence with the Delaware located just a few miles south of the Schuylkill confluence - just on the other side of the Airport. Along these two creeks, some major trail systems, though disconnected, already exist: the Cobbs Creek Trail extends well into Southwest Philadelphia; while at the southwestern-most corner of the City, the last wild lands within the City boundaries were protected with the creation of the John Heinz National Wildlife Refuge in 1972. Trails within the Heinz Refuge already connect Southwest Philadelphia neighborhoods to the Delaware riverfront and to the next adjoining political subdivisions, Pennsylvania's Delaware County; and then the state of Delaware itself.

PEC's feasibility study suggested that the most cost-effective and efficient solution would be to build a connection from the Schuylkill River, across Southwest Philadelphia residential neighborhoods, to the Cobbs Creek Trail; and then extend the Cobbs Creek Trail into the Heinz Refuge. (see figure below)

The preferred alignment for the connection across Southwest Philadelphia turned out to be 58th Street. Not only was this public street corridor one of the streets with shortest distance between the Schuylkill and the Cobbs; but also, all along the south side of the street are located for the most part only large institutional uses such as high school baseball fields, rail yards, shopping mall parking lots, nursing homes, and public recreation centers. In other words, there were few driveways and doorways along this street edge, which made the construction of an off-street trail or Shared-use path possible.

[11] Performed by local planning firm Campbell Thomas & Co in 2008.

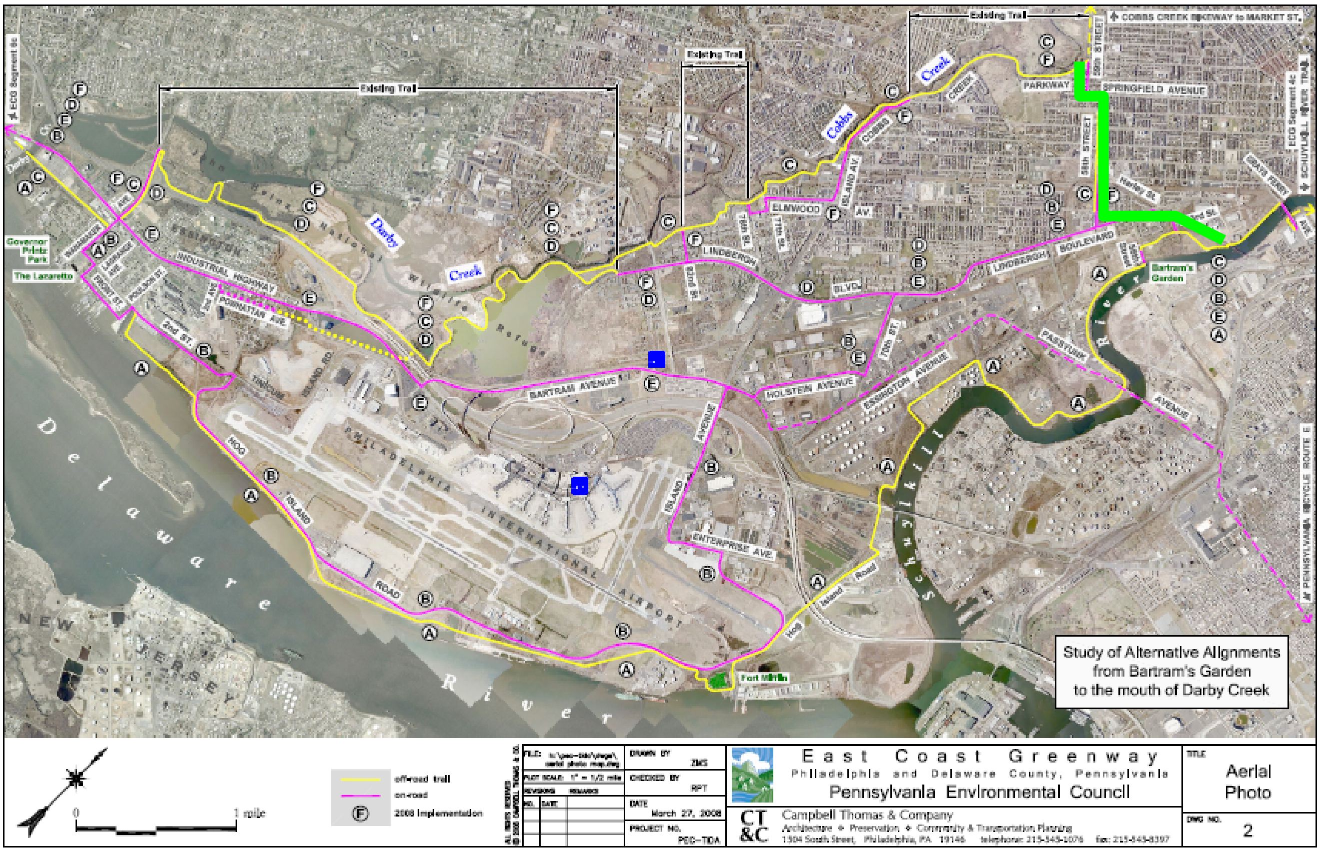


Figure 6 – Alternative Alignments for connecting Center City Philadelphia to Delaware Co.

Yellow line at bottom – Long-Term Preferred alignment along Schuylkill River, down to confluence with Delaware River at Phila Navy Yard (bottom right)

Yellow line at top – Short-Term Preferred alignment along Cobbs Creek, Darby Creek, and Heinz Wildlife Refuge

Green line at top right – Short-Term Preferred alignment for 58th Street Greenway Connection

After an extensive stakeholder and public involvement process conducted by the PEC with City of Philadelphia support, the final alignment and basic concept for the 58th Street Greenway was developed[12]. It basically consists of the reconstruction of the southern sidewalk space along 58th Street, transforming a sidewalk space, previously dilapidated in many spaces, into a continuous shared-use path with multiple pedestrian and intersection improvements.

[12] Conceptual design was completed by Michael Baker, Inc (Horsham, PA) and Toole Design Group (Baltimore, MD. Final design is being completed by Michael Baker, Inc.

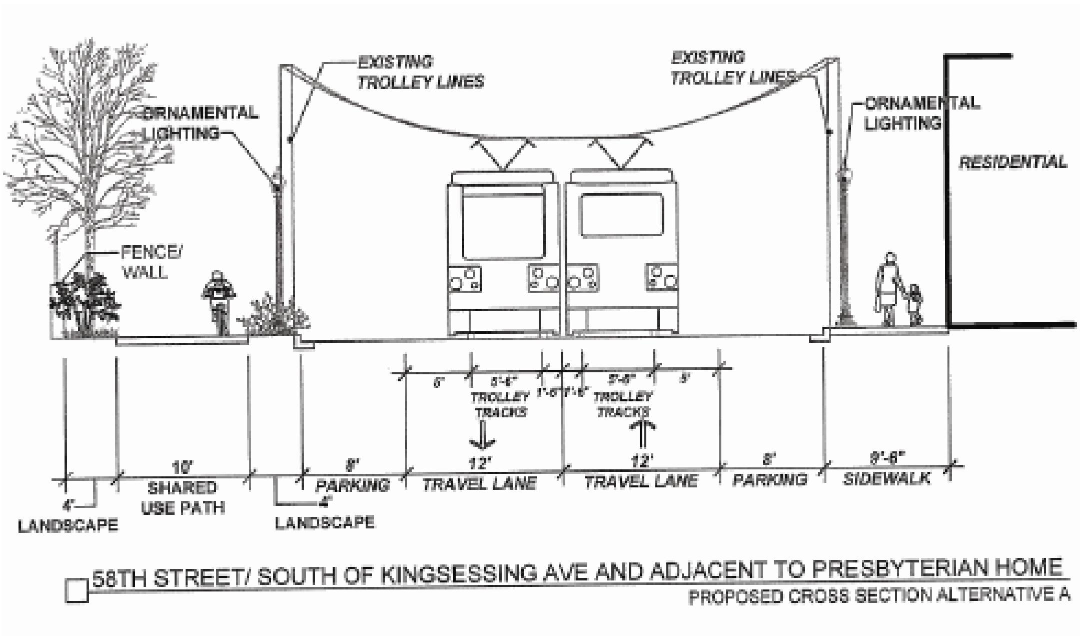


Figure 7 – Proposed Cross-Section for 58th Street Greenway

Following on the footsteps of models seen for the most part in Europe, but also in New York city and Indianapolis, this new greenway corridor is currently fully funded for construction. Once complete, it will represent not only a major connection in the regional network, but will also have multiple other benefits.

It will incorporate innovative stormwater features, helping diminish the stormwater load on one of the City's top ten combined-sewer overflow sewer-sheds. It will provide a new transportation and recreational alternative for one of the most distressed neighborhoods in Philadelphia, connecting them to the Schuylkill River Trail, to the jobs in Center City, and to the Historic Bartram's Garden (the first botanical garden in the nation's history).

Construction of this greenway is expected to start in the Spring of 2011, and is expected to be completed by February of 2012, the deadline for one of its sources of funding, the USDOT's TIGER program.

The Philadelphia Example – Case Study: Benjamin Franklin Parkway Reconstruction

The Benjamin Franklin Parkway is Philadelphia's beloved ceremonial boulevard, and its most recognizable street. Built in the 1920's in the Beaux Arts style, it is the city's most profound urban gesture to the City Beautiful movement. It is home to world-class museums and educational institutions, and along with the historic attractions along Independence Mall is the City's premier tourist destination.

As the "gateway" to Fairmount Park connecting the vast green spaces of the Park to downtown, the Parkway is the most prominent location possible to implement Green Streets practices. The challenge in doing so is that, despite its picturesque vistas to the Art Museum and City Hall, the Parkway has for decades served de facto as a vehicular "superhighway," funneling tens of thousands of cars a day into the downtown from the north and west. While one clear goal of the reconstruction is to transform the street into a truly functional multi-modal transportation environment, the practical demands on the street to accommodate substantial volumes of vehicular traffic were overpowering.

The divided boulevard carries five travel lanes in each direction. Extensive traffic analysis and modeling demonstrated that the peak capacity was only used during a short 2-3 hour span of time during rush hour. Traffic volume for other parts of the day is far below available roadway capacity. Essentially, the 10-lane wide roadway was designed for busy rush hour traffic. The rest of the day it is a sea of empty asphalt.

Through intense negotiation with the city Streets Department and Mayor's Office of Transportation, it was determined that a series of traffic improvements could be made to allow the elimination of one vehicular travel lane in each direction. A number of small interventions were designed to increase the efficiency of traffic movement to compensate for the loss of capacity. For instance, certain turning movements onto the Parkway will be restricted, decreasing traffic volume and presenting the added benefit of increasing the protected pedestrian crossing phase of certain traffic signals. Thus the lane reduction is predicted to have relatively little impact on vehicular traffic flow.

This newly "found" space within the right-of-way will be utilized for a range of improvements to improve the multi-modal functionality and overall sustainability of the Parkway landscape:

- Bicycle lanes will be added, forming a bicycle connection between Center City Philadelphia and the cultural institutions along the Parkway, and with the existing regional bicycle greenway system along the Schuylkill River just beyond the Parkway.
- Medians dividing the boulevard will be widened, to further distinguish the "express" lanes in the roadway center from the "local" lanes at its edge.
- Traffic calming strategies will be employed for the outer lanes, to improve the safety and comfort of pedestrians and bicyclists.
- Pedestrian crossing distances will be reduced by strategically-placed curb bump-outs and refuge islands, which along with adjusted signal timings will greatly improve the safety of pedestrians crossing the wide center roadway lanes.
- Storm water infiltration facilities will be placed at strategic locations, to divert a substantial amount of storm water runoff away from the storm sewer system.

The result is expected to be perhaps the city's most Complete Street, with generous space devoted separately for pedestrians, bicycles, and cars, in a healthy tree-lined environment. It won't be long for the public to judge the success of the scheme for themselves. Construction is set to begin in the fall of 2010, and be completed in 2011.

The Philadelphia Example – The Next Step: Spring Garden Street Greenway

The Spring Garden Street Greenway (SGSG) will transform a 2.2 mile-long east-west artery in Center City Philadelphia into a linear park, a green street, and a high-quality walking and biking trail separate from traffic lanes. Spring Garden Street was chosen as the main connection in Philadelphia because it has sufficiently wide right-of-way available for a separate "bikeway" along the street. In keeping with East Coast Greenway, Fairmount Park, and PWD "Green Street" guidelines, a modified streetscape with trees and plants will provide cutting-edge open-space opportunities and will help manage stormwater runoff.

The SGSG will provide an attractive and direct link for cyclists through Center City. The SGSG will also serve as a valuable public amenity to help ameliorate the current abandon properties, vacant lots, dangerous street intersections, and lack of connections to other routes and destinations in the city. By providing safe and attractive facilities for residents and visitors to walk, jog, and bike in their own neighborhood, this project will improve the quality of life for the community, as the connections between outdoor recreation, healthy lifestyles and economic benefits are realized.

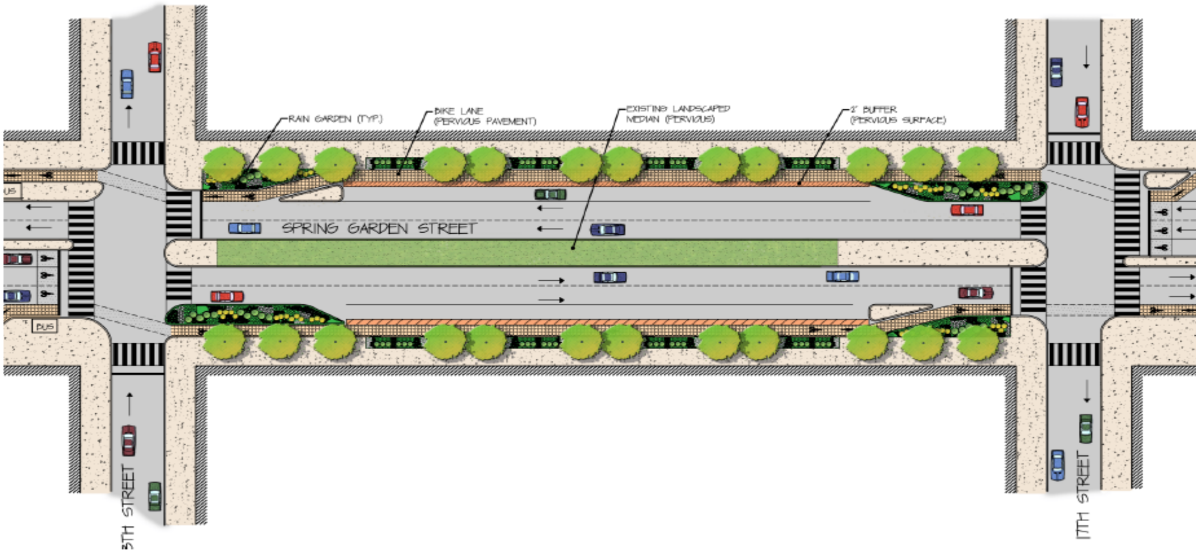
When completed, the SGSG could make Greater Philadelphia's commitment to developing multi-use trails a national model, especially for large cities that want to:

- Utilize relatively small transportation investments to leverage significantly higher environmental and recreational benefits,
- Provide recreational opportunities to a diverse population,
- Leverage small projects into large national initiatives, such as the East Coast Greenway
- Manage stormwater more sustainably,
- Create opportunities for local economic development, and
- Promote healthy lifestyle choices.

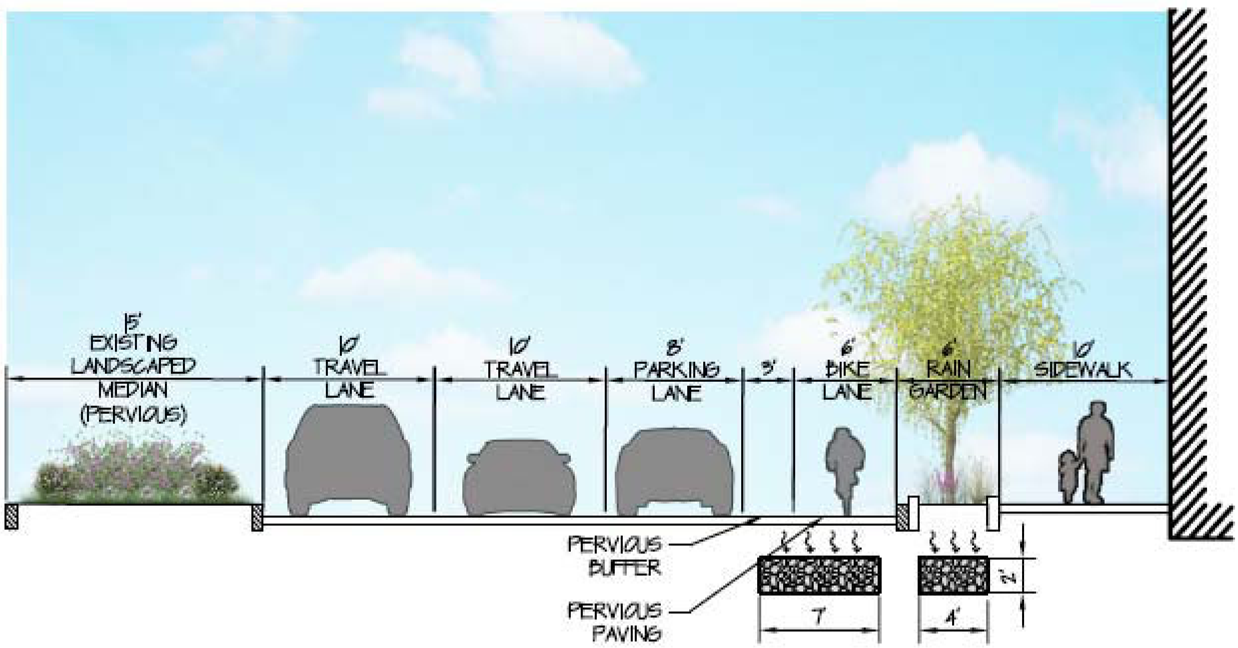
The approach is to implement sustainable storm water management practices along with a high-quality bicycle greenway, as part of an overall Green Streets philosophy.

The existing street is sloped toward the outside curbs. The tactic is to collect storm water along the curb line from the impervious areas of the street and sidewalk, through a variety of interventions, to encourage infiltration and to create underground storage to allow for a controlled release into the sewer system.

Figures 8 and 9, below, show a prototypical plan and cross section view of the proposed new “green street”. While a variety of configurations are possible, this sample configuration is one which achieves the project goals.



To garner the additional space for widened bike lanes, the two travel lanes, each currently at 12 feet in width, would be narrowed to 10 feet each. This additional 4 feet could be used to widen the existing bike lane from 5 ft to 6 ft, and create an additional 3-foot wide buffer. The buffer area could be pavement and traversable by car but still create the separation necessary to increase safety and create a buffer for parked-car and bike interactions. Bump-outs at the intersections would create an additional safety and greening feature.



The buffer strip is designed to be permeable, such as cobbles or other unit paving materials set with void spaces to allow water infiltration. Similarly, the bicycle lane itself could be constructed of permeable paving (permeable asphalt, permeable concrete, and unit pavers are all materials worth consideration) to allow infiltration. Beneath both the buffer strip and bike lane can be a gravel basin to capture the drainage and store it so that time available for infiltration is maximized.

On the sidewalk side of the curb, rain gardens can be created to collect water from the sidewalk and building downspouts as well as water from the street that exceeds the infiltration rate of the pervious paving. Curb bump-outs created to buffer the bicycle lane can also be designed as rain gardens to collect storm water. These rain gardens – planted with appropriate plantings – along with enhanced street tree plantings, will add greatly to the aesthetic value of the street. Additionally, judicious street tree plantings can enhance the street's shade canopy, improving the micro-climate for pedestrians and cyclists, and mitigating the urban heat-island effect that is so prevalent in the dense (and largely impervious) urban center.

Since streets and sidewalks within Center City are almost entirely impervious paved surfaces, these rights-of-way are exempt for storm water regulations enforced by the Philadelphia Water Department (PWD) for development projects. However, as a high-profile demonstration project in the city, Spring Garden Street can be designed to meet the standard PWD requirements while at the same time satisfying the goals for multi-modal circulation.

PWD requirements essentially call for on-site storage of 1" of storm water measured over a site's total impervious area. For Spring Garden Street, this total volume would require approximately 9600 cubic feet of storage area for each typical block. This would be the equivalent of an underground gravel basin 6' wide x 2' deep along the length of each curb line.

As shown in Figure 9, this volume is achievable by constructing basins beneath the areas of permeable paving and rain gardens. In this way, in will be possible to demonstrate that the relatively new requirements enforced for site development can also be met for green streets – in other words, street right-of-way projects can provide substantial benefit to the storm water system city-wide. (Initially on a case-by-case, model basis – but then hopefully with greater positive impact as more and more green streets are built)

Conclusion

Transportation investments have come at times from public, at times from private sources throughout American history. At this time of tight financial resources, new prioritization and leveraging strategies have to be implemented to make projects feasible.

Philadelphia has provided an unlikely leadership in this arena, achieved by collaboration amongst multiple government agencies and non-profit organizations, including the MOT, the PWD, and the PEC. By trial and error and experimentation, these collaborative efforts have achieved real on-the-ground successes – such as the projected expansion of the East Coast Greenway in PA from less than 5 miles in 2007 to over 20 miles projected to be completed by the end of 2012; and the attainment of regional water quality goals, at lower levels of public investment.

Three new prioritization criteria have helped guide these successes so far:

1) Complete the **major spines of the regional trail network**
2) Utilize a "**Complete Streets" TDM strategy**, limit ROW acquisition, and leverage existing maintenance funding to upgrade existing facilities.
3) Leverage **stormwater management funds and goals** to create synergies with other funding sources.

These criteria can be utilized by other cities, regions, and states across the nation; and can help solve some of the largest infrastructure challenges America faces in the 21st Century.

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2 Pennoni Associates, One Drexel Plaza, 3001 Market Street - Second Floor Philadelphia, PA 19104-2897, Tel: 215-222-3000, Fax: 215-222-0384; e-mail: mmorfei@pennoni.com

Improving Bicycle Safety with More Bikers: An Intersection-Level Study

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ABSTRACT

Conventional thinking among transportation engineers in the U.S. finds a linear correlation between the number of bicyclists on a roadway and the number of crashes involving bicyclists. However, studies from Europe have found that with increased ridership comes increased safety in the form of a reduction in the number of crashes per cyclist. Our study examines whether these trends can also be found in the U.S., to what extent does this hypothesis hold, and what other factors might be playing a role in the results. We conducted this research in Boulder, Colorado using estimates of average cyclists per day based on turning movement counts on corridors with both high and low bicycle traffic and related that to five years of bicyclist crash data. The data suggest that while bicycle crashes do seem to increase with motor-vehicle volumes, bicycle crashes tend to stay constant – or even decrease – with increased bicycle volumes.

INTRODUCTION

Even though bicycles and automobiles have been intermingling on our roads for over a century, transportation engineers still have yet to develop a complete understanding of how these two modes interact with respect to crashes. Conventional wisdom tends to assume that bicycle crashes occur at a rate proportional to the volume of bicyclists, the volume of motorists, or some combination of the two. While this line of thinking seems reasonable, a few studies are beginning to make the case that the bicycle/automobile crash relationship is not as simple as it seems.

Jacobsen, examining national safety records from a number of European countries, found that bicyclist fatalities tended to decrease as the amount of bicycling increased (Jacobsen, 2003). At the city scale, an investigation of California cities by Marshall and Garrick found that higher bicycling cities show a much lower risk of fatal crashes for all road users including bicyclists; while Jacobsen, who also studied cities in California as well as the Netherlands, found that bicycle and pedestrian injuries decrease with increased biking (Marshall & Garrick, 2010; Jacobsen, 2003). Lastly at the intersection level, Ekman found that the individual risk to a bicyclist decreases dramatically with bicycle volumes greater than 50 cyclists per hour (Ekman, 1996). One limitation regarding the transferability of Ekman's results is that this is one of the only studies of its kind at this level of geography while another concern for researchers and policymakers in the U.S. is that this study took place in Malmö, Sweden.

So the research question at hand is whether we can find a similar bicyclist safety in numbers phenomenon at the intersection level of geography in a U.S. city. Such a result, in terms of the possibility that the risk to an individual bicyclist diminishes with greater bicycle volumes, could have far-reaching implications in terms of transportation infrastructure, bicycle facility design, and bicycle safety interventions. For example, if – as Ekman found in Sweden – the number of bicyclists on a facility is of greater importance to safety than the facility type or equipment used, then focusing on policies and infrastructure that better accommodate more bicyclists and a greater variety of bicyclist types can help influence a self-reinforcing cycle that improves overall bicycle safety. Hence, this study will examine whether the same conclusions can be made for intersections in a U.S. city, Boulder, Colorado, which with its high bicycle mode share was selected in order to meet the baseline conditions for bicycle volumes established by Ekman. With five years of crash data for 92 intersections, this research expands upon the small but growing body of literature on what could be valuable knowledge in building ourselves safer and more sustainable cities.

LITERATURE REVIEW

While some studies of bicycle safety have been conducted to understand if bicyclists are safer in numbers, the majority are European studies. Lars Ekman first found a non-linear relationship between bicyclist safety and bicycle volume in 1996. In a study of 95 intersections in Malmö, Sweden, Ekman found that for bicyclist volumes greater than 50 cyclists per hour, safety per cyclist increases dramatically due to changes in driver behavior (Ekman, 1996). He also looked at the relationship of bicycle crashes per cyclist to motor-vehicle flow and found that this relationship was not as strong as the relationship with bicycle flow. Following Ekman's study, Leden *et al.* investigated 45 intersections in Gothenberg, Sweden before and after bicycle crossings became raised crossings. He found that the improved bicycle facilities had attracted about 50% more cyclists compared to intersections that did not change. By plotting relative risk (reported crashes per bicyclist) versus bicycle flow per hour, Leden found that increases in flow decreased the relative risk per cyclist. For example, a 50% increase in flow would decrease relative risk by 24% even though the total number of bicycle-related crashes would increase by 14% (Leden, 2000).

Seeing the strong correlation of bicycle-related crashes to bicycle flow from Ekman and Leden's work, Jacobsen examined bicycle and pedestrian data sets from 68 California cities, 47 Danish towns, and 14 European countries. For each dataset, he hypothesized an exponential relationship between crashes and exposure. Using least squares analysis, he found that crashes are related to exposure with exponential growth rates from 0.6 to -2. This indicates that the growth in injuries with exposure is less than linear and in some cases negative. In other words, while injuries may decrease with increased bicycling and walking in some cases, this trend was mainly found in the European data (Jacobsen, 2003). Studies such as Jacobsen's seem to indicate that bicyclists in the U.S. may also experience similar improvements in safety, but these trends are not nearly as well established for North American conditions as for European. One major issue is that such studies are largely impossible in most U.S. cities because bicycle flow rarely exceeds 50 bicyclists per hour, the point at which Ekman found an overwhelming increase in safety. Fortunately, some U.S. cities do in fact find such conditions.

STUDY OVERVIEW

The research agenda of this project required us to select a study site with a critical mass of bicyclists approaching 50 bicyclists per hour, as discussed in the literature review and matching the threshold for safety implications found by Ekman. With one of the highest bicycle mode shares of any city in the U.S. at roughly 10% and a history of counting bicycles using turning movement counts as well as automated inductive-loop detectors, Boulder, Colorado is one of the few cities in the U.S. that satisfies this condition with count data (US Census, 2009; City of Boulder, 2010; Lewin, 2005). Boulder also has an extensive database of bicycle and pedestrian crashes that can be used to examine roadway safety by facility type (Gill, 2007).

Boulder, a city of approximately 100,000 people, is located about 30 miles northwest of Denver at the edge of the Rocky Mountains. Boulder is home to the University of Colorado whose 30,000 students swell the city population in fall and spring. Boulder is well known for its grade-separated bicycle and pedestrian paths, which are integrated into a network of bicycle lanes and on-street bicycle routes. The city is one of three cities in the U.S. to receive the League of American Bicyclists' Platinum Bicycle Friendly Community Award (League of American Bicyclists, 2010).

DATA

The research team combined data from multiple sources to provide a perspective on bicycle crashes by bicycle volume not previously explored. To better understand and analyze the data, a Geographic Information System (GIS) was assembled from the following sources:

- The road network consisted of three layers for Boulder County: highways, county roads, and local roads. The streams water feature layer was also included as a reference.
- The crash database and intersection coordinates were collected from Jacobs Engineering who had been contracted to perform a study for the Colorado Department of Transportation (CDOT) where five years of pedestrian and bicycle accident reports for the city of Boulder from 2001 through 2005 had been condensed into a single database (Gill, 2007).
- Turning movement counts for motor vehicles, bicycles, and pedestrians were gather from the city of Boulder through both electronic and hard copy records and assembled by the research team.

Though the original CDOT crash database included both pedestrian and bicycle crashes, only crashes involving bicycles were examined for this study. There were 502 such records in the database. Each record located the crash by intersection name and each intersection was located by coordinates. The database included 283 locations. This study focused on intersection crashes and excluded mid-block crashes. Crashes located at intersections where turning movement counts were not readily available were excluded from the study. Overall, 247 bicycle-related crashes at 92 intersections were included in this study.

ANALYSIS

After conversion of the crash database into a GIS shapefile, the crashes and the road network shapefiles were merged and used to count the crashes at each intersection. It was then possible to graphically represent the traffic volume and the number of crashes on the same map, as shown in Figure 1.

Where available, the average daily traffic (ADT) and average daily bicycle (ADB) flow were computed from the turning movement counts for each approach by summing the total counts entering and exiting the intersection at each approach during morning, noon, and evening peak hours and dividing by the factor 0.225 as suggested by the city of Boulder based on an empirically derived relationship between daily counts and peak hour turning movement counts (City of Boulder, 2010).

$$ADT = \frac{\sum_{i=1}^{3} MVPHC_i}{0.225}$$

where
i = a counting variable for the three peak hours: AM, noon, and PM
$MVPHC_i$ = total motor-vehicle peak hour count entering and exiting the intersection per approach

On the turning movement count sheets, bicyclists were counted in two different ways. On-street bicyclists were counted in the same manner as motor-vehicles while off-street bicyclists using the crosswalks at intersections are thus counted in a similar fashion to pedestrians in terms of the number of crossings at crosswalks. For this reason, it was necessary to divide the ADB flow into two parts: on-street and off-street bicyclists.

$$On\text{-}street\ ADB = \frac{\sum_{i=1}^{3} (on\text{-}street\ BPHC_i)}{0.225}$$

where
i = a counting variable for the three peak hours: AM, noon, and PM
\ *on-street* $BPHC_i$ = total on-street bicycle peak hour count entering and exiting the intersection per approach

$$\textit{Off-street ADB} = \frac{\sum_{i=1}^{3}(off\text{-}street\ BPHC_i)}{0.225}$$

where
i = a counting variable for the three peak hours: AM, noon, and PM
$off\text{-}street\ BPHC_i$ = total off-street bicycle peak hour count crossing the intersection at each approach

These expressions provide a way to compute the traffic flow at each approach.

Table 1 contains the following information for 20 intersections with the most bicycle-related crashes: the number of crashes involving cyclists, motor-vehicle traffic flow (Intersection ADT), and bicycle traffic flow (Intersection ADB flow). For analysis purposes, it was desirable to have one traffic volume associated with each intersection. Intersection ADT was chosen for this purpose. Intersection ADT is composed of the total average daily traffic entering and exiting the intersection, computed by summing the ADT for all of the intersection approaches and dividing by two.

$$\textit{Intersection ADT} = \frac{\sum_{1}^{n} ADT}{2}$$

where
n = the number of approaches to the intersection
ADT = the total number of motor-vehicles entering and exiting the intersection at an approach, averaged over one day
Intersection ADT = the average daily motor-vehicle traffic entering and exiting the intersection, averaged over one day

Similarly, Intersection ADB flow is comprised of the average daily bicycle traffic entering an intersection, which computed by summing the on-street ADB flow for all intersection approaches, dividing by two, and then adding the number of bicycle crossings of the intersections at the crosswalks. Unfortunately, if a bicyclist uses crosswalks to cross the intersection more than once, this bicyclist will be counted multiple times, once for each time he crosses the intersection. For example, if an on-street cyclist made a left turn, he will be counted once. If the same cyclist instead, chooses to make a left turn by crossing using the crosswalks, he would cross at two crosswalks and thus be counted twice. Thus, this method of computing Intersection ADB results in some double counting, but given the format of the turning movement count sheets, it is not possible to, at this point, determine the extent of over counting. For now, the following expression is used to compute ADB flow:

$$\textit{Intersection ADB} = \frac{\sum_{1}^{n}(on\text{-}street\ ADB)}{2} + (off - street\ ADB)$$

where
n = the number of approaches to the intersection

on-street ADB = the total number of on-street bicycle traffic entering and exiting the intersection at an approach, averaged over one day
off-street ADB = the number of crossings of the intersection by bicyclists on crosswalks, averaged over one day
Intersection ADB = the average daily bicycle traffic entering and exiting the intersection, averaged over one day

Thus, Intersection ADT, as shown in Table 1 for the 20 of the intersections with the highest number of crashes, is the total motor-vehicle traffic flowing through each intersection while Intersection ADB is the total bicycle traffic flowing through each intersection. The number of crashes involving bicycles was then plotted as a function of Intersection ADT (Figure 2) and Intersection ADB (Figure 3).

Crashes per bicyclist were also plotted as a function of Intersection ADB flow as shown in Figure 4. Crashes per bicyclist were computed by dividing the number of crashes at an intersection during the 5-year study period by the Intersection ADB.

When linear regression was performed on these plots, the R^2 values for the trend lines were all less than 0.2, indicating the limited explanatory value of such lines; thus, the trend lines are not shown in the figures.

RESULTS

As yet, the number of data points is insufficient to determine the shape of the relationship of bicycle-related crashes to bicycle and motor-vehicle traffic volumes with statistical confidence. However, observation of the plotted data thus far suggests the following:

- Bicycle-related crashes increase with motorist volumes.
- Crashes per bicyclist decrease with increasing bicycle use.
- The relationship between crashes per bicyclists and bicycle volumes is not linear.

Though the relationship between bicycle-related crashes and volume needs further exploration, it is interesting to see that even with limited data available, the graph of crashes per bicyclist with bicyclist volume suggests a non-linear shape and a decreasing trend as found by previous researchers. It is also interesting to note that Ekman's 50 bicyclists per hour translates roughly to approximately 1,300 bicyclists per day using our estimation of bicycle volume. The division in this data set between higher flow, safer bicycle facilities and lower flow facilities with more crashes may occur around 1,000 bicyclists per day per intersection as shown in Figure 4.

CONCLUSIONS

The data presented herein suggests that bicycle flow volume is an important factor to bicycle safety and is not likely to be linearly related to bicycle-related crash volumes. While bicycle-related crashes do appear to increase with motor-vehicle volumes, bicycle-related crashes may stay constant or even decrease with increasing bicycle volumes. Also, safety per bicyclist seems to increase with increasing bicycle use, especially for bicycle volumes above 1,000 bicyclists per day.

As bicycle use increases and as the pendulum continues to sway toward building more sustainable transportation options, the call to provide safe bicycle facilities will also increase and understanding what factors are most important to bicycle safety is key. Our data suggests that the concept of better safety of numbers for bicyclists, which has been previously identified in various European studies, also appears to be a noteworthy factor for a U.S. city with high bicycle use.

FUTURE RESEARCH

The bicycle flow data presented herein were for 92 of the 223 intersections in the original database. We will enhance this story by continuing to add more bicycle and motor-vehicle volume estimates to the GIS database and graphs. The crash data will be aggregated by bicycle flow and analysis will be done to better understand the relationship of safety to bicycle flow.

ACKNOWLEDGEMENTS

Many people have contributed to make this work possible. Professor Bruce Janson has provided invaluable guidance and advice. Mike Gill at Jacobs Engineering graciously provided the original crash database on which this work is based. The Colorado Department of Transportation funding the creation of the bicycle and pedestrian crash database for Boulder. The city of Boulder facilitated the creation of the original database, collected the turning movement counts for bicyclists, and kindly shared them with the authors. The authors would also like to thank the National Science Foundation for providing indirect funding for this work through their Integrative Graduate Education and Research Traineeship (IGERT) program.

Table 1. Twenty Intersections Studied with the Most Bicycle-Related Crashes

Intersection	Bicycle-Related Crashes (5-year Period)	Intersection ADT	Intersection ADB
Arapahoe AV. & 30th	11	129,013	591
Broadway & Baseline Road	10	105,296	804
Regent Dr & Colorado	8	58,027	1,200
Walnut Ave & 30th Street	8	81,493	378
FOLSOM & ARAPAHOE	7	96,249	2,133
Pearl Street & 28th Street	7	143,262	596
Arapahoe Ave & 33rd street	7	64,338	133
Baseline Road & 29th Street	7	67,600	809*
Baseline Road & 30th St	6	80,667	1,640
Regent Drive & Broadway	6	110,333	1,169
Spruce St. & Broadway	6	65,333	538
Valmont Road & 30th Street	6	111,013	538
Table Mesa Drive & Broadway	6	150,293	280
University & Broadway	5	107,276	1,973
Folsom Street & Canyon Boulevard	5	110,916	1,453
Valmont & Folsom	5	63,911	1,293
Walnut St. & 28th St.	5	99,796	462
Baseline road & 27th Way	4	114,418	1,573
Arapahoe Ave & 17th St.	4	50,667	1,147
Iris Ave & 26th Street	4	69,253	724

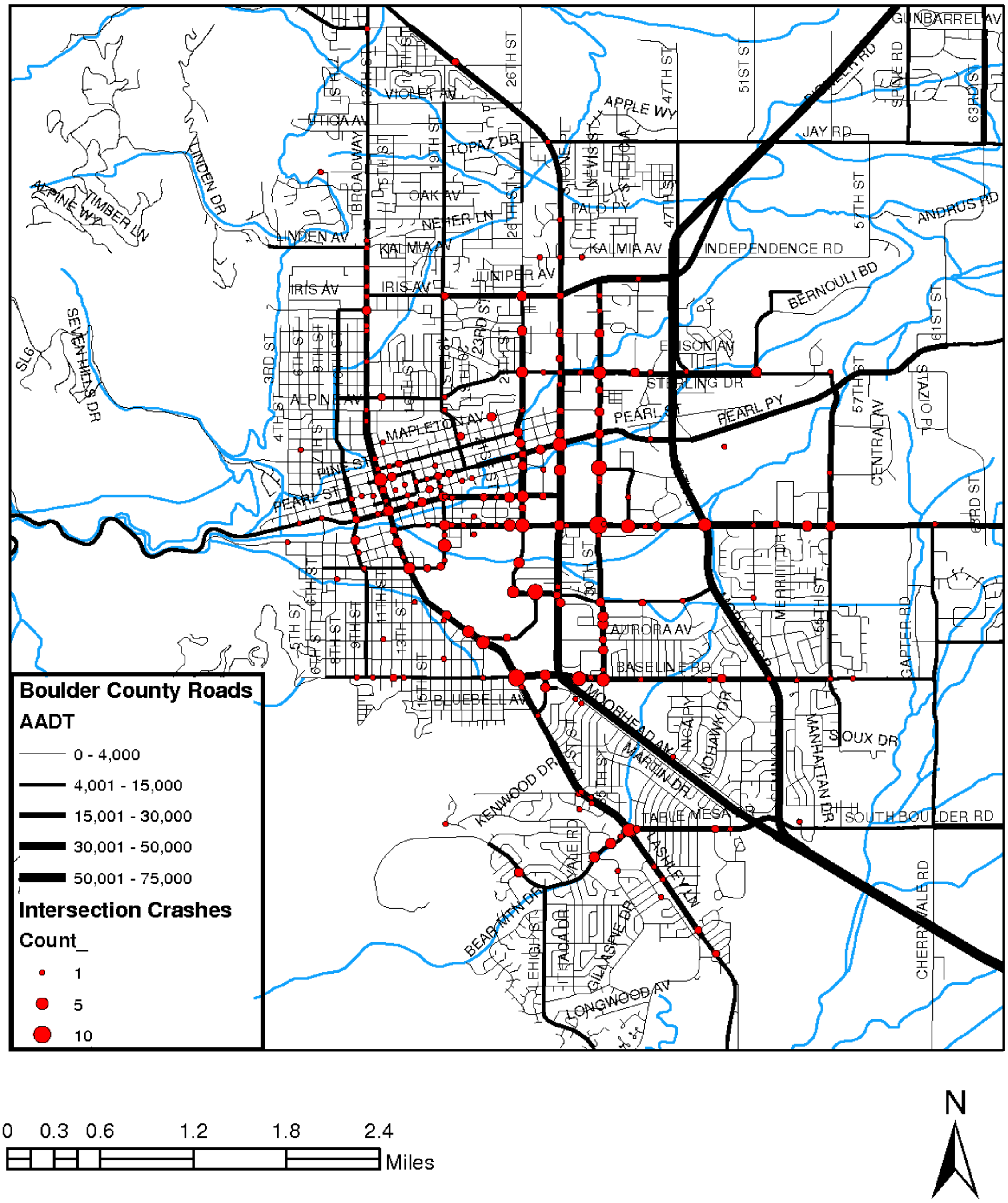

Figure 1. Bicycle-Related Crashes at Intersections in Boulder, Colorado

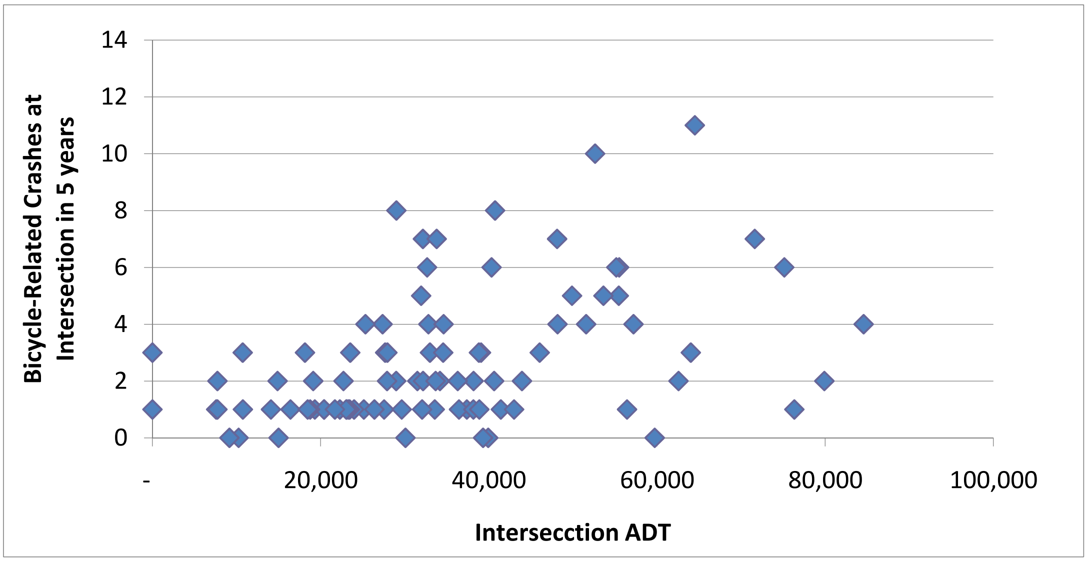

Figure 2. Bicycle-Related Crashes with Daily Motor-Vehicle Traffic

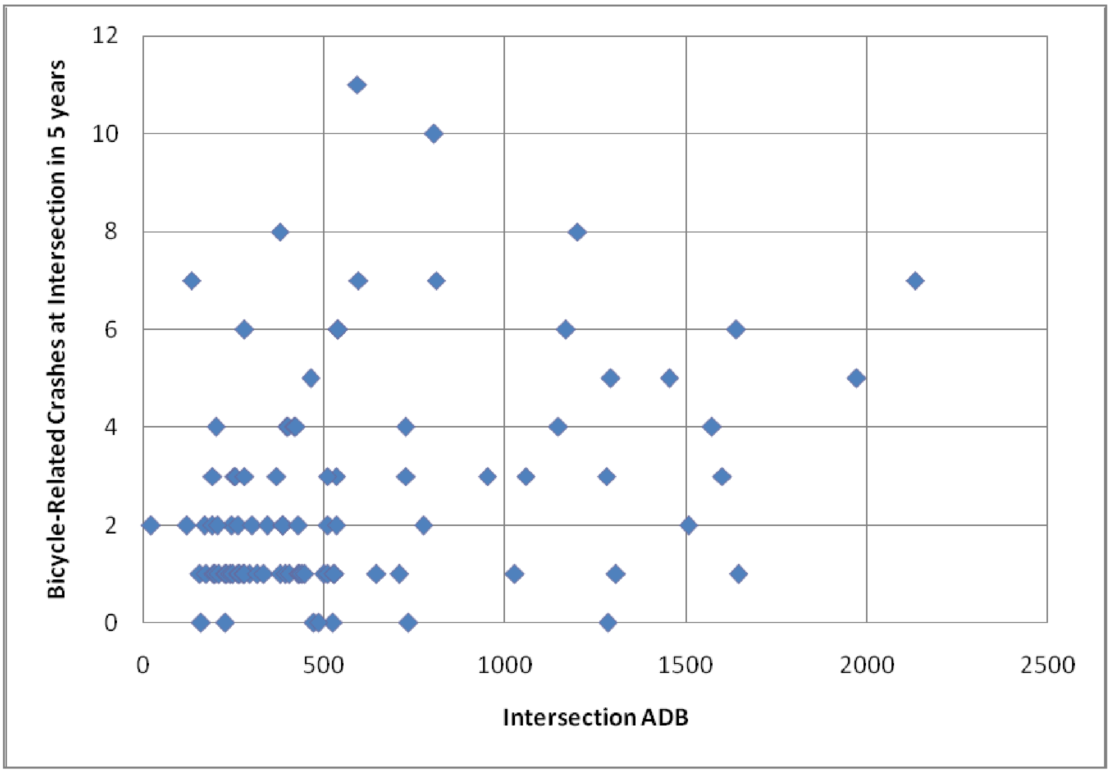

Figure 3. Bicycle-Related Crashes with Daily Bicycle Traffic

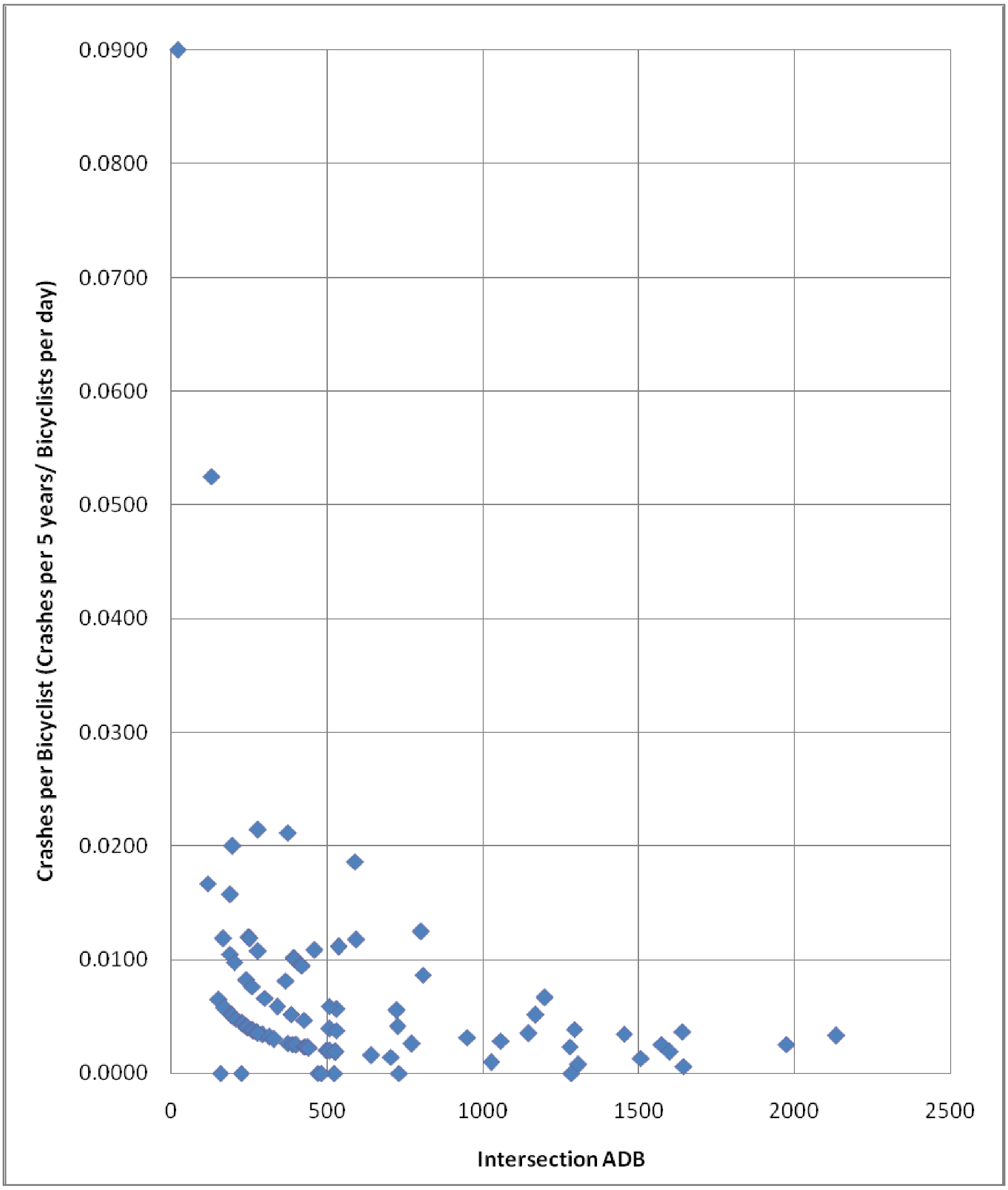

Figure 4. Crashes per Bicyclists with Daily Bicycle Traffic

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Retrofitting with Bioretention and a Bioswale to Treat Bridge Deck Stormwater Runoff

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Abstract. *Stormwater runoff from roadways is a source of surface water pollution in North Carolina. The North Carolina Department of Transportation (NCDOT) is required to implement stormwater BMPs in the linear environment. NCDOT has specific interest in runoff from bridge decks, which is often discharged through drainage holes in the deck directly to the stream below. This research focuses on retrofit stormwater BMPs for bridge deck runoff management. Two bioretention cells and a bioswale were constructed in the easement of a bridge deck on I-540 at Mango Creek. One bioretention cell was adequately sized based on current North Carolina design guidance, while the other was undersized by one-half. Undersized bioretention cells could often be used in retrofit situations; therefore, it is important to understand how an undersized bioretention cell performs with respect to hydrology and water quality. Both bioretention cells employed 0.9 m (3 ft) of fill media, and had an internal water storage layer (IWS) of 0.6 m (2 ft). The bioswale was designed to convey the 2-year storm event. Runoff was piped from the northbound and southbound lanes to the bioretention cells and bioswale, respectively.*

Data collection began in October 2009. Weirs and stage recorders were used to monitor inflow to and outflow from each BMP. Flow-proportional, composite water quality samples were obtained at the inlet and outlet of each BMP. Monitored water quality parameters include TKN, $NO_{2\text{-}3}$-N, NH_4-N, TN, TP, TSS, Cu, Zn, and Pb. For small storms (those with less than 1 in [2.5 cm] rainfall depth), flow volume reductions for the standard and undersized bioretention cells were 50% and 27%, respectively. This shows the hydrologic importance of sizing bioretention cells appropriately when space is available.

Average concentrations of TN (0.74 mg/L), TP (0.12 mg/L), and TSS (31 mg/L) from the bridge decks were relatively low when compared to other highways in North Carolina. Median effluent concentrations for the standard bioretention cell were lower than those for the undersized bioretention cell for all nutrient forms and sediment. Pollutant loads of TN, TP, and TSS were reduced to a much greater extent by the standard bioretention cell due to improved volumetric runoff reductions. The bioswale had similar influent and effluent concentrations for TN, TP, and TSS. Reductions in flow volume for the bioswale were not observed, resulting in poor pollutant load reduction.

Keywords. *Stormwater, BMPs, swales, undersized bioretention, urban runoff, bridge deck, retrofits.*

Introduction

The North Carolina Department of Transportation (NCDOT) is required through NPDES permits to treat stormwater runoff from its facilities across North Carolina. NCDOT has installed many retrofit stormwater devices across North Carolina and has researched the hydrologic and water quality function of several. While research has and is currently being done on runoff from highways in North Carolina, no research has been completed on runoff from bridge decks. In 2008, a total of 79,438 miles of paved highways existed in North Carolina (NCDOT 2008). The NCDOT currently maintains 12,712 bridges, which ranks 13th in the U.S. Little is known about stormwater discharges from bridges, which often discharges directly to surface waters through scupper drains.

During fiscal year 2008, the North Carolina state senate passed N.C. Bill 2008-107. Section 25.18 of this law requires the NCDOT to study the effect of bridge deck runoff from 50 bridges dispersed throughout the three ecoregions of North Carolina. It also mandates that NCDOT study the feasibility and effectiveness of various stormwater best management practices (BMPs) to treat priority pollutants from bridge decks; the results of this portion of the study are presented herein.

While runoff from highways has been studied in detail throughout the world, little research has been completed to characterize bridge deck runoff. A study in Charlotte, NC (Wu et al. 1998) found that an urban bridge deck had a mean runoff coefficient of 0.71. Mean total nitrogen (TN), total phosphorus (TP) and total suspended solids (TSS) concentrations were 2.24 mg/L, 0.43 mg/L, and 283 mg/L, respectively. Mean Cu and Pb concentrations were 24.2 µg/L and 21.0 µg/L. TN and TSS loads from the bridge deck were substantially larger than those from two other highways in the study (one rural and one urban).

Another bridge deck runoff study was completed in Baton Rouge, LA on an overpass on Interstate-10 (Sansalone et al. 2005). Results showed that EMCs of TSS (138 mg/L to 561 mg/L) and COD (128 to 1440 mg/L) were greater than from untreated wastewater in the area. Two bridge decks were studied in southeastern China (Gan et al. 2007). TN from the bridges was extremely elevated, with mean concentrations of 7.32 mg/L and 4.81 mg/L. Mean TP concentrations were 0.39 mg/L and 0.18 mg/L; mean TSS concentrations were 138 mg/L and 416 mg/L.

Yousef et al (1984) studied two bridge decks in central Florida; bridge deck runoff was shown to have elevated heavy metals concentrations when compared to nearby surface water bodies. Marsalek et al. (1997) contend that uncontrolled discharges from bridge decks could substantially impact receiving water bodies, and that stormwater BMPs are needed to remediate these discharges. Two BMPs that have shown promise for stormwater treatment are bioretention and swales.

Bioretention performance has been evaluated both in the laboratory and in the field (Kim et al. 2003; Hsieh and Davis, 2005; Davis et al. 2006; Dietz and Clausen 2006; Hunt et al. 2006; Davis 2007; Hsieh et al. 2007; Hunt et al. 2008; Li et al. 2009).

Research shows that effluent concentrations of TN, TP, TSS, hydrocarbons, and heavy metals are low in comparison to other stormwater BMPs. Also, bioretention can effectively mitigate peak flow rates and volumes through exfiltration of stormwater to the *in situ* soil. For these reasons, bioretention has become one of the most popular BMPs for new construction and in retrofit applications. Pollutant removal and hydrologic improvements from bioretention studies are presented in Table 1. To date, no research has been completed on undersized bioretention cells, which have the potential for widespread use in retrofit applications.

Table 1. Pollutant removal and hydrologic mitigation from bioretention studies in the mid-Atlantic region.

Site Location	Load Reduction (%)	Influent Concentration (mg/L)	Effluent Concentration (mg/L)	Reference
TN Removal				
Louisburg, NC	65	1.7	1.25	Li et al. (2009)
Greensboro, NC	40	1.35	4.38	Hunt et al. (2006)
Charlotte, NC	N/A	1.68	1.14	Hunt et al. (2008)
Graham, NC	56	1.66	0.76	Passeport et al. (2009)
Graham, NC	47	1.66	0.76	Passeport et al. (2009)
TP Removal				
Louisburg, NC	69	0.28	0.18	Li et al. (2009)
Greensboro, NC	-240	0.11	0.56	Hunt et al. (2006)
Charlotte, NC	N/A	0.19	0.13	Hunt et al. (2008)
College Park, MD	79	0.61	0.15	Davis (2007)
College Park, MD	77	0.61	0.17	Davis (2007)
Graham, NC	53	0.14	0.05	Passeport et al. (2009)
Graham, NC	68	0.14	0.06	Passeport et al. (2009)
TSS Removal				
Charlotte, NC	N/A	49.5	20	Hunt et al. (2008)
College Park, MD	59	34	18	Davis (2007)
College Park, MD	54	34	13	Davis (2007)

A research team in Northern Sweden studied several different grassed swales (Backstrom 2002; Backstrom 2003). They found that the swales retained significant amounts of particulate matter during high pollutant loading events. However, when the swales received TSS concentrations below 40 mg/L, pollutant concentrations increased as the water moved through a dry swale. Particles smaller than 25 µm were not trapped efficiently. TSS concentrations were reduced by 79-98% in two laboratory swales and seven field swales (Backstrom, 2003). Dissolved pollutants did not receive any perceptible treatment. The swales studied were regarded as facilities that even out pollutant peak loads, but were not able to consistently reduce pollutant loads.

Export of nitrogen and phosphorus was observed at two field tested swales in Florida (Yousef et al. 1985; Yousef et al. 1987). While concentrations of dissolved heavy metals decreased with increasing swale length, similar conclusions could not be made for N and P species.

Two swales were studied along highway medians in Virginia (Kaighn and Yu 1996). TSS concentrations were reduced by 30% and 49%, while mixed results were observed for COD, TP, and Zn. The authors note that significant variability exists in the swale literature, but that swale design should generally be based upon length, cross-sectional shape, slope, design flow rate, type of vegetation, and infiltration rate of the soil. In another field test of dry swales, Yu et al. (2001) showed that check dams along the swale substantially improve performance for TSS and COD. Mass of TN was reduced by 13%-24%, while TP reductions ranged from 29%-77% at four swales in Taiwan. Kercher, Jr. et al. (1983) argue that swales are preferable to traditional curb-gutter-pipe systems because they help to reduce pollutant loading and they require less land area than conventional systems.

The goals of this research are threefold: (1) examine the quality and quantity of runoff from a raised bridge deck located on I-540 in Knightdale, North Carolina; (2) examine the impact of correctly sized and undersized bioretention cells on bridge deck runoff; and (3) examine the impact of a bioswale on bridge deck runoff.

Methods

To determine the quality and quantity of bridge deck runoff, monitoring was undertaken at a site in eastern Wake County, North Carolina (Figure 1). The site is located just south of the intersection of I-540 and U.S. 64 bypass. Both the northbound and southbound lanes of the bridge at the intersection of I-540 and Mango Creek are being monitored for hydrologic and water quality parameters.

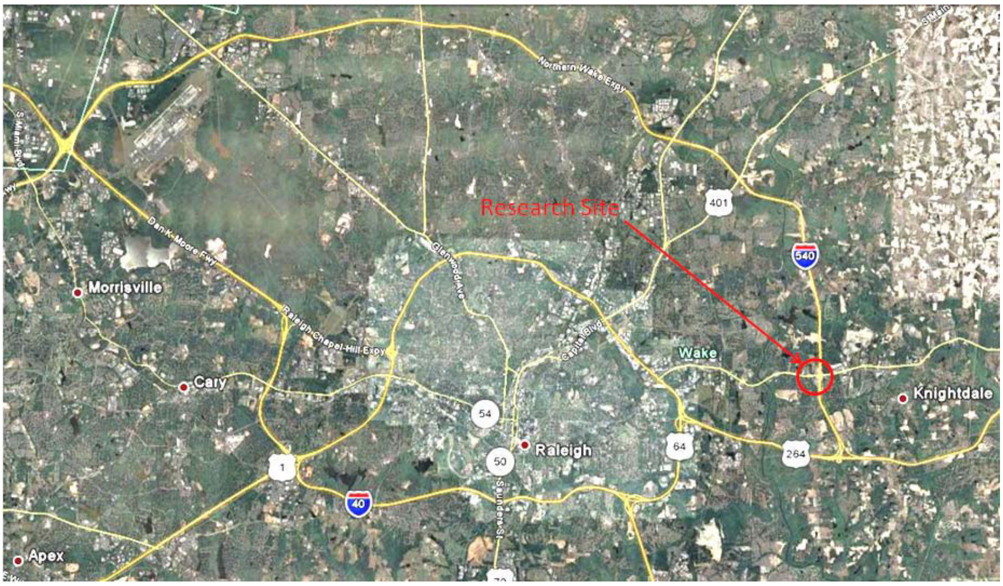

Figure 1. Location of Mango Creek research site.
Source: Googlemaps (2010).

The bridge deck over Mango Creek is three lanes in both directions, with an associated emergency lane (Figure 2). Each bridge deck is roughly 18.3 m (60 ft) wide with a total area of 7,190 m^2 (77,400 ft^2). The bridge decks have scuppers (i.e. drainage orifices) at approximately 3.4 m (11 ft) intervals. Engineering designs were created to route stormwater from the scuppers for a portion of the bridge deck to three stormwater BMPs: a bioswale, a standard bioretention cell with an internal water storage (IWS) layer (hereafter the "standard" cell), and a bioretention cell with half of the standard surface area based upon current NC standards (hereafter the "undersized" cell) (NC DENR 2007). The existing scuppers on both the northbound and southbound bridge deck were retrofitted to drain to 30.5 cm (12 in) diameter PVC pipe (Figure 3). The pipe under the southbound lanes discharged to the bioswale. The flow from the pipe under the northbound lanes was split proportionally, and discharged to both the small and large bioretention cells.

Figure 2. Mango Creek bridge deck (northbound lanes).

Figure 3. Pictures of water delivery systems for bioretention and bioswale.

Both the standard and undersized bioretention cells were designed to be "state of the art" with each having a 23 cm (9 in) ponding depth, a 0.9 m (3 ft) media depth, and a 0.6 m (2 ft) deep IWS layer. The engineered soil media met the current NC DENR regulations of 85-88% sand, 8-10% silt and clay, and 3-5% organic matter (NC DENR 2007). Both bioretention cells were vegetated with Centipede grass sod and had rock-lined forebays to still stormwater as it entered the cells (Figure 4). Other selected characteristics of the two bioretention cells are presented in Table 2. The design surface area of the undersized bioretention cell was one-half that of the standard cell. The system storage volume (i.e. bowl storage, forebay storage, and soil and gravel layer storage) of the undersized cell was 55.6% of the system storage volume of the standard cell.

Figure 4. Standard (left) and undersized (right) bioretention cells at Mango Creek.

Table 2. Characteristics of standard and undersized bioretention cells.

Characteristic	Standard Bioretention Cell	Undersized Bioretention Cell
Length (m)	30.5	21.6
Width (m)	6.1	4.3
Surface Area (m^2)	186	93
System Storage Volume (m^3)	153.8	85.6

The bioswale at the Mango Creek bridge deck was designed to treat the 2-year storm as well as to safely convey the 10-year storm (Figure 5). A rock-lined forebay and straw wattles were used to still flow as it entered the bioswale. The swale had a v-shaped geometry with a 45.7 m (150 ft) length, a sinuous planform, and a 2% longitudinal slope. The bioswale was vegetated with tall fescue sod, and then overseeded with 0.7 kg (1.5 lbs) of bluegrass and 0.7 kg (1.5 lbs) of fescue per 93 m^2 (1,000 ft^2).

Figure 5. Bioswale at Mango Creek.

Monitoring of hydrologic parameters was undertaken at six locations. The inlet to both bioretention cells and the bioswale were fitted with a compound weir (Figure 6, at left), with a 120° v-notch lower potion and a rectangular upper portion. The same weirs were used to measure outflow from the bioretention cells inside drop inlets; outflow rates were measured as the combination of overflow and underdrain flow. A wooden weir box with an associated compound weir was used to measure flow rates at the outlet of the bioswale (Figure 6, at right). ISCO 730 bubbler modules were used to measure the depth of flow over each weir and to calculate flow rate using a derived step-wise stage-discharge relationship, which was field verified.

Monitoring of water quality occurred at five locations: the inlet and outlet of the bioswale, at the inlet to one bioretention cell, and at both bioretention cell outlets. This monitoring design assumes that the stormwater entering both bioretention cells is of similar quality. The flow volumes calculated using the bubbler-weir combination were used by an ISCO 6712 water quality sampler to take flow-proportional, composite samples at each sampling location. Water quality samples were taken to a lab on ice within 24 hours of the end of rainfall, and were analyzed within standard holding times. Samples were analyzed for total Kjeldahl nitrogen (TKN), nitrate-nitrite nitrogen ($NO_{2\text{-}3}$-N), total nitrogen (TN), ammonium nitrogen (NH_4), total phosphorus (TP) and total suspended solids (TSS). Samples were also analyzed for copper (Cu), zinc (Zn), and lead (Pb).

Figure 6. Monitoring installation at inlet (left) and outlet (right) of bioswale.

Results and Discussion

Data collection began in October 2009, and will continue through December 2010. To date, 12, 9, and 12 storms have been collected for nutrient and TSS analysis at the standard bioretention cell, the undersized bioretention cell, and the bioswale, respectively. A summary of rainfall depths for sampled storm events at each of the three BMPs is presented in Table 3.

Table 3. Summary of rainfall for sampled storm events.

Date Sampled	Rainfall Depth (cm)	Standard Bioretention Sample	Undersized Bioretention Sample	Bioswale Sample
11/2/2009	2.57	☑		☑
11/13/2009	10.77	☑	☑	
11/20/2009	1.09		☑	☑
11/24/2009	1.32	☑	☑	☑
12/4/2009	3.58	☑	☑	☑
12/7/2009	1.07		☑	☑
12/10/2009	4.01	☑	☑	☑
12/14/2009	0.68		☑	
1/18/2010	3.58	☑	☑	☑
1/23/2010	2.46	☑	☑	☑
1/26/2010	2.06	☑	☑	☑
2/10/2010	0.66		☑	☑
2/23/2010	0.58			☑
3/3/2010	1.32	☑	☑	☑

Bioretention Results

Nutrients

Bioretention has been shown to be an effective tool for reducing nutrient concentrations from urban stormwater. However, no data exists for undersized bioretention cells. Effluent concentrations for the standard and undersized bioretention cells are presented in Table 4.

Table 4. Median nutrient concentrations for the bioretention cells at Mango Creek.

Median Concentration (mg/L)						
Sampling Location	TKN	NO_{2-3}-N	TN	NH_4N	TP	TSS
Bioretention Inlet	0.34	0.24	0.66	0.11	0.07	20
Standard Bioretention Outlet	0.21	0.10	0.23	0.03	0.07	7
Undersized Bioretention Outlet	0.26	0.16	0.45	0.05	0.08	13

For all nutrient forms and TSS, influent concentrations were reduced by both the standard and undersized bioretention cells. In all cases, the median effluent concentration from the standard bioretention cell was lower than that of the undersized bioretention cell. For TP, the undersized bioretention cell produced nearly the same effluent concentrations as that of the standard cell. However, this may have been due to the near-irreducible influent concentration. While the undersized bioretention cell did not treat stormwater to the same level as the standard cell, the results presented above could allow undersized bioretention cells to receive a portion of the credit that appropriately designed and sized bioretention cells receive.

Another metric that can be used to assess stormwater BMP performance is the use of a target effluent concentration. McNett et al. (2010) characterized water quality levels by correlating various in-stream pollutant concentrations to benthic macroinvertebrate health. In the Piedmont of North Carolina, good water quality concentrations for TN and TP are 0.99 mg/L and 0.11 mg/L, respectively. These concentrations are shown in Figures 7 and 8 as horizontal lines. Target concentrations for TSS are more difficult to establish; in lieu of a standard, a TSS concentration of 25 mg/L has been used as a baseline in Figure 9. For TN, effluent concentrations for both the standard and undersized cells were always below the target water quality level. For TP, one storm event for the undersized cell had an effluent concentration above the 0.11 mg/L benchmark, while the standard cell always produced effluent concentrations below 0.11 mg/L. A similar trend was noted for TSS, where one storm event produced effluent concentrations above 25 mg/L for the undersized cell. It may also be noted that the influent stormwater was relatively "clean" in terms of TN, TP, and TSS, with almost all data points below the good water quality concentrations.

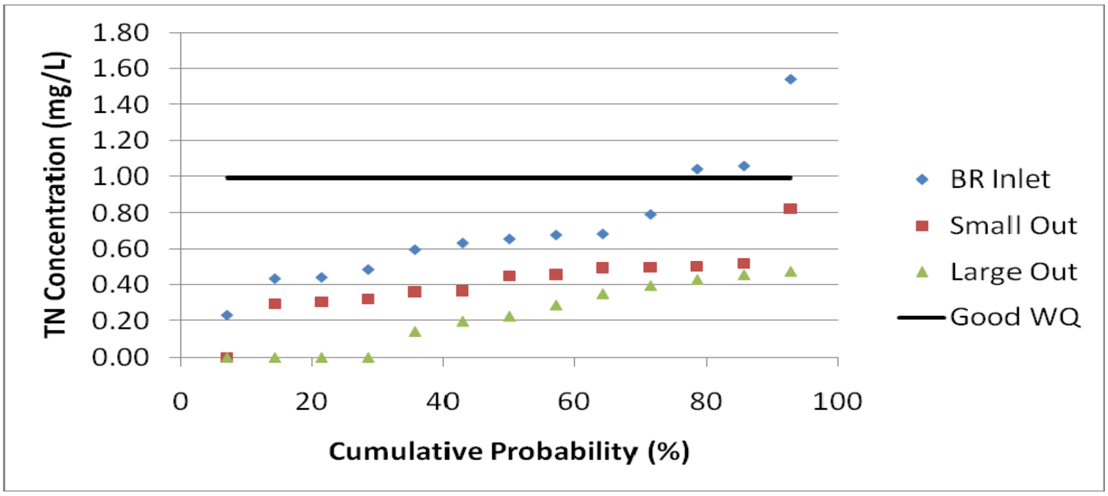

Figure 7. Bioretention Cumulative Probability Plot for TN.

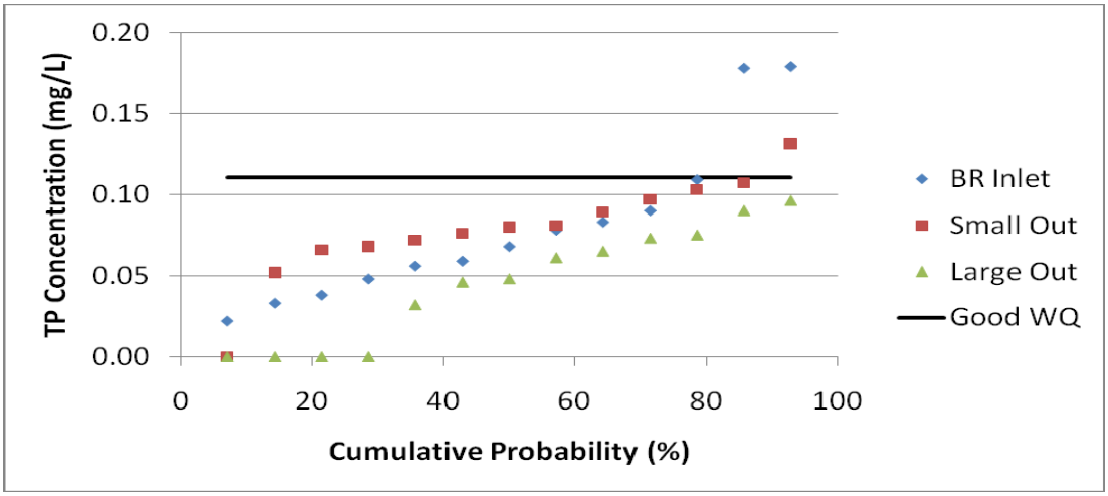

Figure 8. Bioretention Cumulative Probability Plot for TP.

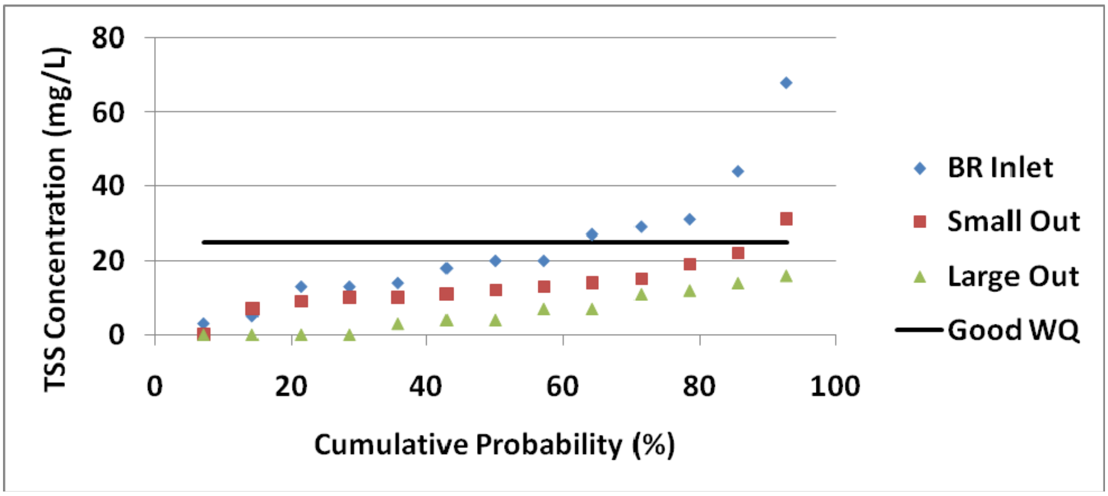

Figure 9. Bioretention Cumulative Probability Plot for TSS.

Heavy Metals

Heavy metals are an urban pollutant of concern that are often derived from vehicular use; no data exist in the literature as to how undersized bioretention performs for reducing metal concentrations. Table 5 presents heavy metal data for five storm events. Median concentrations of copper and zinc were reduced between the inlet and outlet of the bioretention cells. Interestingly, the undersized bioretention cell performed at least as well as the standard cell when the effluent concentration metric was utilized. This may be an artifact of the small number of sampled storms.

Table 5. Median total heavy metal concentrations for the bioretention cells at Mango Creek.

Median Concentration (μg/L)			
Sampling Location	Cu	Zn	Pb
Bioretention Inlet	30	80	BDL
Standard Bioretention Outlet	20	30	BDL
Undersized Bioretention Outlet	10	30	BDL

Hydrology

Hydrologic measurements have been recorded for 14 storm events with rainfall depths less than 2.54 cm (1 inch) for both the standard and undersized bioretention cells. For the standard bioretention cell, the largest storm event with no outflow had a rainfall depth of 1.30 cm. For the undersized cell, the largest storm event that was entirely captured had a rainfall depth of 0.81 cm. Cumulative volume reductions for the 14 storm events were 50% for the standard cell and 27% for the undersized cell. Mean peak flow rates were reduced by 95% by the standard cell and 58% by the undersized cell. These data show the importance of correctly sizing bioretention cells for hydrologic performance; clearly the undersized bowl volume contributes to a consistently greater fraction of outflow and larger peak outflow rates.

Bioswale Results

Nutrients

Roadside swales are nearly ubiquitous practices used to drain highways across the U.S. and the world. However, little data exists on swales used to treat stormwater runoff from bridge decks. Median effluent concentrations from six storm events are presented for the bioswale in Table 6.

Table 6. Median nutrient concentrations for the bioswale at Mango Creek.

Sampling Location	TKN	$NO_{2\text{-}3}$-N	TN	NH_4N	TP	TSS
Bioswale Inlet	0.42	0.21	0.68	0.12	0.08	36
Bioswale Outlet	0.45	0.23	0.66	0.09	0.12	22

The bioswale at Mango Creek did not substantially reduce the concentrations of TN or TP derived from the bridge deck stormwater. Median NH_4N concentrations were reduced by 25% and median TSS concentrations were reduced by 39%. The relatively poor performance for nitrogen and phosphorus species may be due to the low influent concentrations.

Cumulative probability plots for TN, TP, and TSS for the bioswale were compared against indicators of good water quality in North Carolina (0.99 mg/L for TN, 0.11 mg/L for TP, and 25 mg/L for TSS) (McNett et al. 2010). While substantial reductions in TN did not occur (see Table 6) in the bioswale, effluent concentrations often were below the good water quality standard for TN (Figure 10). Median TP concentrations increased in the bioswale, and half of the storms sampled had effluent TP concentrations above good water quality levels (Figure 11). While TSS concentrations were reduced in the bioswale, four of the eleven sampled storms had effluent TSS concentrations above the 25 mg/L benchmark (Figure 12).

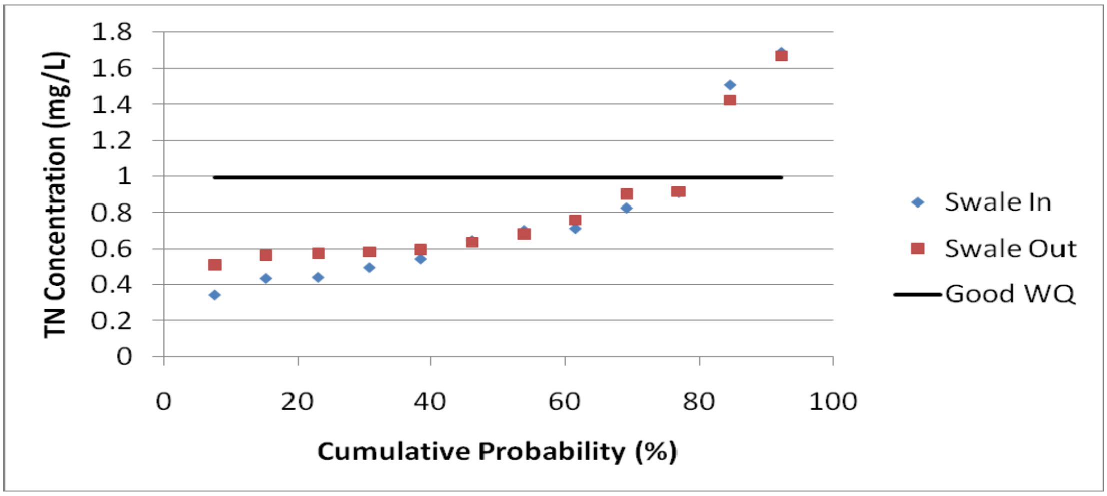

Figure 10. Bioswale Cumulative Probability Plot for TN.

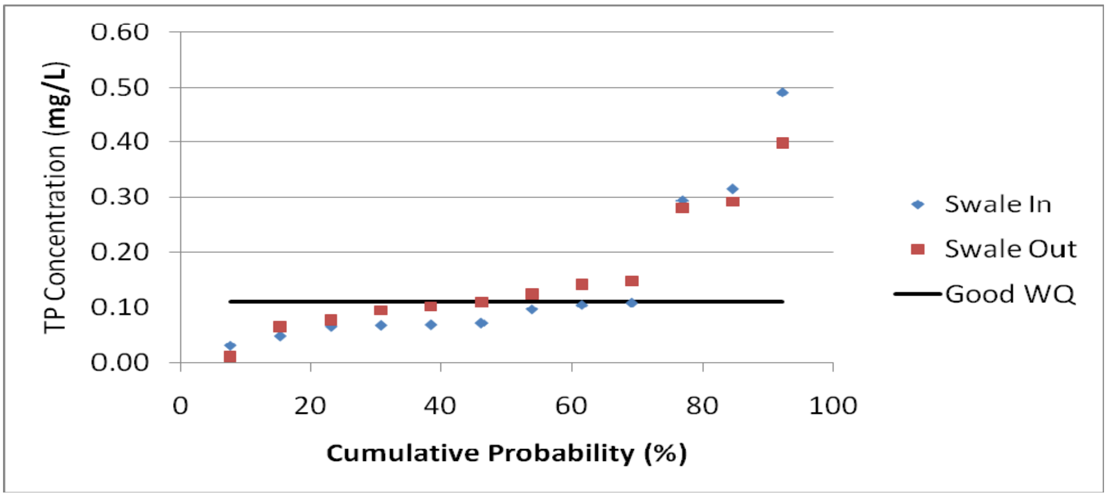

Figure 11. Bioswale Cumulative Probability Plot for TP.

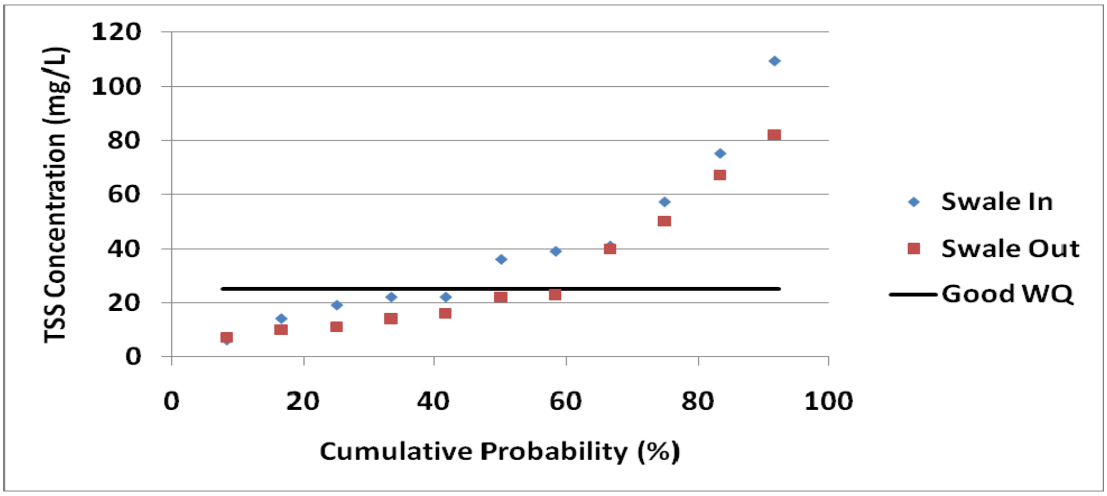

Figure 12. Bioswale Cumulative Probability Plot for TSS.

Heavy Metals

Median heavy metals concentrations are presented in Table 7 for the seven storm events that have been sampled at the bioswale. Median copper and zinc concentrations were reduced as the stormwater passed through the bioswale. Perhaps this was due to the reduction in TSS concentration noted above, as heavy metals are often associated with sediment particles.

Table 7. Median total heavy metal concentrations for the bioswale at Mango Creek.

Median Concentration (μg/L)			
Sampling Location	Cu	Zn	Pb
Swale Inlet	30	100	BDL
Swale Outlet	0	80	BDL

Hydrology

Because the soils onsite were clayey and substantial soil compaction occurred during construction, little infiltration was expected in the bioswale. Therefore, pollutant load reduction of this system was also expected to be relatively poor. Thus far, twelve storm events with rainfall depths less than 2.54 cm have been monitored, with a 0% cumulative volume reduction. Soil amendments or other methods to reduce compaction may be needed if infiltration is desired in a swale.

Bridge Deck Water Quality

For NCDOT, it is important to delineate the differences between runoff quality from roadways and bridge decks, so that appropriate treatment technologies can be used to improve water quality. In Tables 4 and 5, the rows labeled "bioretention inlet" and "bioswale inlet" are representative of the water quality of the northbound and southbound bridge decks, respectively. Pollutant concentrations from each bridge deck are similar for all nitrogen and phosphorus species; median TSS concentrations from the two bridge decks were 20 mg/L and 36 mg/L. Concentrations of TN, TP, and TSS from the Mango Creek bridge decks were well below those from bridge decks studied in Charlotte, NC (TN = 2.24 mg/L, TP = 0.43 mg/L, and TSS = 283 mg/L) (Wu et al. 1998). TSS concentrations were also well below the 138 mg/L reported in bridge deck studies in China (Gan et al. 2007) and Louisiana (Sansalone et al. 2005). Perhaps this is due to differences in dustfall and/or maintenance in China, Louisiana, and North Carolina. The bridge deck at Mango Creek produces relatively cleaner stormwater than other bridge decks in the literature; these reduced concentrations will lead to lessened performance for the bioretention cells and bioswale when using the percent concentration reduction metric.

Conclusions

NCDOT has constructed and maintains 13,712 bridges in North Carolina. In 2008, the N.C. senate passed N.C. Bill 2008-107, which requires the treatment of runoff from these bridge decks to maintain stream health. In this study, three stormwater BMPs were studied to ascertain their effectiveness in treating bridge deck runoff: a standard bioretention cell, an undersized bioretention cell, and a bioswale. Additionally, bridge deck runoff quality was studied.

Bridge deck runoff concentrations for TN, TP, and TSS at the Mango Creek site were well below those for other bridge deck runoff studies in the literature. The standard bioretention cell produced lower nutrient and TSS effluent concentrations than the undersized bioretention cell. The standard bioretention cell reduced runoff volumes to a greater extent than the undersized cell (50% vs. 27%) for all storm events less than 2.54 cm. Undersized bioretention cells will not reduce pollutant loads to the same extent as properly sized bioretention cells. The bioswale studied at Mango Creek did not substantially reduce nutrient concentrations or runoff volumes. Concentrations of heavy metals (Cu and Zn) were reduced by both the bioretention cells and the bioswale.

Acknowledgements

The authors would like to thank the NCDOT for funding this research. We are also grateful to URS Corporation, who designed the BMPs, and NCDOT for BMP installation. The authors thank Shawn Kennedy, who helped immensely with monitoring equipment installation and troubleshooting. Finally, the authors acknowledge the North Carolina State University Center for Applied Aquatic Ecology (CAAE) laboratory for their analysis of water quality samples.

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Towards Green Bridges

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ABSTRACT:
There is no industry standard to define a green bridge. Green standards have been successfully implemented in other industries and can be used as a guide for developing a green standard for bridges. The goals of green design include reducing life cycle costs, energy use, greenhouse gas emissions, pollution emissions, waste, and the use of non-renewable resources to sustainable levels.

The Greenbridges standard proposed herein is meant to provide a starting point for discussions between bridge professionals and the existing developers of highway and infrastructure sustainability rating systems. Greenbridges has a total of six prerequisites and thirty-nine points grouped into seven categories. The categories are: materials & resources, alternative transportation, project delivery process, construction activity, maintenance & access, environment & water, and energy.

Until a standard is available, three primary strategies for reducing environmental impacts of bridge projects are to design for minimum life cycle costs, to use recycled materials to the maximum economical extent, and to provide preferential access to alternative (non-single-occupancy motor vehicles) transportation modes.

IMPETUS FOR GREEN BRIDGES

The goals of green design include reducing life cycle costs, energy use, greenhouse gas and pollution emissions, waste, and the use of non-renewable resources to sustainable levels. According to our code of ethics, Professional Engineers "are encouraged to adhere to the principles of sustainable development in order to protect the environment for future generations." ASTM E2114 defines that sustainable development "meets the needs of the present without compromising the needs of future generations."

It is clear that the existing global patterns of energy use and levels of greenhouse gas emissions are unsustainable. Engineers working in all industries, including the bridge industry, are charged with making the necessary changes.

RECYCLED MATERIALS

A logical first step towards greener bridges is to favor recycled, recyclable, and industrial by-product materials.

Recycled Steel

Structural and reinforcing steel in the USA contains 96% total recycled content (59% post-consumer) as a matter of course. Steel recycling is economically driven by the scrap value of approximately 0.25 dollars per pound. It is to steel's benefit that it is already highly recycled and recyclable, however the process remains energy intensive. Worrell (1999) documents many opportunities for improving the energy efficiency of the steel industry. However, these changes will primarily be driven by government policy decisions, not by revisions to bridge steel specifications. There is no opportunity for bridge engineers to specify "green" steel.

Concrete & Pozzolan Cements

There are significant opportunities for bridge engineers to specify "green" concrete because the energy use and greenhouse gas emissions vary drastically depending on the mix used. Five percent of the world's greenhouse gasses are attributed to the Portland cement used in concrete. China is the world's largest emitter of carbon dioxide; twenty percent of which is attributed to their kilns used for cement production. Portland cement emits more than one ton of carbon dioxide for every ton of cement produced.

Greenhouse gas emissions are zero for pozzolan cements. Use of naturally occurring pozzolan cements (of volcanic origin) dates back to the Roman Empire, as documented by Vitruvius in 25 B.C. Similar natural pozzolan cements were used for the substructures of the Oakland-Bay Bridge and Golden Gate Bridges; both constructed in California in the mid-1930's.

Modern pozzolan cement, referred to as Supplementary Cementing Materials (SCM) or mineral admixtures, are typically not volcanic in origin, but industrial by-products such as fly-ash, blast furnace slag, and silica flume. They, therefore, have no carbon emissions associated with manufacture. Unlike Portland cement, pozzolan cements have no carbon emissions associated with calcination.

Concrete made with a blend of Portland cement and pozzolan cement admixtures has been well established in the bridge industry for over 50 years. Typical specifications call for fifteen percent of the cement, by weight, to be fly-ash with the remainder Portland cement. High performance concrete commonly uses silica flume admixtures of up to ten percent.

Several recent bridge projects have successfully utilized higher percentages of pozzolan cements. The St. Anthony Bridge in Minnesota reduced the carbon emissions associated with cement by up to 85% by using mixes with 69% slag, 16% fly ash, and 15% Portland cement. The New York Times (2009) wrote a positive article and graphic diagram on the "green" concrete used for this bridge. The Sunshine Skyway Bridge in Florida used concrete mixes with fly ash content of 50% replacement for Portland cement. The Cooper River Bridge in South Carolina used 43% fly ash; the low permeability of this concrete allowed for the use of uncoated rebar to meet a 100-year design life.

The use of pozzolan cements as admixtures has focused on the lower material costs and improved material properties, such as permeability and strength, when compared with pure Portland cement. The reduced energy use and greenhouse gas emissions have merely been a happy side-benefit. To date, the majority of bridges built with high percentages of pozzolan cement have been design-build projects with construction cost savings and improved materials properties driving the material selection. Traditional design-bid-build projects have rarely used high percentages of pozzolan cement, instead defaulting to standard specifications instead of project specific concrete mix design.

There is significant opportunity for increased use of pozzolan cements in the bridge industry; the majority of fly-ash, a proportion of which is structural grade, continues to be landfilled.

Concrete has no scrap value. When demolishing existing concrete structures, the waste concrete will likely be landfilled unless the contract documents require recycling. The reinforcing steel, however, is likely to be recycled regardless. Per the Steel Recycling Institute, 65% of the reinforcing steel from concrete structures demolished in the US in 2006 was recycled. To remove the reinforcing steel, the concrete must first be crushed.

Aggregates for Concrete

When locally available, by-product aggregates including waste rock from quarries, mines or mills, are environmentally preferable to virgin aggregates.

Recycled & By-Product Wearing Surfaces

It is common in many states for reclaimed asphalt pavement to be recycled into hot-mix or warm-mix pavement and for reclaimed concrete pavement to be recycled as aggregate for new pavements. Concrete made with reclaimed concrete aggregate has reduced strength, but is suitable for barriers, pavements, and non-structural applications. Crushed waste concrete is also commonly recycled (downcycled) for use in highway base courses or fill.

Lightweight synthetic aggregates made from a blend of fly-ash and recycled plastic have been developed by the University of New Hampshire. This synthetic aggregate can be used in lightweight concrete that meets ACI standards and is awaiting field tests for bridge decks.

"Synthesis of Highway Practice 199: Recycling and the Use of Waste Materials and By-Products in Highway Construction" by Collins and Ciesielski (1994) provides an extensive review of available materials and uses. Examples include using shredded scrap tires and roofing shingle waste in wearing surfaces. Using scrap tires in asphalt has been found to increase pavement life and reduce road noise.

Recycled Plastic Piles

The primary bridge related application for recycled plastic piles has been for pier protection fenders, in conjunction with recycled plastic lumber. Various styles and manufacturers of plastic piles are available. They typically consist of a recycled plastic matrix, a uv protecting additive, and structural reinforcement. The structural reinforcement can be glass fibers embedded in the plastic matrix or bar-sized cages of steel, fiber glass or FRP. Recycled plastic piles have been used by CalTrans, New Jersey DOT, Virginia DOT, New York State DOT, and the Port Authority of NY&NJ.

The US Navy has used recycled plastic piles with internal steel reinforcing bars at installations around the world to replace timber fender systems. Per Alling (1998) of the Naval Postgraduate School, while the initial material costs for plastic piles are more expensive than timber (approximately double), the plastic piles have significantly lower life cycle costs due to decreased maintenance and replacement costs (plastic piles last double to ten times longer).

A different style of composite pile consists of an FRP tube (not recycled plastic) filled with otherwise un-reinforced concrete. Virginia DOT has experimentally used these piles as load carrying members for the pier foundations of two bridges.

Construction Waste

Bridge construction projects generate large amounts of construction waste which typically is landfilled. Green building projects often divert 95% of the construction waste for recycling or re-use. The extra labor required to sort the waste is more than paid for by the scrap payments and elimination of landfill tipping fees. The online Construction Waste Management Database developed by the National Institute of

Building Science can provide the contact information for nearby companies that haul, collect, and process recyclable construction debris.

Recycled Materials Standards

Countless existing standards, published by AASHTO, ASTM, ACI and others are available to specify the recycled materials discussed herein for bridge work. The "User's Guide for By-Products and Secondary Use Products in Pavement Construction" published by Recycled Material Resource Center of the University of New Hampshire (2009), provides a thorough and up-to-date reference.

EXISTING GREEN DESIGN STANDARDS

There is no industry standard to define the attributes of a green bridge.

Two existing highway sustainability rating systems, Greenroads and GreenLITES, have been applied to bridge projects. The Federal Highway Administration (FHWA) is in the process of creating a Sustainable Highways rating system, to be released at the end of 2010. Since these systems have been created and weighted for highway and not bridge projects, it is not yet clear that they are fully applicable.

The American Society of Civil Engineers (ASCE), in partnership with the American Public Works Association (APWA) and the American Council of Engineering Companies (ACEC), is creating an sustainable infrastructure project rating system, to be released at the end of 2010. Harvard University has also established the Zofnass Program which is creating a framework for evaluating infrastructure sustainability. Since both of these programs aspire to rate the sustainability of all forms of infrastructure, at all scales, they aspire to be applied to bridge projects.

It is not yet clear which, if any, of the above systems will be implemented by the bridge industry and become a standard.

All green standards require more than just a publisher. They also require a dedicated professional staff to administer project applications and documentation.

PROPOSED GREEN BRIDGE STANDARD

The proposed Greenbridges standard has a total of six prerequisites and thirty-nine points grouped into seven categories. The categories are: materials & resources, alternative transportation, project deliver process, construction activity, maintenance & access, environment & water, and energy. A summary of each category is provided below. Details of each point are found in Appendix A, including references to similar points in the LEED, SPiRiT, and Greenroads standards.

The Greenbridges standard proposed below is not meant to be a functioning green standard. It is meant to provide a starting point for discussions between bridge professionals and the developers of highway and infrastructure sustainability rating systems.

The Greenbridges standard proposed below draws from three existing green design standards: LEED, SPiRiT, and Greenroads. LEED is an acronym for Leadership in Energy and Environmental Design; this standard certifies green buildings. LEED is administered by the US Green Building Council, a non-profit organization founded in 1993. SPiRiT is the Sustainable Project Rating Tool developed by the US Army for their facilities. Since 2000 all new army facilities and infrastructure have been required to be built to green standards. Greenroads was introduced in 2009 to certify roadway and pavement projects. This standard was developed at the University of Washington with funding from the federal US Department of Transportation as well as several state and regional departments. Greenroads documentations states "Bridges, tunnels, walls and other structures are not explicitly considered in Greenroads, but they are not explicitly excluded either." and "Comments are welcome regarding adjustments that would need to be made to be more reflective of sustainable activities for bridges and tunnels."

Materials & resources
Six Credits: Use materials that are recycled, recyclable, and industrial by-products. One credit is earned for recycled material content of 20% with additional credits accumulated for 40%, 60%, 80% and 90%. Use regionally extracted and manufactured materials to reduce the impacts of shipping. Regional is defined by an eight hundred kilometer (500 mile) radius from the project site.

Alternative transportation
Five Credits: Encourage transportation alternatives to single occupancy motor vehicles. Provide pathways for pedestrians and cyclists. Provide designated lanes for busses, light-rail transit, car pools, and low-emission vehicles.

Project delivery process
One Prerequisite: Perform bridge life cycle cost analysis in accordance with NCHRP Report 483. Perform life cycle assessments, using the free software eiolca.net, to compare the environmental impacts of competing bridge proposals.
Seven Credits: Use design charettes to develop context sensitive solutions. Consider future uses and demolition/salvage of the bridge. Develop innovative designs. Include green design accredited professionals.

Construction activity
Three Prerequisites: Divert 75 % of the on-site construction and demolition waste from landfills for reuse or recycling. Control erosion and stormwater. Prepare a construction noise mitigation plan.
Six Credits: Track water and electricity use. Provide on-site environmental awareness training. Reduce fossil fuel use and emissions of the construction equipment.

Maintenance & access
Two Credits: Produce a maintenance manual at the time of design, including estimated maintenance activities, frequencies and costs. Provide safe and productive maintenance access.

Environment & water
One Prerequisite: Comply with the applicable environmental laws.
Nine Credits: Minimize destruction to the local ecology around the bridge site. Minimise erosion, stormwater sedimentation, construction dust, particulate, noise, and light pollution. Minimise the heat island effect. Prefer the redevelopment of brownfield or urban sites instead of developing agricultural or wetland sites. Use native vegetation with no irrigation.

Energy
One Prerequisite: Commission the bridge electrical systems after construction to verify that the actual energy used conforms to the design values.
Four Credits: Minimise the life cycle costs of the bridge electrical equipment and lighting. Sign a multi-year contract to procure grid-source green electricity.

The proposed Greenbridges standard will be used to award points to bridge projects. A designated minimum point value (15 points, for example) will be required for a bridge project to be certified as green.

LIFE CYCLE ASSESSMENT

Life cycle assessment can be used during the study phase of bridge projects to compare the environmental impacts of competing proposals. Carnegie Mellon University has developed free software, available at www.eiolca.net, which is well suited for the assessment of bridge projects.

The first step is to perform a bridge life cycle cost analysis in accordance with NCHRP Report 483 (as mandated by SAFETEA-LU legislation). This total life cycle cost includes agency, user, and vulnerability costs. The agency costs include design, construction, maintenance, rehabilitation, and salvage/disposal.

Life cycle costs are the inputs used by the www.eiolca.net software to determine the project outputs in terms of global warming potential, conventional pollution, toxic releases, energy use, as well as employment and economic activity. The life cycle assessment of each bridge is estimated to require 40 man-hours to perform.

The environmental impacts associated with construction and maintenance have a similar order of magnitude over the life of the bridge. This is based on typical annual bridge maintenance costs of 1% of bridge replacement costs, as reported by Yanev (2007) of the New York City DOT.

Since a large proportion of maintenance resources are used to maintain paint, joints, and drainage, bridge designs that minimize or eliminate this work are preferred.

Which structural material is environmentally preferable: steel or concrete? Bridge engineers can answer this question for specific projects by performing life cycle assessments of the competing proposed design alternatives. Life cycle assessments published by Horvath (1998), Dennison (2004), and Struble (2004) indicate that embodied energy and greenhouse gas emissions are of the same order of magnitude for steel and concrete bridges. Concrete bridges using high percentages of pozzolan cement will tend to be environmentally preferable when compared with painted steel bridges.

BRIDGES AND CLIMATE CHANGE

The Transportation Research Board published Report 290 (2008) entitled "Potential Impacts of Climate Change on US Transportation". This report says "there is a need for making changes in [design] standards that focuses first on long-lived facilities, such as bridges (page 11)." The report indicates that the solution for dealing with climate change will be a combination of two strategies: adaptation and mitigation.

The adaptation strategy means adjusting to the climate changes that will occur. In terms of bridge design, this means designing based on weather model predictions instead of historical weather data. Twenty-first century weather will not be the same as twentieth century weather. There will be a need for our bridges to withstand higher sea levels, increased storm loads and frequencies, and increased temperature ranges. This adaptation strategy will be implemented by updating and revising the existing AASHTO bridge design specifications that will apply to new bridge designs. Adaption will also require assessing and retrofitting existing bridges.

The mitigation strategy means reducing the severity of climate change by reducing greenhouse gas emissions. The green standards and project sustainability rating systems are part of the mitigation strategy that is in the process of being deployed in industries across the economy and the world.

COSTS ASSOCIATED WITH GREEN BRIDGES

Bridges with lower life cycle costs will tend to have lower environmental impacts, in terms of material and energy use. In other words, the least expensive bridge alternative is also likely to have the least associated emissions and embodied energy. The key is to consider the total costs for design, construction, use, maintenance, demolition, and salvage; not merely initial construction cost. Policy makers have responsibility for internalizing externalities.

Many recycled materials, including steel, pozzolan cements, wearing surfaces aggregates, and construction waste, are cost competitive – in terms of both initial cost and life cycle cost – with the virgin alternatives.

Davis Langdon (2006) performed detailed investigations into the costs associated with LEED and found "there is no significant difference in average [construction] costs for green buildings as compared to non-green buildings." Kats (2003) came to a similar conclusion when investigating the costs associated with the thirty-three LEED certified municipal buildings built by the state of California. The Federal GSA decided to fund its green building mandate by allocating a 2.5% construction budget increase. RSMeans estimates that average additional costs associated with green building construction are 2% to 5%, the majority of which are attributed to design and engineering.

Whichever estimate is used, the sources agree that the initial investment in green building is rewarded by many times over the life of the structures. This is due to lower life cycle costs in the form of decreased energy, water, and waste use.

This indicates that applying green standards and project sustainability rating systems need not increase bridge construction costs and will certainly reduce life cycle costs and maintenance costs in particular.

THE MARKET FOR GREEN BRIDGES

Twenty-three billion dollars of LEED certified green buildings were constructed in the USA in 2007, including nearly three billion dollars of office buildings for government agencies.

Hundreds of green buildings have been constructed by agencies that own bridges, such as: Virginia DOT, Caltrans, US Army Corps of Engineers, MTA Bridges & Tunnels, Federal DOT, New York City DOT, and the Seattle DOT. Many additional municipalities, including the state of Arizona and the city of Chicago, have created mandates for all new facilities to be built to LEED certified green buildings.

The development of the Greenroads design standard was sponsored by the DOTs of Washington State, California, Texas, and Minnesota.

This indicates that green standards and project sustainability rating systems have the potential to create an active and growing market.

CONCLUSION

Green design has entered the public consciousness and the mainstream newspapers and magazines. The public, the taxpayers, the politicians, and the policy-makers want to be assured that public funds are being used to build environmentally friendly infrastructure.

Green standards, a.k.a. sustainability rating systems, are a tool that can encourage existing "best practices" to see more widespread use. They can also spur innovation to speed the development of new "best practices." Green design standards have been successfully implemented in other industries. Now is the time for their application to the bridge industry.

Appendix A – Proposed Green Bridge Design Standard
The following categories are proposed for the Green Bridge standard: materials & resources, alternative transportation, project deliver process, construction activity, maintenance & access, environment & water, and energy. A summary of each category is provided below, as well as in the body of this paper. The title for each point is given below. References are provided to similar points in the LEED Version 2.2, SPiRiT 1.4.1, or Greenroads Version 0.95 standards.

Materials & Resources, 6 points
Use materials that are recycled, recyclable, and industrial by-products. Use regionally extracted and manufactured materials.

MR Credits 1, 2, 3, 4, & 5 – Recycled Materials
See LEED MR Credit 4, SPiRiT MR Credit 4 and Greenroads MR-4

MR Credit 6 – Regional Materials
See LEED MR Credit 5, SPiRiT MR Credit 5 and Greenroads MR-5

Alternative Transportation, 5 points
Encourage transportation alternatives to single occupancy motor vehicles. Provide pathways for pedestrians and cyclists. Provide designated lanes for busses, light-rail transit, car pools, and low-emission vehicles.

AT Credit 1 – Pedestrian Facilities
See LEED SS Credit 4, SPiRiT C4, and Greenroads AE-3-9

AT Credit 2 – Bicycle Facilities
See LEED SS Credit 4, SPiRiT C4, and Greenroads AE-3-9

AT Credit 3 – Public Transportation Facilities
See LEED SS Credit 4, SPiRiT C4, and Greenroads AE-3-9

AT Credit 4 – High Occupancy Vehicle Facilities
See LEED SS Credit 4, SPiRiT C4, and Greenroads AE-3-9

AT Credit 5 – Low Emission Vehicle Facilities
See LEED SS Credit 4, SPiRiT C4, and Greenroads AE-3-9

Project Delivery Process, 1 prerequisite, 7 points
Perform life cycle assessments, using the free software www.eiolca.net, to compare the life cycle costs and environmental impacts of competing bridge proposals. Use design charettes to develop context sensitive solutions. Consider future uses and demolition/salvage of the bridge. Develop innovative designs. Include green design accredited professionals.

PDP Prerequisite 1 – Life Cycle Assessment

See Greenroads PR-8, PR-9, and MR1

PDP Credit 1 – Educational Outreach
See Greenroads PR-5

PDP Credit 2 – Context Sensitive Solutions
See Greenroads AE-3-9

PDP Credit 3 – Holistic Project Delivery and Design Charrettes
See SPiRiT FDP Credit 1

PDP Credit 4 – Adaption, Renewal and Future Uses
See SPiRiT CM Credit 2

PDP Credit 5 – Demolition Procedures, Costs, and Salvage Values

PDP Credit 6 – Innovation in Design
See LEED ID Credit 1 and Greenroads EP-1

PDP Credit 7 – Green Design Accredited Professional
See LEED ID Credit 2 and Greenroads EP-2

Construction Activity, 3 prerequisites, 6 points
Divert construction and demolition waste from landfills for reuse or recycling. Control erosion and stormwater. Track water and electricity use. Provide on-site environmental awareness training. Reduce fossil fuel use and emissions of the construction equipment.

CA Prerequisite 1 – Construction & Demolition Waste Management Program
See LEED MR Credit 2, SPiRiT C2 and Greenroads PR-7 & CA-2

CA Prerequisite 2 – Temporary Erosion and Stormwater Control Plan
See LEED SS Prerequisite 1, SPiRiT R1, Greenroads PR-10

CA Prerequisite 3 – Construction Noise Mitigation Plan
See Greenroads PR-11

CA Credit 1 – Quality Management System
See Greenroads PR-6 & CA-1

CA Credit 2 – Track Water Use
See Greenroads CA-3

CA Credit 3 – Fossil Fuel Use Reduction
See Greenroads CA-4

CA Credit 4 – Equipment Emission Reduction

See Greenroads CA-5

CA Credit 5 – Environmental Awareness Training
See Greenroads CA-6

CA Credit 6 – Warranty or Performance Based Fees
See Greenroads CA-7

Maintenance & Access, 2 points
Produce a maintenance manual, including estimated activities, frequencies and costs. Provide safe and productive maintenance access.

MA Prerequisite 1 – Maintenance Plan, Costs and Manual
See SPiRiT CM Credit 1 and Greenroads PR-2 & PR-3

MA Prerequisite 2 – Maintenance Access
See SPiRiT CM Credit 2

Environment & Water, 1 prerequisite, 9 points
Minimize destruction to the local ecology around the bridge site. Minimize erosion, stormwater sedimentation, construction dust, particulate, noise, and light pollution. Minimize the heat island effect. Prefer the redevelopment of brownfield or urban sites instead of developing virgin greenfield sites. Use native vegetation with no irrigation.

EW Prerequisite 1 – NEPA Compliance
See Greenroads PR-1

EW Credit 1– Sustainable Stormwater Management
See LEED SS Credit 6, SPiRiT SS C6 and Greenroads PR-4, EW-2&7, & PT-5

EW Credit 2 – Reduced Site Disturbance
See LEED SS Credit 5, SPiRiT SS C5, Greenroads MR-2

EW Credit 3 – Environmental Management System
See Greenroads EW-1

EW Credit 4 – Native Vegetation and No Water Use
See LEED WE Credit 1, SPiRiT WE C1 and Greenroads EW-4

EW Credit 5 – Ecological Connectivity
See Greenroads EW-5 & EW-8

EW Credit 6 – Light Pollution
See LEED SS Credit 8, SPiRiT SS C8 and Greenroads EW-6

EW Credit 7 – Heat Island Reduction

See LEED SS Credit 7, SPiRiT SS C7 and Greenroads PT-4

EW Credit 8 – Site Selection
See LEED SS Credit 1, 2 & 3 and SPiRiT SS C1, C2 & C3

EW Credit 9 – Noise Pollution Reduction
See Greenroads PT-6

Energy, 1 prerequisite, 4 points
Minimize the life-cycle costs of the bridge electrical equipment and lighting. Commission the bridge electrical systems after construction to verify that the actual energy used conforms to the design values. Use grid-source green electricity.

E Prerequisite 1 – Commissioning of the Electrical Systems
See LEED EA Prerequisite 1 and SPiRiT EA R1

E Credit 1 – Optimize Energy Performance
See LEED EA Credit 1 and SPiRiT EA C1

E Credit 2 – Grid Source Green Electricity
See LEED EA Credit 6 and SPiRiT EA C6

E Credit 3 – Enhanced Commissioning of the Electrical Systems
See LEED EA Credit 3 and SPiRiT EA C3

E Credit 4 – Measurement & Verification
See LEED EA Credit 5 and SPiRiT EA C5

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Best Practices in Addressing NPDES and Other Water Quality Issues in Highway System Management

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ABSTRACT

The Domestic Scan Program was developed to highlight innovative practices of high-performing transportation agencies that could be beneficially adopted by other interested agencies. The Scan Program provides the opportunity for technology transfer on a relatively economical basis with significant benefits on a national scale.

The Clean Water Act (CWA) places requirements on Departments of Transportation (DOTs) for the discharge of stormwater from their systems through the National Pollutant Discharge Elimination System (NPDES). Non-compliance with NPDES permits can impact project design, engineering and construction schedules and increase construction time and costs. Successful compliance with NPDES permits requires the appropriate transfer of information and accountability through multiple phases of project delivery. State DOTs that are under NPDES Municipal Separate Storm Sewer System (MS4) Phase I or Phase II permit coverage are anticipating implementation of the total maximum daily load (TMDL) process which poses potential stormwater permitting concerns based upon the method of implementation chosen and the types of receiving water impairments addressed.

This paper summarizes a Domestic Scan for stormwater that occurred in July, 2009. Four primary topics were selected as the subject of this Scan. Benefits of this Scan include better insight into stormwater requirements during the project delivery process, improved compliance with NPDES permits, and reducing project delays associated with NPDES violations and noncompliance. The Scan provided an excellent opportunity to document lessons learned and share experiences to assist individual DOTs in negotiating, developing, implementing and tracking TMDL programs as part of NPDES MS4 compliance.

OVERVIEW

The field of stormwater quality is dynamic, owing to a complex and expanding regulatory structure. Stormwater regulations are administered by the United States Environmental Protection Agency (USEPA) based on the Federal Water Pollution Control CWA or Clean Water CWA (CWA) but most states are authorized to implement the program, with oversight retained by the USEPA. The delegated Federal system may also operate in parallel with state water pollution laws that are different and beyond those contained in the CWA. This structure creates a challenging basis for the development and dissemination of national stormwater guidance in support of the CWA.

The National Pollutant Discharge Elimination System (NPDES) permitting program is authorized under the Clean Water Act to control the discharge of pollutants from industrial and municipal point sources to waters of the United States. NPDES discharge permits are issued on a five-year cycle to owners of storm drain (sewer) systems. Receiving waters that are 'fishable and swimmable' is a stated goal of the CWA, and Federal regulations require that stormwater shall not 'cause or contribute' to a violation of water quality standards. This goal is achieved through the application of best management practices (BMPs) to reduce the discharge of pollutants to the maximum extent practicable (MEP). The CWA does not explicitly define MEP, and the lack of quantitative performance metrics has proved to be both a problem and perhaps the only feasible way to regulate surface water quality at the present time. The subjectivity of the definition of MEP allows for needed flexibility from a regulatory standpoint but can become problematic for NPDES permit holders due to the provision of the CWA that allows for citizen enforcement. Many state transportation agencies are facing or involved in third party litigation relative to their stormwater programs, diverting resources from program implementation, facility construction and operation and maintenance.

Stormwater program requirements and third party lawsuits have created an urgent need for more effective and efficient tools for stormwater program managers to maintain receiving water beneficial uses. The vast majority of the state and federal highway systems have historically been been constructed to convey stormwater quickly away from the highway to protect property and motorist safety, with less planning or infrastructure for stormwater quality mitigation. The limited space and safety requirements within the highway right-of-way make it difficult, expensive and in many cases impractical to retrofit treatment controls or match the predevelopment hydrologic conditions.

The Scan Team met formally and via conference call to focus the potential topics for the Scan. Four topics were ultimately chosen that represent the most urgent challenges facing DOT stormwater programs. A Desk Scan report was developed to further refine the topics and determine potential Scan sites. Criteria for selection of candidate scan sites included those with a well-developed stormwater program located in states that were highly regulated and dealing with more dynamic stormwater regulations such as Total Maximum Daily Loads for impaired water bodies. The Team was looking for innovative responses to stormwater program implementation challenges, with an eye not only on opportunities for technology transfer, but also on helping to continue the national dialogue to improve stormwater quality regulation.The programs that were initially selected to participate in the Scan geographically represented most areas of the country, however due to constraints on the Scan Team travel dates as well as staff resources at DOT programs, locations on the west coast were not in the final trip agenda. The DOT programs that were visited as a part of the Scan were:

- New York State DOT
- District of Columbia DOT
- Maryland State Highway Administration
- North Carolina DOT
- Texas DOT
- Florida DOT

Amplifying questions were developed by the team and sent to the Scan sites before the site visit to allow them to center their preparations on the specific areas of interest to this Scan. The amplifying questions expanded on the primary topic areas that collectively comprise the study questions. The four topic areas for this Scan are:

1. **Total Maximum Daily Loads (TMDLs)**. This topic includes Total Maximum Daily Load (TMDL) implementation and water quality credit trading and banking. TMDLs are emerging as a primary issue for DOT programs as more water bodies are listed as ‘impaired’ according to Section 303 of the Act, and DOTs are named as stakeholders of the TMDL. Credit trading and banking are likely to play a key role in DOT compliance with TMDLs given limited ROW for the installation of BMPs and limited authority to regulate the source of constituents within the ROW.

2. **Best Management Practices (BMPs).** BMPs are the primary vehicle for compliance with the requirements of the Act. NPDES permittees are continuously refining BMPs (for either during construction and post-construction) to reduce their life cycle cost while improving their effectiveness. A current trend in BMP development and application includes Low Impact Development (LID) approaches which emphasize vegetated controls and the objective of maintaining pre-development hydrologic conditions on a site. A highway-specific LID model has not been universally defined for highway systems and an objective of the Scan was to assess the LID implementation strategies nationally. Another focus under this topic was on non-structural BMPs, approaches that embrace source control of potential pollutants rather than removal of pollutants from stormwater runoff.

3. **DOT Practices and Procedures.** The implementation strategy of the stormwater program and its framework and structure can play a decisive role in program success. This topic focused on the various approaches for tracking and maintaining treatment BMPs in the field with the objective of seeking

low-cost solutions to a man-hour intensive process. This topic also included the development of annual reports (required under most NPDES permits) and assessment of the DOT stormwater program.

4. **Regulatory.** DOT communication with state and federal regulators is crucial to a successful stormwater program due to the subjectivity inherent in the application of the regulations. This topic sought to identify the characteristics of functioning partnerships between the regulatory agency(ies) and the DOT. Also included was an assessment of the 401 certification process – required when applying to modify a jurisdictional wetland under Section 404 of the Act. Of particular interest was the application and administration of 401 requirements in the context of the more comprehensive DOT NPDES stormwater program.

It was recognized that not all topics would be covered at each Scan site and not all approaches to the topic areas would be nationally applicable.

SUMMARY OF INITIAL FINDINGS AND RECOMMENDATIONS

The Scan travel included site visits to six programs over a period of two weeks. At the conclusion of the site visits, the Team met in Orlando, Florida for one day to discuss the findings and information gathered from each program. The Team agreed that the Scan topics are of national importance, and that continuing dialogue on the topics is important to improve the effectiveness of DOT stormwater programs. The NPDES stormwater program remains in the early stages of implementation and significant gains in the program efficiency and effectiveness must occur in the future. The initial findings and recommendations of the Scan Team are organized under the four Scan topics.

Total Maximum Daily Loads (TMDLs)

There was a wide variety of awareness and program resources dedicated to TMDLs among the Scan sites visited by the Team. Each of the states visited had an active TMDL program and were engaged in developing TMDLs and TMDL implementation plans. However, some Scan sites, such as Texas DOT, have not been named or assigned a load allocation for any of the state's TMDLs. All of the programs agreed that TMDLs were the single most important compliance issue they would likely face in the foreseeable future in terms of DOT resource impacts. Some of the most important aspects of the TMDL program and steps a DOT can take to prepare for and implement TMDLs are:

- DOTs are uniquely impacted by TMDLs. Since DOTs operate throughout the entire state, and cross virtually all of the watersheds within the state, they are a potential stakeholder in all TMDL listings.

- DOTs need to take a leadership role in the TMDL process. TMDL policy needs to be rooted in good science. DOTs can act as a catalyst to bring stakeholders together to develop the necessary technical studies. DOTs need to be recognized as an expert in water quality management with valuable data to assist in the TMDL development process.

- A clear, measurable pathway to TMDL compliance is essential. The TMDL language must be concise and define spatial, temporal and hydrologic conditions of operation. Specific waste load allocations must be assigned with a quantifiable endpoint. Assignment of loads should not be left as a task for the stakeholders. TMDLs are about accountability.

- TMDLs need to be integrated. TMDLs are typically completed and implemented for a single waterbody/pollutant combination. A program that at least looks forward to future TMDLs for the waterbody should be developed to ensure that flexible control strategies are selected.

None of the Scan sites had an established water quality trading program with the exception of the Maryland SHA, but this program was not operated for TMDL compliance. All of the DOTs agreed that credit trading programs would be important, perhaps necessary, to comply with TMDL load allocations given the limited ROW available for retrofit of controls.

Best Management Practices (BMPs)

BMP development, implementation and operation and maintenance are the foundation of DOT stormwater programs. The DOTs with the most advanced programs and quantitative assessment metrics were generally those that included a research program, typically partnering with a local university. The North Carolina DOT, Texas DOT and Florida DOT are notable examples. In some cases, multiple universities are engaged with ongoing programs (such as TxDOT and the Texas Transportation Institute at Texas A&M University and the Center for Research in Water Resources at the University of Texas at Austin). Exceptional research is occurring in many program areas that has the potential to reduce DOT compliance costs and increase receiving water quality. Some of the more notable active and recent research includes:

- Polyacrylamide Application. North Carolina State University (NCSU) has an exceptional research program evaluating the applications of polyacrylamide (PAM) for the reduction of turbidity in stormwater discharging from construction sites. Passive application of PAM using a variety of delivery mechanisms appears to safely and dramatically reduce runoff turbidity. This research is very topical given the pending promulgation of effluent limit guidelines (ELGs) for construction sites by the USEPA.

- Nutrient Removal with Bioretention BMPs. NCSU is also researching the potential for bioretention BMPs to reduce nutrients in highway stormwater runoff. This research is important since nutrients are a leading cause of impairment in receiving waters and nitrogen is highly soluble, limiting the effectiveness of many conventional BMPs.

- Batch Detention. The University of Texas at Austin (UT) has developed a low cost retrofit application for wet or dry detention basins that significantly improves removal efficiency for particulate constituents. An active pond outlet (requiring no human operator) detains stormwater runoff in quiescent conditions, improving removal compared to conventional basins with passive outlets. The system also allows the possibility of creating a network of basins linked by telemetry and operated by a rainfall-runoff model for even greater system efficiency gains.

- Permeable Friction Course Overlay. The researchers at UT have also determined that an open graded friction course applied over a conventional pavement section can dramatically improve highway runoff water quality. This practice is especially appealing in light of the associated benefits (enhanced safety, reduced noise) and broad applicability for retrofit of existing highways.

- Stormwater Harvesting. The University of Central Florida (UCF) is engaged in developing approaches to harvesting (use or re-use) of stormwater runoff for landscape irrigation. In addition to being a sustainable approach, stormwater harvesting may become an important application to meet hydromodification mitigation requirements and is an important LID application. However, there is substantial question as to how stormwater harvesting can be applied to highway systems.

The Scan Team found less advances in the development of source control applications for highway systems, though some of the approaches that merit mention are:

- The elimination of mowing for aesthetics. Mowing by some programs such as in Texas is being curtailed and implemented for safety reasons only, possibly reducing a source of organic nitrogen.
- Reduction in use of salt and deicers by using more sophisticated application technology (DDOT).
- Reduction in herbicide and pesticide application (TxDOT and NCDOT).
- Advanced practices in public education such as illegal dumping reporting by adopt-a-highway crews (NCDOT).

DOT Practices and Procedures

Treatment BMPs become ineffective if they are not operated and maintained correctly. BMP O&M is a resource intensive element of a stormwater program so effective use of maintenance forces is a priority. Several Scan visit locations had developed relatively advanced inspection and tracking programs that could serve as a model for adoption by other DOTs.

- Construction Site BMP Inspection. The Maryland SHA has a sophisticated quality assurance program for ensuring construction site water quality compliance. An independent inspector is assigned to review compliance and provide an overall letter grade for the site. Depending on the outcome of the inspection, the inspector is empowered to levee a range of punitive measures on the contractor as well as the SHA personnel. There is also a generous incentive program to reward compliance at defined milestones.

- Post-construction BMP tracking. The New York State DOT has developed a database program to track post-construction BMP attribute data and maintenance activities. The MS Access® database includes project information, practice information, inspection information and maintenance information. The system can generate inspection forms detailing the location maintenance history. A future enhancement will include location –specific maintenance schedules. The Maryland SHA has also developed a similar BMP maintenance tracking system using a 'response table' to assess maintenance needs at the indexed sites.

- Design, Build, Operate, Maintain. The Maryland SHA is piloting a design-build program for retrofit treatment BMPs. The program (acronym DBOM for Design, Build, Operate, Maintain), administers a performance based contract for a BMP with a 3-year maintenance period. The maintenance portion of the contract can be extended at the option of the SHA for additional 3-year increments.

Program annual reporting and effectiveness assessment received less emphasis at most of the Scan sites, reflecting that relatively speaking the NPDES program is in the early stages of implementation. Clearly this is a subject that deserves additional research and program enhancement by DOTs since it is a relatively resource-intensive activity. A notable exception is the North Carolina DOT which has reduced the contents of its annual report significantly by establishing regular communication with its regulator. NCDOT holds monthly coordination meetings with DNR NPDES coordinators, and quarterly meetings with DEP. This continuous communication has allowed the DOT to eliminate a large portion of the annual reporting required as a part of the NPDES permit.

Regulatory Coordination and 401 Certifications

Good coordination with state regulators (all locations visited in this Scan were operating in states with 'delegated' authority to implement the NPDES program) was universally agreed to result in a more effective stormwater program. Nearly all Scan locations reported that a partnership with the state regulator resulted in fewer delays in project delivery and reduced cost for program implementation. How this effective communication is achieved is partially based on the structure of the DOT and that of the regulator, as well as the culture of both agencies. However, there are some fundamental attributes of the programs that are successful in creating a collaborative relationship between the DOT and the regulatory authority:

- Create a Culture of Environmental Stewardship. The DOT must 'walk the talk' and be committed to creating a program of environmental compliance and excellence. Many elements can contribute to this objective, including a robust research program, continuous communication and program transparency. Avoiding centralization of environmental responsibilities (breaking down silos) will also promote ownership, compliance and stewardship within the organization. Finally, the most effective programs have buy-in from the highest levels of the organization.

- DOT Funded Positions. Several of the Scan sites fund positions at the regulatory agency to increase service (reduce plan review time) and technical expertise (examples are the Maryland SHA, NCDOT and TxDOT).

- Flexibility and Willingness to Change. Stormwater regulation is a dynamic environment with the standard of care (MEP) rapidly evolving. This can be counter to a traditional DOT culture that values safety as the first priority necessitating a deliberate pace when altering policies, procedures and practices. The successful DOT stormwater program is proactive and uses tools such as bench and field scale pilot testing of new approaches.

- Understanding of Program Costs. A constructive dialogue with regulatory agencies should include program costs to assess the balance with benefit, but many of the DOT programs do not accurately assess and record implementation costs.

- Education. The regulators, DOTs and general public need to receive education on stormwater program costs, benefits and programs to ensure continuous process improvement and support.

Another aspect of this topic area was the 401 certification program as a part of the 404 permitting process. Some states (such as California and Oregon) have seen a divergence in the application of the 401 and 402 programs, creating project delivery issues and unanticipated increases in project budgets. The Team found that at the Scan sites visited, the 401 requirements of the Act were fairly well integrated into and consistent with the Section 402 program requirements. This is a topic that may become more of an issue in the future and should remain a part of the national stormwater discussion.

PLANNED IMPLEMENTATION ACTIVITIES

The Team is committed to implementing the findings of this Scan. The national dialogue on DOT stormwater programs remains one of the most important issues today with respect to the environment and the future potential for increasing program cost. Many important programs, strategies and BMPs were identified in this Scan that would be of benefit if implemented at other DOTs. The Team plans to initiate the following implementation activities immediately upon completion of the Scan Report:

- Publication of articles in journals and other industry related publications including ASCE Magazine, Stormwater Solutions and the APWA Reporter.
- Presentations at AASHTO committees, TRB sessions and ASCE and other conferences. An abstract is currently being prepared for the 2010 TRB Conference.
- Use of the project Powerpoint® developed for the scan trip for in-house DOT presentations and presentation to local transportation organizations by the Scan Team members.
- Integrate the team's findings into other association and industry groups such as the AASHTO Center for Excellence.
- In-reach within FHWA and USEPA.

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Green Street Retrofit in an Urban Transportation Infrastructure

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ABSTRACT

The City of Santa Monica's Watershed Management Program requires post-construction Best Management Practices (BMPs) for private and public construction projects, both new development and redevelopment (retrofits), to reduce the amount of stormwater runoff and to improve runoff quality entering the Santa Monica Bay.

While the city's watershed management program has been and continues to be successful in promoting Low Impact Development (LID) strategies for individual parcel projects, the transportation grid is a harder area to incorporate BMPs. Transportation infrastructure involves other complexities of development, such as underground utilities, grade limitations, parkways, traffic flow and safety vehicle movement. To demonstrate the feasibility of incorporating the green street BMP strategy in an ultra urban, built-out setting, the city obtained a state grant to build such a green street.

With this state financial injection, the city retrofitted a hardscaped, landscape-lacking, densely populated, multi-family street surrounded by commercial land uses. The Bicknell Avenue Green Street Project demonstrates how an urban street can be retrofitted with a combination of BMPs, low-volume irrigation and climate-appropriate landscape. The result is an aesthetically attractive, greener street with less impermeable surfaces that infiltrate up to 80% of wet weather flows.

The Bicknell Avenue Green Street project featured the use of multiple BMPs within the right of way. This project utilized porous concrete, curb extensions, depressed landscape bio-retention areas, catch basin fossil filter inserts, and underground arched plastic infiltration chambers surrounded by medium sized washed aggregate. These BMP devices were chosen to remove the typical pollutants

found within the first-flush rainfall (3/4" storm) and reduce the amount of sediment reaching the infiltration chambers. The finished project treats the flow rate and infiltrates the volume of the runoff generated from the first-flush rainfall.

The project was completed in spring 2009 and has been subjected to multiple rain events during the 2009/2010 rainy season. Visual observations of the project after a storm event show that trash, debris and sediment are captured either in the bio-retention areas or in the catch basin fossil filter inserts. Additionally, based on visual observations, runoff within the gutter system is significantly reduced by the time it reaches the public catch basin near the end of the project and runoff can been seen within the catch basins and show that the infiltration basins are being filled.

Whenever a jurisdiction plans to retrofit a street or build a new one, LID features must be included in the site design for a green street. By demonstrating the efficiency of a green street along with other green street projects in Santa Monica, the City hopes to set a new standard for Southern California streets and encourage other jurisdictions to "jump on the bandwagon" and replicate this LID strategy. Green streets should become the new standard for transportation infrastructure.

INTRODUCTION

The City of Santa Monica's Watershed Management Plan and Urban Runoff Pollution Ordinance (Programs) promote the use of low impact development (LID) design in construction projects for the specific purpose of harvesting most storm water for use, infiltration or treatment (and release), reducing the amount of runoff flow and pollution that leaves the city and enters the Santa Monica Bay. This watershed approach to managing urban runoff is in accordance with the Sustainable City Plan of Santa Monica, which states in part that natural resources, including any local resources such as runoff, are to be used wisely and that the environment is to be protected from pollution. These Programs incorporate this principle during the design of construction projects, private and public, and requires post-construction structural Best Management Practices (BMPs) to harvest runoff. Moreover, these Programs shift from a paradigm of runoff being viewed as a waste product and of paving over permeable surfaces to a new paradigm of viewing runoff as a local natural resource for use, incorporating permeable, while hard, surfaces (to support vehicular traffic) in new designs. Besides promoting local water resources and sustainability (quantity), these Programs help the city meet NPDES requirements for water quality.

The City has an urban runoff mitigation code, requiring that runoff from newly constructed or redeveloped buildings or properties be reduced through the installation of post-construction BMPs. This strategy accomplishes two goals: harvests a local water supply for present immediate use or future extraction, and prevents a water pollution problem from entering the bay, the single largest source of water pollution in the country. The watershed plan focuses city resources on efforts to incorporate retrofit BMPs within private and public properties, and the public storm drain system, for the purposes of treating or reducing runoff before it leaves city boundaries and enters another jurisdiction.

One urbanized area that receives little attention for LID and BMPs because public projects are too small or infrequent is the transportation infrastructure.

Regular activities like road/alley resurfacing or gutter replacement generally do not stimulate post-construction BMPs and LID thinking, much less planning. And in a built-out city such as Santa Monica, no new roads, alleys, and curb and gutters are being installed to warrant such sustainable replacement. These impermeable areas are not addressed adequately in terms of watershed management and urban runoff pollution mitigation.

An agency can relatively easily control the implementation of post-construction BMPs on individual parcels, but addressing runoff from the transportation infrastructure is difficult. An individual parcel can be considered a point source with a property owner and a few controllable points of discharge. Our transportation-scape is harder to control with many more points of discharge, with large inputs of runoff and varying concentrations and types of pollutants from private parcels, and with extensive pollution from vehicles, probably the most widespread sources of pollutant – oil and grease, and heavy metals. Developing a strategy to address urban runoff pollution for this sector of land use has daunting challenges, especially for municipalities with limited funds and expanding pollution control regulations, e.g. TMDLs.

This presentation describes the Bicknell Avenue Green Street Project as a unique demonstration project whereby the transportation infrastructure can be modified to become more sustainable, incorporating LID and BMPs. Bicknell Avenue is a built-out, highly urbanized residential-commercial street that was retrofitted to harvest all dry weather and most wet weather runoff into the parkways and under the road, resulting in a number of benefits: capturing and infiltrating storm water into the ground, keeping a pollution source out of the bay, reducing impermeable surfaces and the resultant pollution and heat island effect, and creating an inviting atmosphere for local residents.

These types of projects demonstrate the City's commitment to LID principles to reduce runoff pollution and improve environmental health, to its Sustainable City Plan, and to creating more open space in a built-out urban setting. This project was designed to work with nature to harvest runoff for infiltration and improve water quality of local water bodies. Lastly, the City has also drafted a 5-year LID plan to promote numerous structural BMPs specifically for the transportation infrastructure so that during routine roadway-parking city maintenance and upgrades, BMPs such as permeable biofilters, gutters, intersections, alleys and parking lots will be installed. Finally, the City hopes that other municipalities will learn from the City's experiences and follow in this sustainable path for the transportation infrastructure.

PROJECT OVERVIEWS

Statement of Project Purpose & Objective

Bicknell Avenue Green Street Project

This green street project installed a number of BMPs: impermeable roadway asphalt surfaces were replaced with pervious concrete for the parking lane; parkways were doubled in width (taking up some of the impermeable roadway) and depressed to receive runoff from the curbs; gutter catch basins with filters were installed to pre-treat the runoff and direct it to sub-surface infiltration chambers under the parking lanes; climate-controlled sub-surface drip irrigation systems; and climate-appropriate plant species.

The City's intent is to replicate this type of project wherever the opportunity presents itself and given good economic indicators, such that when expanded to other streets, alleys and parking lots, this BMP system can remove significant amounts of runoff and its pollutants, and lead to a reduction in the number of pathogen exceedences and corresponding beach postings at beach storm drain outlets, and restore and protect the water quality and environment of local coastal waters, estuaries and near shore waters of the Santa Monica Bay. Through this objective, beneficial uses of the bay will be protected and preserved; and water quality objectives will be achieved by reducing the pollutants of concern most common in urban runoff: trash, debris, sediments, oil and grease, nutrients, heavy metals and organics. In addition, this project will help the city comply with various NPDES, TMDL, NPS and watershed restoration programs and to better safeguard aquatic habitats and beaches for wildlife and people.

The overall project objectives:

- Removal of 100% of floatables and solids through entrapment (screening) in the permeable and infiltration BMPs (for all dry weather and up to 80% of wet weather flows);
- Removal of up to 70% of Total Suspended Solids (TSS), oil and grease, and other soluble pollutants attached to solids through the BMPs in and under the street and parkways (removal efficiency will vary based upon influent concentrations); and
- Harvest and treatment through these BMPs (biofilter and infiltration into the ground) instead of out to the Bay; all dry weather volume and initial wet weather volume (first flush) from up to a ¾" storm event, which is approximately 80% of wet weather events.

Scope of the Green Street Project

This project removed existing impermeable asphalt and installed pervious concrete for the parking lane on both sides of the 100 block Bicknell Avenue (Figures 1, 2 and 3), which is the first block from the bay. In addition to this BMP, catch basins with filters (Figure 4) to treat runoff were installed in the gutters to capture runoff and divert it into concave plastic sub-surface storage chambers under the parking lanes (Figure 5), where runoff percolates into the ground and is treated by the soil ecology. A final BMP involved some four feet on each side of the street being converted and added to the parkway (Figure 6) to double the width of the existing narrow parkways (Figure 1) and allow for more collection and storage of runoff from the gutter; these parkways were also depressed to hold runoff from roof downspouts (see two white pipes in Figure 6). This project treats all dry weather flowing from this small highly urbanized area in the south-western part of the City. The project is also sized in terms of storage volume to capture and treat up to 80% of wet weather flows from the same area. The storage capacity is about 4,000 cubic feet, or over 30,000 gallons per storm event up to ¾". Runoff from the project location normally flows into the Santa Monica Bay, a marine coastal habitat, sand beach bottom. The watershed that drains to the project area is 1.5 acres and is 100% built-out. The land uses are transportation, residential and some commercial.

These two objectives for year-round treatment demonstrate how such structural BMPs can improve water quality in the coastal marine area, can lead to less frequent exceedences for bacteria, and can improve beneficial uses of our coastal waters near storm drain outlets.

Construction of the project occurred between December 2008 and March 2009. Testing of the project occurred after construction with simulated rain events. An opening day event occurred in July 2009. Water quality monitoring occurred in January-February 2010, and is expected to continue in the winter 2010-11 season.

The project demonstrates to other municipalities that roadways and parkways can play roles in abating runoff and pollution while adding to sorely needed green spaces. "Greening" asphalt or concrete also reduces surface temperatures and heat gain, which is an issue in urban communities.

PROJECT EFFECTIVENESS

To determine the effectiveness of the Bicknell Project, water samples were taken during three storms in the winter months in early 2010. The monitoring system has two monitoring wells, one at 8" and one at 26" below the surface. Runoff is sampled from each well, tested for a variety of pollutants of concern, and compared influent to effluent, and the two effluent samples compared from the two different soil depths, which will indicate if more depth of soil leads to improved water quality.

Pollutants found in the runoff, at least up to the maximum storage capacity of the parkways, underground storage chambers and the pervious concrete, are 100% removed because the runoff is removed from the municipal separate storm sewer system by the BMPs.

Water quality analyses of the influent water demonstrated that a variety of common pollutants were not detected, e.g. at non-detect levels, such as organics, oils, grease, amongst others. This can be attributed to infiltration of the volume generated through the first flush rain event.

The project structural BMPs have been successful in removing commonly found, such as nitrates, ammonia, COD, BOD, pH and heavy metals. The test results showed that the BMPs were effective as noted below:

- Over 75% removal of heavy metals
- Over 60% removal of nitrates and ammonia
- Over 50% removal of BOD and COD

The test results also demonstrated that an increase of turbidity and ortho-phosphates was found within the runoff. This may be attributed to the runoff passing through the bio-retention areas prior to entering the test wells. Results for bacteria were inconclusive, as the data varied greatly.

For BMPs that remove all runoff from the public right-of-way, the effectiveness is 100%. Moreover, when runoff is put back into the ground where it can recharge aquifers or be stored in cisterns for later non-potable uses, runoff offers a partial solution to our diminishing reliability of local water supplies, including challenges presented by drought and environmental protection.

5-YEAR LID WATERSHED PLAN, 2010-2015

The city approved its first 5-Year LID plan, promoting sustainable strategies for watershed management. This plan includes over a dozen different strategies to manage urban runoff, from harvesting stormwater out of storm drains under or adjacent to parks for storage and use onsite to rebates for rainwater harvesting in rain barrels and cisterns. But an important component of this plan is to address those areas used for transportation: roadways, alleys, intersections, gutters and surface parking lots. Because the city is built out and no longer adding to the transportation grid, the opportunity to install LID transportation features is minimal. Thus, the city has created the opportunity for retrofits through this plan and funding from its Clean Beaches and Ocean special tax, approved by voters in November 2006. The following strategies will be implemented:

- Permeable Alleys: As part of the city's regular capital improvement program, a number of alleys are reconditioned each year. The plan requires that a permeable BMP be included to collect and treat runoff flowing along the alley, which often includes runoff from private properties.
- Permeable Intersections: Whenever an intersection has to be repaired or reconstructed, the city will include a permeable BMP system to collect and treat runoff from the street and surrounding watershed.
- Permeable Gutters: A number of years ago, the city began a pilot effort to replace impermeable concrete gutters with pervious concrete. This program will now become standard operating procedures when the appropriate conditions exist, that is, good infiltrating soils and cost-benefit. While pervious concrete was used in the past, other permeable products can be used if found to function more effectively over the long-run. One challenge for pervious concrete is maintenance. With most of the city's streets lined with trees, tree droppings can be a source of clogging if the right street cleaning equipment is not available.
- Permeable Parking Lots: Whenever the city has the opportunity to upgrade a parking lot, a variety of BMPs are available to install depending upon the extent of the retrofit. One can use permeable surfaces for the parking stalls and/or driving lanes, biofilters at strategic locations to collect runoff for infiltration and storage/use, or a combination, which was done at the Bicknell Project. However, using many BMPs can raise the cost of such a project when one BMP will suffice. Each project is site-specific.
- Curb Extensions: Used in the Pacific Northwest, this depressed biofilter BMP offers an economy of scale because the BMP is put at the end of a street instead of the length of the street, focusing the cost and collection at one or two locations. This strategy also removes some impermeable area and adds permeable landscaped parkway area. The city has many wide streets with narrow parkways that do not have to be so wide. This BMP offers advantages when placed in streets with large upstream watersheds to collect large amounts of runoff. The Bicknell Project used a modified version of this

strategy, extending the curbs the entire length of both sides of the street, which is more costly strategy and not necessary if you can focus the storage in one or two locations.

- Green Streets: As described above, the Bicknell Project was the city's first venture into this strategy. Second and third green street projects are under design, one a smaller version will be completed in late 2010, and one a larger venture in final construction design and is expected to begin construction in latter 2011.
- Sidewalk Mini-Wetlands and Tree Wells: The city is exploring the use of this category of BMPs for specific street locations with ongoing nuisance dry weather runoff, whether from ineffective enforcement efforts to curb nuisance flows from over irrigating, or from cooling system discharges, which are legal. The concept is to install these BMPs in a sidewalk or parkway that is adjacent to a nuisance flow in the gutter. For example, a local hospital has a cooling system that discharges to the curb; the resultant daily runoff flows for blocks before reaching a storm drain. This flow could be diverted out of the gutter into one of these BMPs, which also offers an aesthetic alternative to the surrounding concrete sidewalks, asphalt streets and buildings, a small oasis amongst the inanimate structures. In a few residential locations, daily flows occur from overspray irrigation systems due to the inherent inefficiencies (design, placement next to hardscapes, and excessive flow beyond what the landscape requires) of such irrigation practices.

CONCLUSIONS

The use of various permeable BMPs to convert impermeable transportation infrastructure areas to permeable surfaces has proven effective in eliminating gross pollutants and soluble pollutants as most runoff is captured in the Bicknell Avenue Green Street Project. Moreover, the city's first 5-Year LID Plan to focus on upgrading more of the transportation infrastructure, that is, to make more sustainable in terms of harvesting rain water and storm water instead of allowing such polluted water to flow into the Santa Monica Bay, offers robust opportunities to address pollution from a public right-of-way closer to the source of production and not at the end of a storm drain pipe. Gross pollutants, e.g. trash and debris, are removed at the surface, trapped in catch basin filters and depressed parkways. Soluble pollutants are infiltrated into the soil and treated by the soil matrix, including plant roots. Initial water quality sampling and analyses showed that the system installed is effective in reducing heavy metals, nitrates, ammonia, BOD, COD and pH. Future testing in the watershed may provide additional data regarding the overall efficiency of the system as a whole.

Meeting the Project Objectives

1. Removal of 100% of floatables and solids (for all dry weather and up to 80% of wet weather flows). Objective 1 is being met.
2. Removal of 70% of TSS, oil and grease, and other soluble pollutants attached to solids through the primary stage vortex unit (efficiency

removal will vary based upon influent concentrations). Objective 2 is being achieved because the removal efficiency is 100% for pollutants through infiltration.

3. Harvest and treatment through the various BMPs (instead of out to the Bay) of all dry weather and most wet weather volume. Objective 3 is being met.

Challenges

For future projects, rainwater harvesting and non-potable use should be incorporated, e.g. cistern, under the parkways or parking lane for an onsite supply of irrigation water to irrigate parkway landscapes, and to reduce the use of potable water.

Lessons Learned

Whenever a jurisdiction plans to retrofit or build a new street, alley, gutter, or parking lot, LID features must be included in the site design for a green street. By demonstrating the efficacy of a green street along with other green transportation grid strategies, the city hopes to set a new standard for Southern California streets and encourage other jurisdictions to "jump on the bandwagon" and replicate this LID strategy. Low impact development planning should become the standard for new and retrofit transportation infrastructure projects.

Figure 1. Bicknell Avenue before project installation. Note narrow parkway and impermeable parking lane.

Figure 2. Installation of pervious concrete parking lane.


Figure 3. Project completion. Note pervious concrete lane with widened parkways, and catch basins in gutter.

Figure 4. Gutter catch basin with filter to pre-treat/screen runoff as it flows into the basin and then into the sub-surface storage chamber.

Figure 5. Sub-surface storage chamber under parking lane.

Figure 6. Depressed parkways receive runoff from gutter through curb cuts or roof downspout pipes (note 2 white pipes in center of parkway from adjacent building roof).

Permeable Friction Course for Sustainable Highways

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Abstract

A permeable friction course (PFC) is a 50 mm layer of porous asphalt placed on top of conventional, impermeable pavement. This paper describes a multi-year research effort on the water quality and hydraulic aspects of PFC. Water quality monitoring of three field sites near Austin, Texas showed a 90% reduction of total suspended solids (TSS) compared to conventional pavement. Significant reductions were also observed for total copper, total lead and total zinc, though concentrations of dissolved constituents were not significantly different.

The hydraulic properties of PFC are of interest to assess the drainage capacity of the pavement and the effects of clogging. The properties investigated in this study were the porosity and the hydraulic conductivity. Porosity was measured from core specimens and found to range from 0.12 to 0.23. Hydraulic conductivity was also measured from core specimens and ranged from 0.1 to 3 cm/s. A new field method for measuring the in-situ hydraulic conductivity of PFC was developed and compared to the laboratory measurements.

Predictions of the water depth on PFC roads are needed to assist designers in selecting a pavement thickness and to evaluate the effects of clogging. A Permeable Friction Course Drainage Code (PERFCODE) was developed to make these predictions. Measured porosities and hydraulic conductivities were used as inputs to

PERFCODE. Outputs were the variation of water depth through a storm and the runoff hydrograph. The modeled hydrograph is compared to runoff hydrographs obtained by field measurement.

Introduction

Permeable Friction Course (PFC) is an innovative paving material that is applied as a sacrificial layer on top of conventional pavement. The benefit of PFC is that it allows water to drain through the overlay rather than on the surface of the roadway. During rain events, water seeps into the porous layer, hits the underlying impervious boundary, and flows to the side of the road by gravity. By removing water from the road surface, PFC improves safety by reducing splashing and hydroplaning. In addition to safety benefits, PFC has also been shown to reduce concentrations of pollutants commonly observed in highway runoff.

In addition to the water quality aspects of using PFC for stormwater treatment, the hydraulic characteristics and drainage performance PFC are of interest because these factors ultimately determine whether or not drainage stays off of the roadway surface. This is an important point because many of the driver safety and water quality benefits of PFC come from the fact water drains within the porous layer and not on the pavement surface.

The hydraulic characteristics studied here include the hydraulic conductivity and porosity. These properties are important because they are needed to predict the drainage performance of PFC and because they are expected to change as the pavement clogs over time. Clogging may be an important process for both the water quality and drainage performance of PFC. The hydraulic conductivity or porosity could serve as a metric for the performance of PFC over time.

During the course of this research, the National Cooperative Highway Research Program (NCHRP) issued Report 640 entitled “Construction and Maintenance Practices for Permeable Friction Courses” (NCHRP, 2009). The report signifies the growing popularity and importance of PFC layers for highways in the USA. Several of the future research needs listed in the report are addressed in part by this research:

- Field work to document how water flows within a PFC layer
- Methods for selecting the minimum PFC thickness
- Consideration for water sheets on the PFC surface
- Development of a method to determine the permeability of PFC layers

Field work included constructing a monitoring site to measure runoff hydrographs from a PFC roadway. The dynamic simulation model developed in this research accounts for sheet flow on the PFC surface and seepage through the porous layer; it can be used to evaluate methods for selecting the thickness of a PFC layer.

Water Quality

Water Quality Methodology

There are three sites where water quality data were collected during the course of this study. Two of the sites are found on Loop 360 near RR 2222 in Austin, TX. The third site is located on RR 620 near Cornerwood Drive in Round Rock, TX (north of Austin). Water quality was monitored at Site 1 on Loop 360 since March 2004 prior to the installation of PFC in October 2004. Passive samplers were used to monitor stormwater runoff until the system was replaced with an automatic sampler in December 2006.

Site 2 is located 0.3 miles south of Site 1 on the shoulder of the northbound lane near Lakewood Drive. The passive samplers are located about 200 feet apart, one each for PFC and conventional pavement. The proximity of the two samplers allowed for paired samplings to occur where conditions (rainfall depth, storm intensity, traffic counts, etc.) could be assumed homogenous. The locations for the samplers were chosen so that neither would be affected by the close proximity of the transition from PFC to conventional pavement. Further detail about the construction of Sites 1 and 2 is available given by Stanard et al. (2008).

In October 2004, TxDOT implemented a PFC overlay project on this section of Loop 360. The overlay was applied on top of the existing conventional asphalt according to TxDOT specifications (TxDOT, 2004). Runoff sampling at the site was discontinued during the overlay installation and resumed upon completion of the overlay project.

Site 3 is located on either side of Cornerwood Drive on the southbound shoulder of RR 620. The two passive samplers are located about 450 feet apart. Candaele et al. (2008) determined that the hydraulic conductivity and effective porosity of PFC at RR 620 is much lower than that at Loop 360. The goal of adding this third research site was to observe the differences in water quality for a pavement that does not drain as rapidly. The hypothesis was that as the permeability of PFC decreased the water quality would approach that of conventional pavement.

Site 3 passive samplers were installed in January 2009 on the shoulder of RR 620. Setup is very similar to that of Site 2. Locations for samplers were based on the closest combination of paired sampling as well as ease of access. Both boxes are located adjacent to parking lots.

Water Quality Results

At Site 1, five samples of runoff were collected from the conventional pavement and 47 samples of runoff were collected after the PFC overlay. A total of 15 storms were monitored at Site 2 with paired samplers, while eight paired samples were collected at Site 3 on RR 620 during 2009. A summary of the observed reductions in concentration in the runoff from PFC overlain pavements compared to conventional asphalt pavement is presented in Table 1.

The data indicate that the runoff generated from the PFC surface has consistently lower concentrations of particles and particle associated pollutants than that from the traditional asphalt surface. Concentrations of TSS, total phosphorus, and total lead, copper, and zinc are statistically significantly lower in runoff generated from the PFC surface than in runoff generated from the conventional asphalt surface. These data indicate that the PFC has little to no effect upon the concentrations of dissolved constituents in the stormwater runoff.

After more than 5 years of monitoring at Site 1, no significant correlation between discharge concentrations at the edge of pavement and time since installation or cumulative rainfall volume has been observed. As an example, Figure 1 presents the concentrations of total suspended solids for each of the monitored events at the original site. Figure 2 presents the paired TSS concentrations from Site 3, which highlights the very consistent reduction in TSS observed during the study. It is very apparent from this figure that the reductions are both substantial and very consistent. The interested reader should consult Barrett (2008) for additional information on the water quality benefits of PFC.

Table 1: PFC Pollutant Removal for all Sites

Constituent	Site 1 Reduction %	Site 2 Reduction %	Site 3 Reduction %
TSS (mg/L)	92	88	93
TKN (mg/L)	11	16	67
NO_3^+/NO_2 (mg/L)	9	-52	25
Total P (mg/L)	48	63	77
Dissolved P (mg/L)	24	21	37
COD (mg/L)	4	20	68
Total Copper (µg/L))	50	57	63
Dissolved Copper (µg/L)	-77	-44	24
Total Lead (µg/L)	91	88	93
Dissolved Lead (µg/L)	NA	NA	NA
Total Zinc (µg/L)	83	84	86
Dissolved Zinc (µg/L)	53	40	44

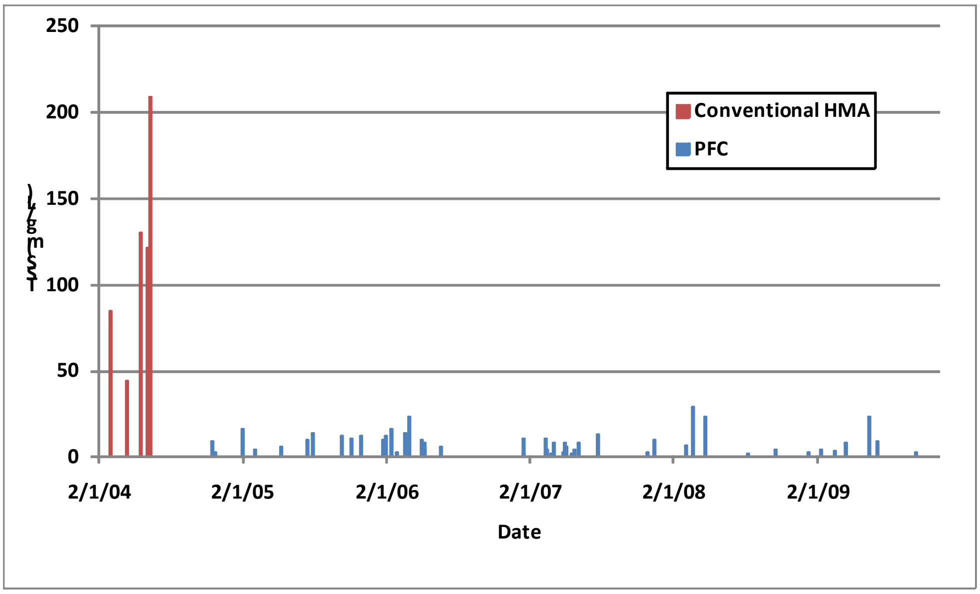

Figure 1: TSS concentrations over time at Site 1

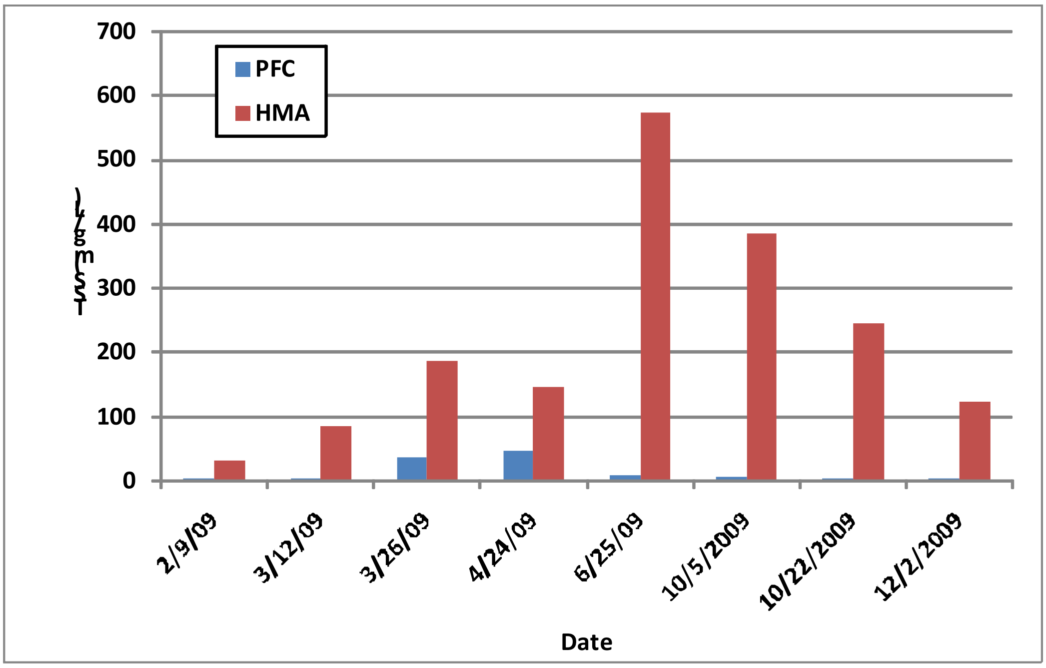

Figure 2: TSS Concentrations at Site 3

Hydraulic Properties

The hydraulic properties of PFC are of interest to assess the drainage capacity of the pavement and the effects of clogging. The properties investigated in this study were the porosity and the hydraulic conductivity. In order to perform laboratory assessments of these properties, core specimens were extracted from PFC roadways at three locations around Austin, TX.

The porosity of each core was determined using a differential submerged unit weight method (Regimand and James, 2004). This method compares the submerged weight of a saturated and unsaturated core specimen in order to calculate the porosity. The porosity measured from core samples ranged from 0.12 to 0.23. A statistical decrease in porosity was observed at each of the three roadway locations over time suggesting the clogging of the pore space due to trapped sediment (Klenzendorf, 2010).

The cores were analyzed in the laboratory to determine the hydraulic conductivity using a series of constant head flow tests. The apparatus consisted of two metal plates the upper of which was equipped with a standpipe for introducing flow to the core. To conduct the test, a PFC core sample is fastened between the plates with flexible rubber gaskets on both the upper and lower sides of the core (except for an opening beneath the standpipe). The core setup is submerged in a bath, and the bath water level determines the head on the radial periphery of the core. A peristaltic pump is used to provide a constant flow rate through the standpipe. An ISCO bubbler is used to determine the head in the standpipe (change in head through the core), and laboratory glassware and a stopwatch are used to determine the flow rate produced by the pump. This gives a relationship of head as a function of flow rate (Figure 3).

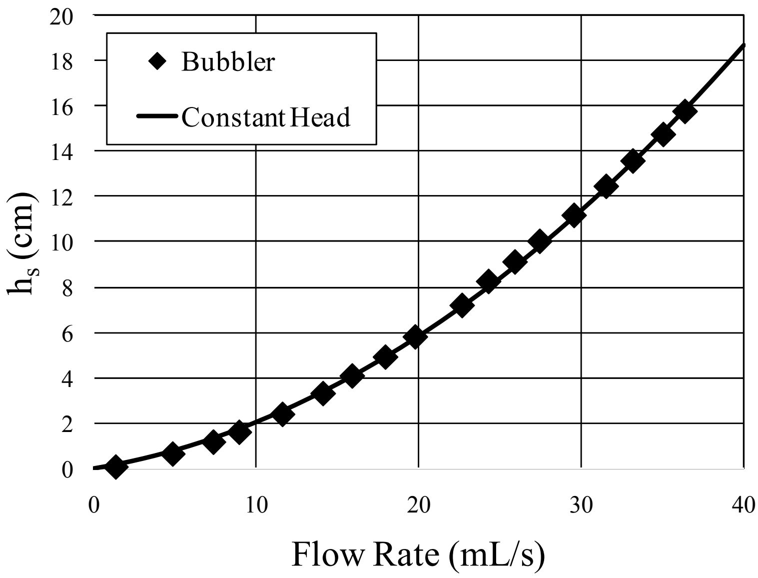

Figure 3: Head versus flow rate data and model fit for laboratory tests of Core 1-2-S

The nonlinear relationship between head and flow rate indicates that inertial flow effects occur and consequently Darcy's law for flow through porous media does not apply. Charbeneau et al. (in press) describe the methodology for proper determination of the hydraulic conductivity considering these nonlinear effects and radial geometry. Based on that work, the hydraulic conductivity of core specimens and ranged from 0.1 to 3 cm/s. A statistical analysis of these data show that the hydraulic conductivity has remained constant over time despite a decrease in porosity. Core specimens collected from Loop 360 have the greatest hydraulic conductivity, whereas specimens from RR 620 have the lowest hydraulic conductivity.

In addition to constant head laboratory tests, a series of falling head tests were conducted in the field. The field test is useful in order to determine the hydraulic conductivity or extent of clogging without extracting cores, which might alter their hydraulic properties. The falling head test is conducted using a testing apparatus developed for this research (Figure 4). The test apparatus consists of a solid metal disk with a radius 22.9 cm and a standpipe with radius 5.1 cm. Silicon vacuum grease is applied to the underneath of the metal disk in order to seal the PFC surface voids and prevent water from flowing between the interface of the roadway and metal disk. The testing process is conducted by first applying the vacuum grease evenly over the bottom surface of the plate. The plate is then pressed on the PFC surface in order to force the grease into the surface voids of the PFC. The standpipe is completely filled and allowed to drain multiple times in an attempt to saturate the PFC layer. Due to the slope of the roadway, the PFC void space cannot be fully saturated without a constant water supply, but this initial drainage helps in removing air bubbles from the PFC layer. Finally, the falling head test is conducted by starting a stopwatch at the initial head value. The split function is used to stop the watch at an intermediate head value, and the test is ended when the head has reached the bottom of the standpipe. The average times from three falling head tests are taken to determine the modified Forchheimer coefficients hydraulic properties at the test location.

Figure 4: Field test apparatus

A falling head test was performed near the coring location where the core shown in Figure 3 was extracted. The test yielded a hydraulic conductivity value of 3.45 cm/s, which is slightly larger than that found for the laboratory core sample. The interested reader should consult Klenzendorf (2010) details on determining the hydraulic properties of PFC.

Drainage Behavior

Predictions of water depths on PFC roadways are of interest because the water quality and safety benefits of the pavement are due to the fact that drainage is contained within the pavement. Under small rainfall intensities, drainage is contained within the PFC layer, but under higher rainfall intensities drainage occurs both within and on top of the PFC. The permeable friction course drainage code (PERFCODE) was developed to study this two-dimensional unsteady drainage process.

Given a rainfall hyetograph, geometric roadway information, and PFC hydraulic properties, the model predicts the variation of water depth within and on top of the PFC layer through time. The porous layer is treated as an unconfined aquifer of variable saturated thickness using Darcy's law and the Dupuit-Forchheimer assumptions. Surface flow is modeled using the diffusion wave approximation to the Saint-Venant equations. A mass balance approach is used to couple the surface and subsurface phases.

PERFCODE was applied to monitoring Site 1 near Austin, Texas. This is the same monitoring site described above; a gutter directs runoff to a flume where water samples are collected. A comparison of modeled and measured hydrographs is shown in Figure 5. The model predicted peak flows of the proper time and magnitude, and the shape of the hydrograph generally matches the field observations. The model predicted a peak flow 3.7 L/s, which is 97% of the measured value of 3.8 L/s. The difference between the modeled and measured flow rates (residual) had a mean 0.029L/s, with the largest residuals associated with high flow rates. This comparison suggests that the model parameters were consistent with field conditions and lends credibility to the associated depth predictions.

During this simulation, maximum depth in the domain of interest was 51.4 mm above the impervious layer, which represents a sheet flow depth of 1.4mm. This maximum occurred near the edge of the right traffic lane (Figure 6). This peak occurred 1 hour after rainfall began and during the peak rainfall intensity of 80 mm/hr. Under these conditions, sheet flow begins 1.6m from the grade break for the left hand shoulder.

The model was also used to analyze the effect of PFC during this event by re-running the simulation without a PFC layer. A comparison of the results showed that PFC reduced the sheet flow thickness by an average of 0.35mm, a 25% reduction. Perhaps more importantly, PFC reduced the duration of sheet flow conditions by 2 hours, or 80%. Further details on the development and application of PERFCODE are given by Eck (2010).

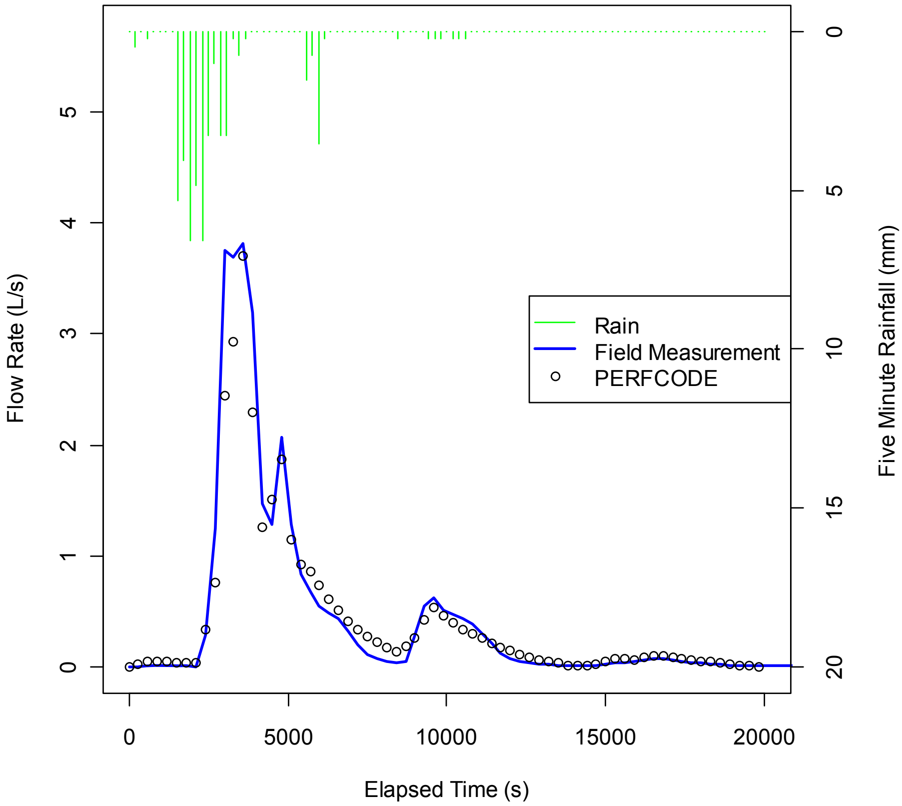

Figure 5: Comparison of modeled and measured hydrographs

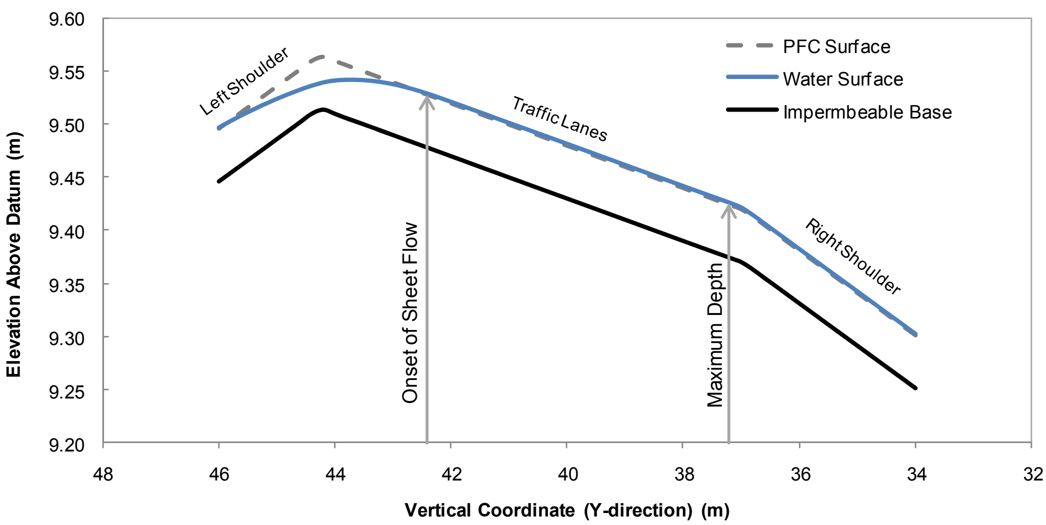

Figure 6: Drainage profile for maximum depth conditions

Conclusions

Porous asphalt overlays are proving to be a versatile material for highway pavements. The ability to provide safer driving conditions in wet weather by eliminating the splash and spray effect and the prevention of hydroplaning promise many safety benefits. The added benefit of improved water quality is becoming better understood.

Runoff generated from a PFC surface is of better quality than that from the traditional asphalt surface. In particular, constituents associated with particles have much lower concentrations in PFC runoff. Concentrations of dissolved constituents are similar in runoff from conventional pavement and PFC. Many regulatory agencies in the US require an 80 percent reduction in the amount of TSS discharged from new developments. The TSS removal observed during this project easily exceeds this threshold; consequently, this type of overlay has now been approved by the Texas Commission on Environmental Quality as a Best Management Practice (BMP) for highways in lieu of ponds, filters, or other structures commonly constructed to treat stormwater runoff.

A critical component in the assessment of the water quality benefits of PFC is whether the pollutant reduction observed in this study will persist over the life of the pavement. This study covered roughly half of the pavement life, and observed no decrease in water quality benefits of PFC. Porosity measurements did show that PFC clogs over time, but such clogging was not associated with an increase in pollutant concentrations. It seems likely that trapping particles and particle associated pollutants accumulate within the pore structure will cause more runoff on the surface of the pavement resulting in concentrations that might not be significantly different from those observed in runoff from conventional asphalt pavements. In addition, clogging of the pores in the pavement will likely reduce the other benefits associated with PFC (spray and noise reduction).

New methods based on radial flow have been developed to measure the hydraulic conductivity of PFC in the lab and in the field. The non-destructive field test is especially helpful because extraction of core samples is not required. Field measurements in the Austin area showed that the hydraulic conductivity of PFC ranged from 0.1 to 3 cm/s.

A new simulation model—PERFCODE— has been developed to simulate the drainage process for PFC roadways. The model quantifies the extent to which PFC reduces the duration of sheet flow conditions compared to conventional pavement. Modeling results also showed that PFC changes the hydrology of small events by attenuating the peak flow, though impacts on the hydrology of major events were negligible. Modeling further showed that steady state equations (Charbeneau and Barrett, 2008 and Eck et al. 2010) are suitable for design purposes.

In sum, PFC promises many exciting benefits. By integrating driver safety and watershed protection into the roadway itself PFC represents a major contribution to a sustainable transportation infrastructure.

Acknowledgements

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Realizing the Benefits of the Planning and Environmental Linkage (PEL) Process: Federal Boulevard (5^{th} Avenue to Howard Place), Denver, Colorado

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ABSTRACT

With limited transportation funding, the completion of timely National Environmental Policy Act (NEPA) studies that can be accepted by the Federal Highway Administration (FHWA) and the Colorado Department of Transportation (CDOT) is an increasingly difficult task. FHWA has developed the planning and environmental linkage (PEL) process, which outlines a process similar to the one required by NEPA yet does not require a project funding commitment. The PEL process is intended to streamline future NEPA studies, saving cost and time. In 2009, Denver conducted a PEL study for Federal Boulevard, an urban, north-south principal arterial roadway that is under the jurisdiction of CDOT as State Highway 88. The goal for the PEL was to develop a Proposed Action designed to: improve safety, increase efficiency for all modes of transportation, relieve traffic congestion, and improve multi-modal mobility (pedestrians, bicycles, public transit, and private/commercial vehicles). The Federal Boulevard PEL case study demonstrates the benefits of a PEL in assessing a project's viability and supporting prioritization for design and funding. This paper discusses the approach that was taken in performing the PEL, the decisions that can be made, the documentation that is required to fulfill PEL requirements, and how the PEL will be used to streamline the NEPA process as the project is funded and implemented. The PEL is a tool that can be used to plan the future vision for a corridor despite a lack of committed funding, all the while providing a streamlined process for successful future NEPA studies.

1.0 INTRODUCTION: WHAT IS PEL?

This paper presents the results and describes the benefits of a Planning and Environmental Linkage (PEL) study recently completed by the City and County of Denver, in cooperation with the Federal Highway Administration (FHWA) and Colorado Department of Transportation (CDOT). **FHWA defines PEL as a voluntary approach to transportation decision-making that considers environmental, community, and economic goals early in the planning stage and carries them through project development, design and construction** (FHWA, 2008). The PEL process is intended to lead to better decision-making that minimizes duplication of effort, promotes environmental stewardship, and reduces delays in project implementation (CDOT, 2009).

Decision-making for transportation projects involving federal actions begins with transportation planning before proceeding to project development, which includes environmental assessment as required by the National Environmental Policy Act (NEPA). These two processes are intended to work in tandem, with the results of the transportation planning process feeding into project development, including the NEPA process. In practice, however, transportation planning and NEPA analysis have sometimes become disconnected, resulting in duplication of work and delays in implementing needed transportation projects.

Congress recognized the need to streamline the transportation decision-making process in the current transportation funding legislation (SAFETEA-LU) which emphasized the need to include environmental considerations in the planning process and better link planning with NEPA. Accordingly, The Federal Highway Administration (FHWA) and Federal Transit Administration (FTA) have been working with state and local transportation agencies for the past several years to reduce duplication of work and resulting delays as projects move from planning to project development. The PEL process is one important result of these efforts. PEL can be applied to state-wide and regional planning efforts, as well as corridor/project-specific planning.

From a corridor/project-specific standpoint, the PEL process can be used to identify project-specific benefits, issues, concerns, and opportunities at the planning stage, often before project funding has been allocated, at a level of detail and documentation appropriate for use in a later NEPA process. **A corridor/project-specific PEL study may be used to establish project purpose and need, analyze alternatives, and evaluate environmental impacts and mitigation, all within a framework that can be used in a future NEPA process.** To illustrate this, **Figure 1** contrasts the traditional “planning then NEPA” approach with a PEL approach.

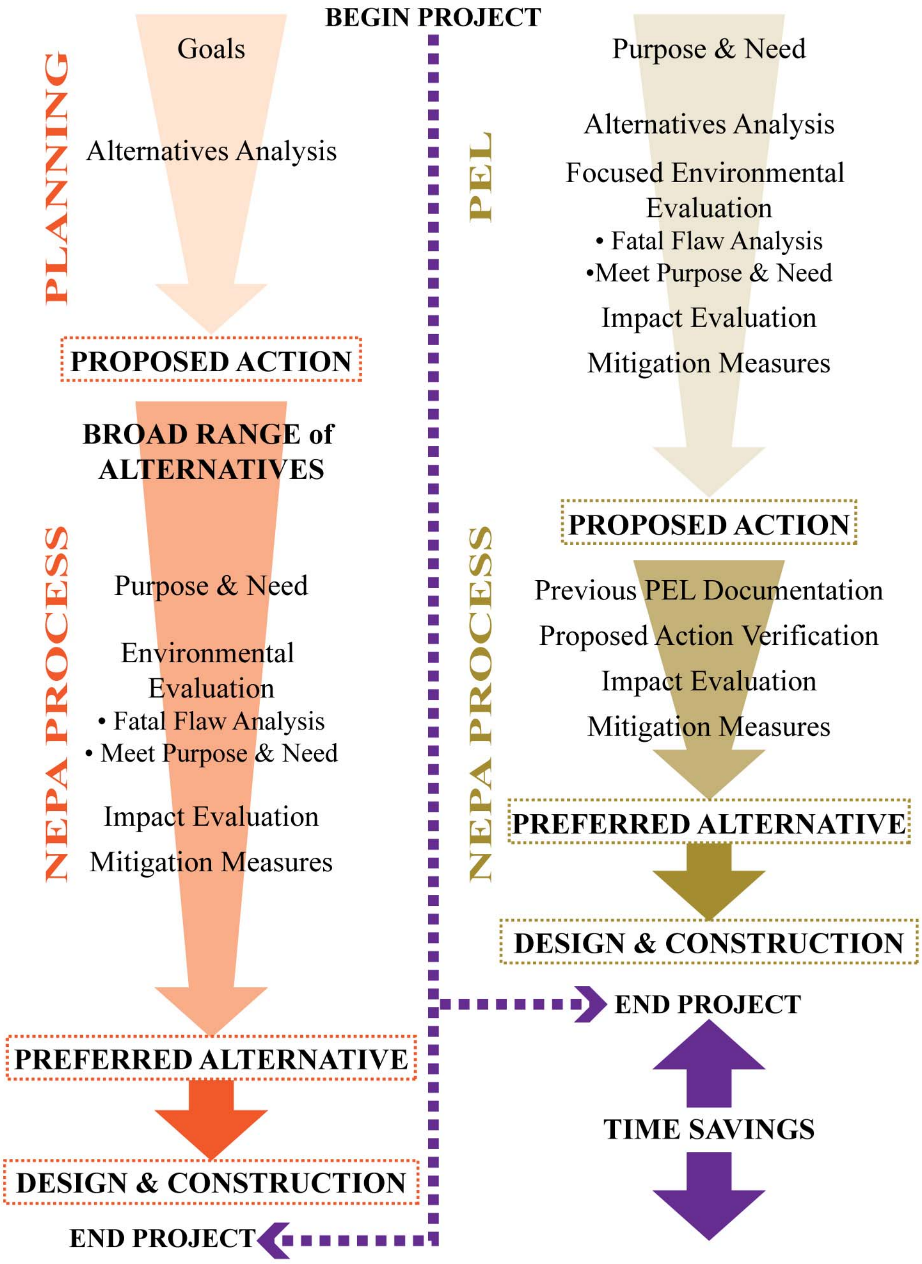

Figure 1. Example Comparison of “Planning then NEPA” and PEL Processes

2.0 CASE STUDY: HOW CAN PEL BE APPLIED?

The City and County of Denver recently concluded a PEL study for Federal Boulevard, an urban, north-south principal arterial roadway that is under the jurisdiction of CDOT as State Highway 88. The Federal Boulevard PEL case study demonstrates the benefits of a PEL in assessing a project’s viability and supporting prioritization for design and funding. The City and County of Denver chose to conduct a PEL because the project is only partially funded. Since completion of the PEL, 30 percent engineering design has been funded.

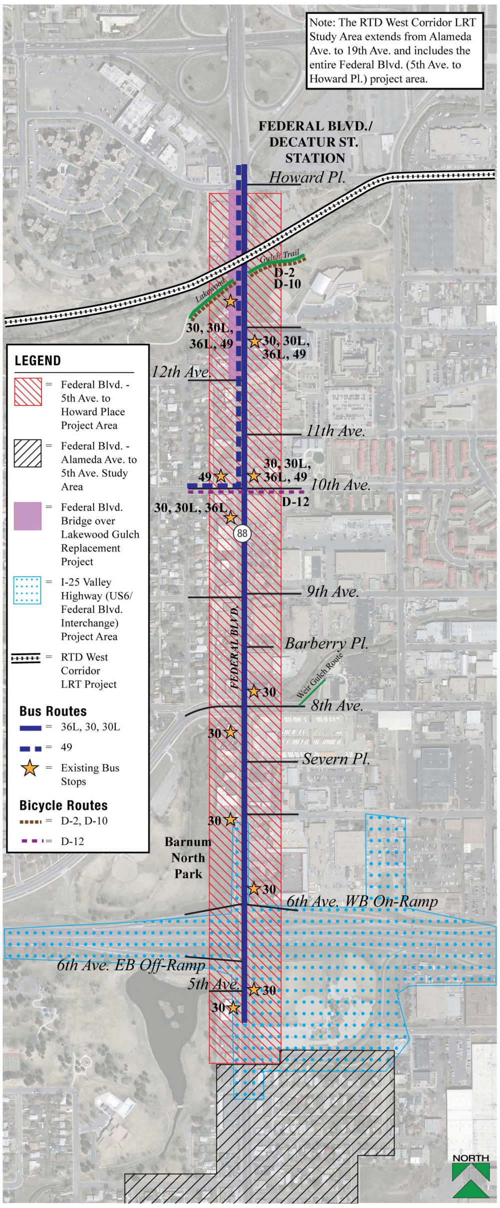

Figure 2. Federal Blvd. (5th Avenue to Howard Place) PEL Study Area

2.1 Study Location and Description

The first step in the Federal Boulevard PEL was to identify a study area based on the understood project needs. Identification of a study area is important to not only identifying the resources that will be evaluated but also to determine the resources that will not be evaluated as part of the study. To be able to lay the appropriate groundwork for further NEPA analysis, the project must have independent utility and logical termini to the extent that the project provides a functional transportation system even in the absence of other projects in the area.

The identified study area extends approximately one mile along Federal Boulevard from 5th Avenue on the south to approximately Howard Place on the north, as shown on **Figure 2**. East-west boundaries include the alley between Federal Boulevard and Grove Street to the west and portions of the first row of parcels immediately adjacent to Federal Boulevard to the east. The study area includes portions of five city parks: Barnum Park, Barnum East Park, Barnum North Park, Paco Sanchez Park and Rude Park and overlaps with the Weir Gulch bicycle route and the Lakewood Gulch trail. Federal Boulevard's character along the corridor is predominantly commercial with a few single-family residences. Light industrial facilities with some residential areas are present in the neighborhoods east of the study area. The neighborhoods to the west are primarily residential.

2.2 Other Transportation Projects in the Vicinity

In addition to the corridor-specific, citywide, metropolitan area, and statewide plans that include the study area, a series of transportation projects are planned in and within the vicinity of the study area. These transportation projects include:

- Regional Transportation District (RTD) FasTracks West Corridor light rail transit (LRT) project, which is currently under construction, will extend 12.1 miles from downtown Denver (approximately three miles east of Federal Boulevard) to Golden (approximately nine miles to the west of Federal Boulevard).

- CDOT I-25 Valley Highway project includes the reconstruction of I-25 from Logan Street to US 6 and west on US 6 to Federal Boulevard.
- Denver and CDOT Federal Boulevard (Alameda Avenue to 5^{th} Avenue) project, includes a planned cross-section for Federal Boulevard from Alameda Avenue to 5th Avenue, consisting of: three northbound 11-ft lanes, three southbound 11-ft lanes, a 16-ft raised median, and an 8-ft pedestrian zone.

A major strength of the Federal Boulevard PEL study was the identification of and coordination with other transportation projects in the vicinity. This afforded Denver the ability to make minor changes in the adjacent projects to accommodate likely impacts from the Proposed Action identified in the PEL.

2.3 Existing Conditions

To adequately develop a purpose and need statement, the existing conditions, such as roadway deficiencies that contribute to the needs, must be understood. This section of Federal Boulevard currently serves large vehicular volumes combined with high frequency bus service and significant pedestrian volumes. The road section contains substandard lane widths, a series of off-set and T-intersections, many private accesses, a narrow two-way-center-turn lane, an existing lane imbalance with three southbound and two northbound through lanes, and a lack of consistent ADA compliant sidewalks. The following lists unique modal conditions:

<u>(Vehicle) Auto</u> - Federal/Decatur LRT station park-n-Ride will be located south of Howard Place and east of Federal Boulevard.

<u>Pedestrian</u> - Several land uses in the study area are major sources of pedestrian trip generation. These land uses include: the Denver Department of Human Services central office, The Invesco Field at Mile High stadium, Rude Recreation Center, and the future Federal/Decatur LRT station.

<u>Bicycle</u> - Federal Boulevard is not a designated bicycle route yet several bicycle routes cross the corridor.

<u>Public Transit</u> - Eight bus routes currently provide services in the study area, including four that travel along Federal Boulevard.

2.4 Agency Coordination

The Federal Boulevard PEL built upon long-range planning and agency coordination previously conducted in the study area. The Denver Regional Council of Governments (DRCOG) and CDOT had previously evaluated the Federal Boulevard corridor in the *2035 Metro Vision Regional Transportation Plan* (DRCOG 2007) and the *2035 Statewide Transportation Plan* (CDOT 2007). Both plans identified Federal Boulevard as a multi-modal arterial with specific goals and improvement strategies that were incorporated into the PEL.

A scoping meeting was held to kick-off the project with FHWA, CDOT, and Denver in attendance. In addition, resource agencies were invited to participate in one-on-one scoping meetings. Resource agencies provided specific technical expertise and regulatory oversight on various environmental issues and potential project impacts.

Agency involvement activities included regular progress committee meetings held with agency participants through a Project Management Team. During these meetings key questions and concerns, such as the level of impact associated with environmental justice considerations and cumulative impacts were discussed in detail. The consultant team and city and agency representatives explored and discussed benefits and trade-offs of alternative alignments and design concepts. The Project Management Team was essential in ensuring that the elements of the PEL study met comprehensive and acceptable documentation requirements necessary for a future NEPA process.

The need for the Federal Boulevard PEL study Proposed Action is based on safety, capacity, and multi-modal connectivity. **Figure 3** depicts the existing and projected (2035) operational and roadway deficiencies for the study area.

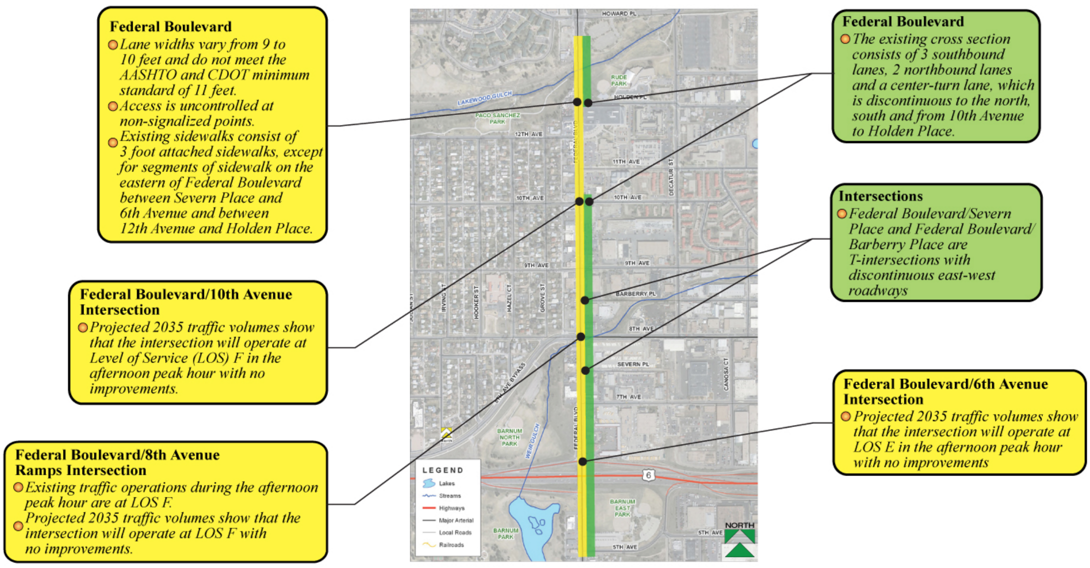

Figure 3. Existing and Projected 2035 Operational and Roadway Deficiencies

2.5 Project Purpose and Need

Development of a purpose and need statement is a primary element of the NEPA process. The Federal Boulevard PEL study included a purpose and need statement for use in alternatives analysis that was developed in concert by Denver, CDOT, and FHWA. **The benefit of this collaboration will be to streamline future NEPA studies with a previously accepted purpose and need statement**. The purpose of the PEL study is to:

- Improve the safety and efficiency
- Relieve traffic congestion

- Improve multi-modal mobility (pedestrians, bicycles, public transit, and private/commercial vehicles), linking with existing and planned sections of Federal Boulevard to the north and south

2.6 Objectives for the PEL Study

With the project purpose and need identified, the following operational and design objectives were established for use in evaluating alternatives:

- Improve the safety and efficiency by:
  - Providing a third northbound lane from 5th Avenue to 10th Avenue and from Holden Place to approximately Howard Place to address the lane imbalance through these sections of Federal Boulevard;
  - Widening the northbound/southbound lanes to meet American Association of State Highway and Transportation Officials (AASHTO) and CDOT minimum standards;
  - Managing access from left and right-turn movements at non-signalized points.
- Relieve traffic congestion by allowing the system to operate at a level of service (LOS) considered acceptable for major arterial intersections in the Denver metropolitan area (In traffic engineering terms, this equates to a goal of LOS D or better during peak hours given the year 2035 traffic projections with regional growth).
- Improve multi- modal mobility by:
  - Linking with existing and planned sections to the north and south;
  - Complying with ADA standards;
  - Increasing pedestrian/bicycle mobility and access to bus stops;
  - Enhancing access to the Federal/Decatur LRT station.

Multi-modal connectivity, the ability to provide connections between different modes of transportation, was a crucial feature in this planning process. Denver Public Works has been supporting the need to prioritize multi-modal connectivity both through the Strategic Transportation Plan (Denver 2008) and the Living Street Initiative. Multi-modal streets (Living Streets or Complete Streets) consider all modes with equal importance and provide a better use of public right-of-way by serving more people in the same amount of space and a wider range of users. These concepts were actively included in the Proposed Action as a result of following the PEL process.

2.7 Alternatives Analysis

Alternatives were analyzed, including a No-Action Alternative that was used as a benchmark for alternative comparison. The intent of developing numerous alternatives was to identify a full range of alternatives to address operational and roadway deficiencies as they relate to the purpose and need of the project. The Federal Boulevard PEL documented the alternative development and screening process so that future NEPA documentation could be based on the PEL analysis and not require re-evaluation of the alternatives. The purpose and need statement and alternatives analysis are key NEPA elements of the PEL process that are necessary to ensure that alternatives with fatal flaws or that do not meet the purpose and need are not carried forward and considered viable alternatives.

The goal of the screening process was to identify and refine the transportation improvements that best met the purpose and need of the project, while protecting the human and natural environment. Alternatives were evaluated with respect to the transportation benefits provided, public input, and environmental consequences. Due to the nature of the project corridor and the constraints identified, the alternative screening process was iterative and focused on the proposed alignment and cross-section of Federal Boulevard in the study area. A five-step screening process was employed. This analysis included gathering early public feedback and comment, studying conceptual alignments, providing alternative cross-sections, refining alternatives, and verifying alignments.

The fundamental philosophy in the screening process involved identifying notable positive and negative characteristics of the alternatives, and screening the alternatives one-by-one as the determinations were made. If a certain attribute (or attributes) of an alternative showed promise, an attempt was made to retain the individual attribute. The Federal Boulevard PEL Proposed Action, which has been identified by Denver, CDOT, and FHWA, balances transportation improvements to meet the project purpose and need with the environmental and social considerations.

2.8 Public Involvement

A public involvement program was conducted to involve local community groups, businesses, citizens, and low-income and minority populations in the decision-making process. The goal of the public involvement program was to provide meaningful public involvement throughout the process and solicit feedback from the community on the purpose and need statement, alternatives developed, the alternatives screening process, and the environmental analysis. The public comments received were utilized as part of the alternative screening process and will be used as a resource for future NEPA documentation.

For the Federal Boulevard PEL, public involvement activities included presentation to small groups, distribution of postcards and flyers to the community, door-to-door-outreach to businesses along Federal Boulevard, and an open house. The postcards and flyers that were distributed to the community were bilingual (English/Spanish), and a Spanish translator was available at the public meeting and small group meetings so that all members of the community could participate.

2.9 Identification of a Proposed Action

The final proposed action, see **Figure 4**, included a 103 foot total width cross-section with three eleven foot travel lanes in each direction, a 16 foot raised curb median, and an 8 foot pedestrian zone. The new pedestrian zone will include a five foot sidewalk and a three foot buffer from the street along with ADA compliant crossings at each intersection.

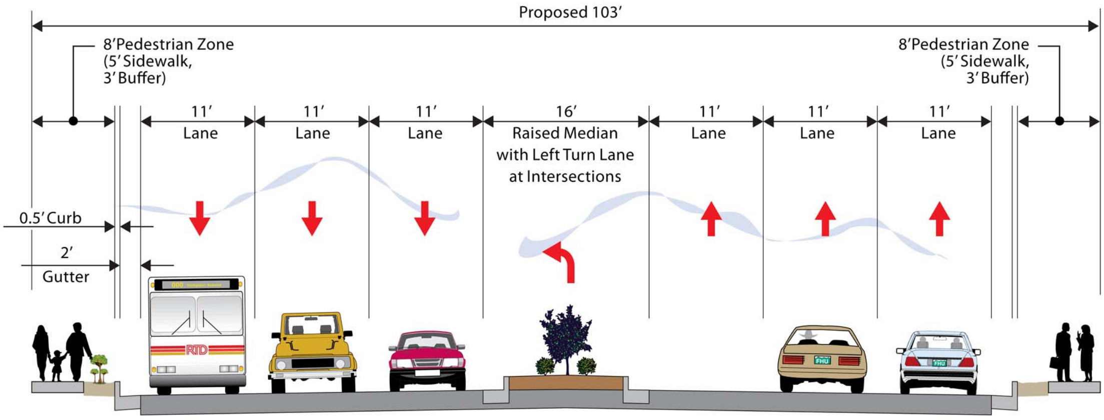

Figure 4. Proposed Action Cross-Section

The Proposed Action was determined to have met the purpose and need and had been reviewed by FHWA and CDOT, as well as the local community. The identification of the Proposed Action for the entire project corridor from 5th Avenue to Howard Place was consistent with FHWA's objective of analyzing and selecting transportation solutions on a broad enough scale to provide meaningful analysis and avoid segmentation. The Proposed Action addressed the safety, traffic operations and multi-modal connectivity needs identified through the PEL as follows:

<u>Safety and Traffic Operations</u>

Safety was a major concern along the project corridor. A detailed crash review showed that the overall three-year average crash rates for the study corridor were three to four times higher than the statewide average rates for all crash types. As traffic is predicted to increase, the addition of a third northbound lane would reduce congestion along the corridor and decrease the probability of crashes. Widening the northbound and southbound lanes to a minimum of 11 feet would provide greater room for vehicles to avoid rear-end crashes and provide vehicles adequate space to pass buses in the right lane of the roadway. Wider lane widths also are expected to reduce sideswipe (same direction) crashes.

Widening the roadway to include three lanes in the northbound direction, as already exists for the southbound direction would benefit operational performance. The addition of the third northbound lane would be most significant during times when a bus must stop for boarding or alighting of passengers by providing additional space for vehicles to pass buses in the right lane.

The raised median would replace the painted two-way left-turn lane and eliminate left turn movements at T-intersections. This would prevent northbound vehicles from making unprotected turns across three lanes of traffic and limits vehicles to right-in/right-out movements except at major intersections.

The addition of an 8-ft pedestrian zone would provide pedestrians and bicyclists protection from the adjacent roadway. Updated curb ramps would improve safety at intersections and meet ADA requirements.

Many properties along Federal Boulevard have more than one access, which increases the probability for accidents. By implementing access management principles, improved safety for all members of the traveling public will result. To accomplish these access management goals, where feasible, accesses for businesses will be combined, relocated, and potentially shared in order to reduce traffic conflicts along Federal Boulevard. While identified as a goal for the Proposed Action, more detailed discussions with property owner(s) will need to occur prior to implementing any proposed access modifications. This is a good example of a level of detail that is subject to change over time and can be identified as a next step following the PEL study and tabled until further NEPA analysis is able to move forward.

Multi-Modal Connectivity

The Proposed Action would affect the four modes of transportation as follows:

- (Vehicle) Auto – Vehicles will experience shorter travel times through the corridor, resulting in decreased congestion, improved LOS, and more efficient access to the Federal/Decatur LRT station.
- Pedestrian – Pedestrian facilities, such as sidewalks and curb ramps, will be upgraded to meet ADA standards. A continuous 8-ft pedestrian zone will provide greater spacing between pedestrians and the roadway and provide improved access to the bus stops and the Federal/Decatur station.
- Bicycle Mobility – Although Federal Boulevard does not have a dedicated on-street bicycle lane and is not a designated north-south bicycle route, the addition of a third northbound lane will improve safety for bicyclists traveling along Federal Boulevard. The continuous 8-ft pedestrian zone will reduce pedestrian and bicycle conflicts, provide access to the east-west bicycle routes, as well as improve access to the bus stops along Federal Boulevard and the Federal/Decatur LRT station.
- Public Transit – Buses will share the same improved travel times as autos, which increases the on-time performance of buses in the corridor and improves access to the Federal/Decatur LRT station. Providing an 8-ft pedestrian zone will improve passenger safety (both pedestrian and bicyclist) during boardings and alightings at bus stops.

2.10 Environmental Analysis

The environmental analyses conducted for this PEL focused on resource areas based on the characteristics of the study area and on input from the stakeholders instead of attempting to evaluate a larger expansive list of resources. The resources that were considered and the analyses performed are generally consistent with NEPA, its implementing regulations, and with FHWA and CDOT guidelines. Resources were introduced and followed by:

- Environmental Consequences – Discusses the impacts on the resource that would be expected under both the No-Action Alternative and the Proposed Action

- Mitigation – Describes the recommended mitigation measures that have been identified to address adverse impacts that would be expected with the Proposed Action

It is important to note that when adverse impacts were predicted, efforts were first made to avoid or minimize the adverse impacts. Recommended mitigation measures were then developed to address adverse impacts that could not be avoided.

One of the most challenging conversations during the PEL process was the consideration of environmental justice and social equity. This discussion was based around the acquisition of a business that provides food, and other goods and services to the Sun Valley neighborhood. Detailed neighborhood reconnaissance identified two other businesses providing similar goods and services and a community garden within the neighborhood as well as another branch of the same retailer within less than a mile of the impacted location. The PEL study was able to identify this community concern as an issue that will need to be resolved during NEPA.

Another key consideration was the cumulative impacts of not just the proposed action, but also other projects within the study area. Cumulative impacts result when the effects of an action are added to or interact with the effects of other actions in a particular place and within a particular time. It is the combination of these effects, and any resulting environmental degradation, that is the focus of the cumulative impact analysis. While impacts can be differentiated by direct, indirect, and cumulative impacts, the concept of cumulative impacts takes into account all disturbances because cumulative impacts result in the compounding of the effects of all actions over time. The cumulative impacts of an action can be viewed as the total effects on a resource, ecosystem, or human community of that action and all other activities affecting that resource no matter what entity (federal, non-federal, or private) is taking the action. This is an important component of the PEL because future projects will most likely be smaller and not evaluate the Federal Boulevard corridor in their entirety.

2.11 Agency Acceptance

Since the Proposed Action identified in the PEL study is unfunded at this time, FHWA and CDOT could not approve a "decision document", such as a FONSI or ROD for the project. However, both CDOT and FHWA acknowledged completion of the PEL study. **The benefit of this acknowledgement is to confirm the continued participation of Denver, CDOT, and FHWA in the project as individual projects are initiated, funding becomes available, and future NEPA studies are completed**.

3.0 CONCLUSION: WHAT ARE THE BENEFITS OF PEL?

With the authorization of SAFETEA-LU and creation of the PEL by FHWA, the planning process has been significantly enhanced in terms of the types of projects which can be performed. With the project-specific PEL process, a municipality may now initiate and lead the planning process in coordination with the MPO and DOT. By combining environmental and planning efforts, a project without identified funding sources can determine a Proposed Action which can then be used to streamline the completion of a future NEPA study.

The primary objective of the PEL process is to assess a transportation need in order to determine a Proposed Action with enough detail that the Proposed Action can be selected as the Preferred Alternative through future NEPA documentation. In order to accomplish this goal, key components must be included within the Proposed Action including independent utility/logical termini, a purpose and need, an analysis of the environmental impacts, and mitigation measures to mitigate adverse environmental impacts of the Proposed Action.

The Federal Boulevard PEL has been used to demonstrate an application of the PEL process to a specific project. The benefits of the PEL process included:

- Streamlining effort realized in terms of cost and time savings for future NEPA studies
- Meaningful public involvement
- Coordination with other nearby projects
- Collaborate with adjacent projects right-of-way acquisition
- Early agency scoping with resource agencies
- Greater understanding of estimated construction cost, identification of potential cost sharing, and advancing to a “shovel ready” stage for potential funding

The Federal Boulevard PEL case study demonstrates the benefits of a PEL in assessing a project’s viability and supporting prioritization for design and funding. The PEL is a tool that can be used to plan the future vision for a corridor despite a lack of committed funding, through a process complementary to future NEPA studies.

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LED Streetlight Application Assessment Project Pilot Study in Seattle, WA

Dana Beckwith, Edward Smalley, Mark Yand, Lok Chan, Xiaoping Zhang

[Abstract] Recent studies have found that light emitting diode (LED) technology is becoming competitive for streetlight applications with the commonly employed high intensity discharge (HID) light sources such as high pressure sodium (HPS) and metal halide (MH). The expectation is that LED street lighting technology will not only provide more efficient light distribution and increased uniformity, but will also save energy and reduce maintenance costs.

Seattle City Light (SCL) has a street lighting system of nearly 84,000 street and area lights that use predominantly HPS light sources. Because of the potential benefits of installing LED luminaires as a replacement for these lights, SCL launched the *LED Streetlight Application Assessment Project Pilot Study* to evaluate LED luminaires for photometric performance, energy efficiency, economic performance, and the impact of the new lights on SCL streetlight system. Project findings will be used by SCL to develop a strategy for the installation of LED streetlights in developing an energy efficient lighting system.

The major elements of this project included LED luminaire selection, simulated photometric performance of selected LED products using AGI32, field photometric performance evaluation at selected test sites, and economic performance evaluation in comparison to HPS luminaires. In addition, since combining LED roadway luminaires with new light control systems provides many new options for overall light control, facilitating maintenance, increasing luminaire life, and further reducing operating costs, a preliminary review of current cutting-edge lighting control systems were explored.

Introduction

Recent studies have found that light emitting diode (LED) technology is becoming competitive for outdoor applications with the commonly employed high intensity discharge (HID) light sources such as high pressure sodium (HPS) and metal halide (MH). The expectation is that LED street lighting technology will not only provide more efficient light distribution and increased uniformity, but will also save energy and reduce maintenance cost.

Seattle City Light (SCL) has a street lighting system of nearly 84,000 street and area lights that use predominantly HPS light sources. Because of the potential benefits of installing LED luminaires as a replacement for these lights, SCL launched the *LED Streetlight Application Assessment Project Pilot Study* to evaluate LED luminaires for photometric performance, energy efficiency, economic performance, and the impact of the new lights on SCL streetlight system. The project findings will be used by SCL to develop a strategy for the installation of LED streetlights in developing an energy efficient lighting system.

This study was conducted in collaboration with Pacific Northwest National Laboratory (PNNL), representing the DOE, and is part of the DOE Solid-State Lighting GATEWAY Demonstration program, which is designed to showcase emerging LED lighting products.

Objectives

SCL conducted this study to evaluate LED streetlights and their ability to bring energy-saving lighting to Seattle neighborhoods and streets. To assess benefits of LED streetlights, this project focused on the following key objectives:

- Select a suitable LED product(s) for use by SCL on residential roadways.
- Evaluate the lighting, economic, and energy consumption performance.
- Evaluate the ability for LED products to produce a 40 percent energy savings compared to existing HPS cobra head style luminaires.
- Develop a functional specification and recommendations for the installation and maintenance of these products.
- Identify next steps to increasing energy efficiency of LED lighting.

Study Area and Test Sites

Capitol Hill and South Park areas (Figure 1) were selected by SCL for this project. Factors considered during the study area selection included roadway type, community socioeconomic makeup, size of street level retail, mix of single family and multi-family housing, and other factors such as park fronts. Test Sites 2 and 10 in Capitol Hill Area and Test Sites 11 and 12 in South Park were included in the study.

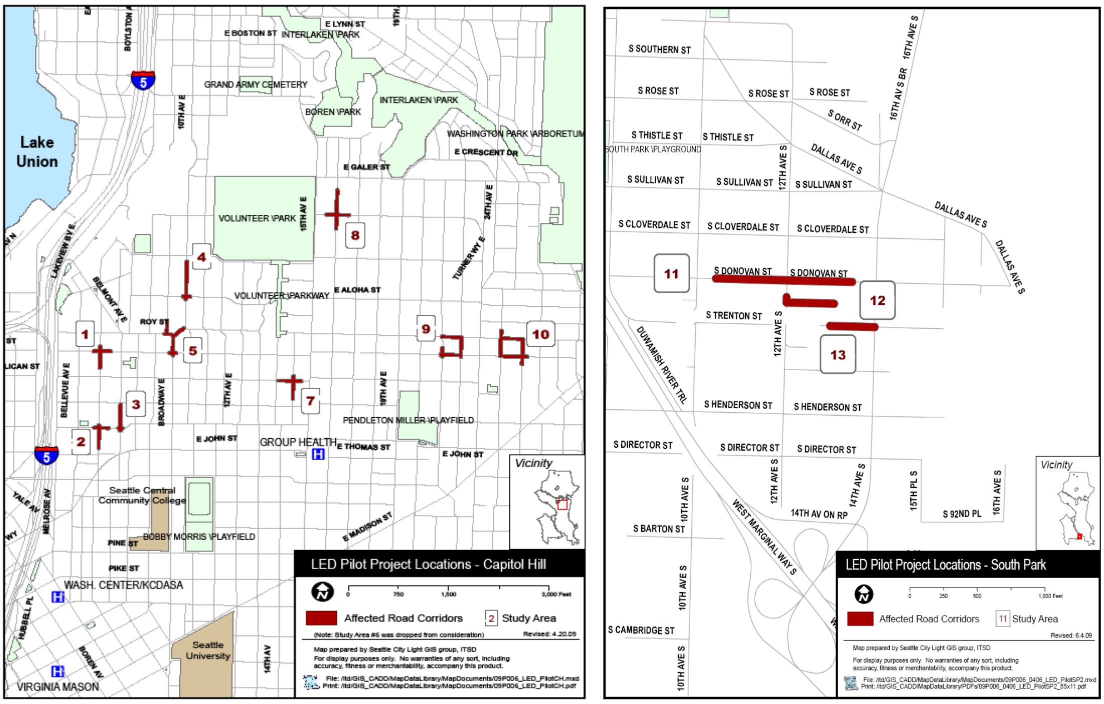

Figure 1 – Test Sites (Capitol Hill and South Park)

Luminaire Testing and Results

The SCL LED Application Assessment project pilot study was conducted in two stages. In the Stage I Capitol Hill test sites, SCL selected LED luminaires from two vendors, conducted computer simulation, and field testing. Before and after field comparisons for the replacement of HPS cobra head style luminaires with LED luminaires were conducted. The Stage II South Park test sites included selecting and testing up to three additional LED streetlight luminaires with an emphasis on luminaires that are considered "Made in America" as well as further testing select luminaires from Stage I. A field testing methodology was also developed for the Stage II test sites.

Aside from test site selection (previously discussed), the major elements of this pilot project included:

- LED luminaire selection.
- Simulated photometric performance evaluation of selected LED products.
- Field photometric performance evaluation.
- Economic performance evaluation in comparison to HPS luminaires.

Candidate LED luminaires were selected from criteria developed specifically for this study which included:

- Photometric performance (Stage I and II).
- Pricing (Stage I and II).
- "Made in America" status (Stage II only).
- Manufacturers' production capabilities (Stage I and II).

In this document, rather than identifying vendors and luminaires by name, a coding system was developed in this project to identify the vendors and luminaires under test. The vendors are coded as "A", "B", "C", "D", "E", and "F", and their different types of luminaires are distinguished by numeric numbers. For example: a luminaire code A1 means Vendor A, Luminaire 1. The luminaires tested under Stage I included A1, B1, C1, D1, E1, and F1.

Under Stage I testing, it was found that the field tested Vendor A luminaires performed favorably. However, information gained from public feedback, indicated the color temperature was too cool (too blue) and created a somewhat dismal and unwelcoming environment. Since the Vendor A luminaire performed well in Stage I testing and was a "Made in America" product, it was added to the list of manufacturers to be tested under Stage II with the plan to test a warmer color temperature in the range of 4000°K to 4300°K (less blue with more red and yellow light) and change the light distribution from Type III to Type II. As with the Vendor A luminaire, the Vendor C luminaire would be tested at the warmer color temperature with a Type II distribution. Therefore luminaires A2, A3, C2, and C3 were added to the Stage II testing.

The performance of luminaires selected for testing was simulated using the lighting analysis software AGI32. Tests were conducted for a typical residential roadway section and for field conditions at each test site. Major factors considered when ranking the candidate luminaires included:

- Luminaire mounting height.
- Average maintained illuminance values.
- Uniformity ratios (average/minimum).
- Light pole spacing[1].

The light loss factor (LLF) used for the analysis assumed the following:

- Luminaire Dirt Depreciation factor (LDD): based on a clean to very clean environment and a seven-year maintenance cycle. A clean environment with an LDD of 0.85 was assumed for the initial luminaire selection. Additional simulation analysis under the Stage II test sites assumed a very clean environment with an LDD of 0.92.
- Lamp Lumen Depreciation factor (LLD): obtained from each of the luminaire manufacturers and based on the manufacturers LM-80 test data.

Selected LED luminaires were field tested for photometric performance at the Stage I and II sites. The LED photometric measurements were compared to measurements from existing HPS luminaires, City of Seattle Standards, and the Illuminance values recommended for local roadway facilities in the Illuminating Engineering Society of North America's, *RP-8-00 Reaffirmed 2005, American National Standard Practice for Roadway Lighting* (RP-8-00). The Stage I testing was conducted by PNNL and Stage II testing was conducted by the Lighting Design Lab (LDL).

Results Summary and Findings

The simulation and field test results from the Stage I and Stage II Study Areas show from an illuminance level perspective, LED luminaires are a viable option to replace existing HPS luminaires. Minimum illuminance levels, as published through the RP-8-00 can be met[2]. Seattle's average illuminance requirement is only met by some of the larger LED luminaires being tested under the study. These larger luminaires mean lower cost savings due to the larger LED arrays in use. Important findings from the computer simulation and field tests included:

1. Not all luminaires met the average maintained illuminance and uniformity values required by National or Local Standards. It is important to conduct simulation and field testing of each type of LED luminaires to understand their photometric performance.

2. Type II light distribution minimized back lighting onto private property more than the Type III distribution pattern. This was apparent in both the simulation and field tests.

3. In the Stage II South Park area field tests, the initial lumen output of the LED luminaires is approximately two times greater than the design year of the lighting system (in this case the design year of the system is seven years into the future). This additional lumen output is wasted energy. New control systems and dimmable drivers can be used to reduce initial lumen output and then increase it as the lamp

lumen depreciation increases. In theory, this means a longer life for the luminaire since it is being driven at a lower amperage during the first few years of its life. Based on the higher initial illuminance level value and not a depreciated future value if the extended life is beyond the desired period for luminaire replacement, this would make the lower wattage luminaries like A4 a viable and economic option.

4. Public feedback on the field installations at the Stage I test sites identified the "cooler" color temperatures from 5500°K to 6000°K created a dismal and unwelcoming environment. Subsequent installations of luminaires at the Stage II sites with a warmer color temperature from 4100°K to 4300°K created a more welcoming and comfortable environment.

5. General Stage I public feedback supported the pursuit of additional installations of LED luminaires.

6. Approximately 25 percent of Vendor C's luminaires installed in the test sites have failed (two out of eight) under Stage II. There have been no failures of the field installed luminaires from Vendor A.

7. A lamp dirt depreciation factor (LDD) of 0.92 was determined to be appropriate for residential streets.

Conservation Incentives

The following energy conservation incentive programs have been identified:

- **SCL Conservation Division**: With the installation of energy efficient streetlights, the SCL Conservation Division will pay back $0.22 per kilowatt-hour saved. The incentive amount is returned to SCL as a one-time rebate.
- **Washington State Transportation Improvement Board (TIB):** TIB has a selection process for agencies to apply for grants. TIB funding programs are available if the project falls under three categories: Urban Arterial Program, Urban Corridor Program, or Urban Sidewalk Program.
- **Department of Energy:** Provides funding and grants through various conservation energy programs. Local governments can apply for block grants to improve energy efficiency and renewable energy systems.
- **Qualified Energy Conservation Bonds**: These bonds are issued through state or local governments for financing governmental programs to reduce greenhouse gas emissions and other conservation purposes.
- **The Clinton Climate Initiative (CCI)**: CCI can help by advising on project management, purchasing, financing, and technology.

Economic Analysis -Simple Payback

The economic analysis focused on simple payback calculations methods and included SCL incentive rebates. The analysis was based on the replacement of 100-watt HPS luminaires (consuming 142 Watts) on residential roadways. Maintenance costs, energy rates and power consumption of existing luminaires were obtained from SCL. The following assumptions were included in the calculations:

- 15-year luminaire life cycle.
- Maintenance cycle of seven years.
- LED luminaire failure rates of 10 percent.
- $0.22 incentive rebate per kilowatt-hour saved.

Using simple economic payback calculations and setting aside energy conservation goals of 40 percent savings over currently used HPS luminaires, LED luminaires can be an economical alternative. With SCL conservation rebates of $0.22 included in the overall calculation for each kilowatt-hour saved, the following payback periods were realized for the Stage I and Stage II luminaires under study:

- Small LED array luminaires
  - Luminaire A1 (39 watts) – 1.9 years
  - Luminaire B1 (58 watts) – 3.3 years
- Medium LED array luminaires
  - Luminaire C2 (75 watts) – 4.7 years
  - Luminaire A2 (109 watts) – 6.1 years
- Large LED array luminaires
  - Luminaire C3 (137 Watts) – 13.8 years
  - Luminaire A3 (142 Watts) – 14.6 years

When the SCL energy conservation goal of 40 percent energy savings is taken into account, a luminaire must consume 85 watts of energy or less. Only luminaires A1, B1 and C2 fell into that category. However, A1 and B1 are not an option due to their photometric performance.

A continued improvement in LED luminaire efficacy is expected over the short term. This will continue to reduce costs and increase savings in operations costs. Taking advantage of new control systems with dimmable drivers is an option that can provide additional energy savings.

Recommendations

Luminaire

Based on the analysis conducted in this study, the following luminaire has been identified as a viable option for replacement of 100-watt HPS cobra head style luminaires in residential areas. These recommendations are being made not because the luminaire meets the 40 percent energy reduction goal, but because of their economic, photometric, and maintenance performance. The following recommendation is subject to change as LED products with better photometric and economic performance are available.

Recommendations (Luminaire):

1. **Luminaire A2: 60LED-Type II Distribution-4300K-525mA**
2. **General Recommendations: Type II Light Distribution, Correlated Color Temperature of 4000°K to 4300°K**

Luminaire A2 performed favorably with the following characteristics:

- Power consumption: 109 Watts
- Distribution: Type II
- Initial Lumens: 4,968 (60 LED Array)
- Correlated Color Temperature: 4300°K
- Color Rendering Index: 75 minimum
- Driver Current: 525mA
- Efficacy: 46 lumens/Watt
- IP Rating: IP66
- Weight: 16 lbs

The computer simulation test of the luminaire generates an illuminance level of 0.65fc, which falls between the RP-8-00 requirements. The field test revealed that the LED luminaires generally produced higher illuminance levels than the existing HPS luminaires.

As a late development in the study, Vendor A has released their new generation luminaires. The new generation luminaires are designed to provide better uniformity than the previous products. In an effort to provide up to date information, a review of the new generation luminaires showed better photometric performance with greater spacing and comparable uniformity than the previous products. It is anticipated that an economic evaluation of the new generation luminaire will yield similar results to the previous generation. The new generation luminaire should be considered as a replacement for the previous luminaire product. The new generation luminaire is as follows:

Luminaire A2 Rev. 11/02/09: 60LED-Type II Distribution-4300K-525m

Specification

A functional specification has been developed for SCL to use in purchasing LED luminaires and the evaluation of future luminaires for residential roadways. The specification is based on the research conducted on LED luminaires available on the market today, computer simulations, and field testing.

Recommendation (Specification):
Review specification every six months to take into account rapid advances in the LED lighting technology.

Luminaire Selection

LEDs are a new and rapidly developing technology in the roadway lighting arena. An understanding of industry lighting standards, manufacturing (including an in-depth understanding of heat dissipation), and testing of LED products is essential to making good decisions on luminaire selection.

Recommendation (Luminaire Selection):

1. **Utilize an LLD factor based on LM-80 tests.**
2. **Utilize an LDD factor of 0.92 for residential roadways.**
3. **Require independent LM-79 and LM-80 test results for all luminaire submittals.**

Recommended Next Steps

LEDs are an instant on/instant off technology with no start-up or re-strike time. Combining LED roadway luminaires with new light control systems provides many new options for overall light control, facilitating maintenance, increasing luminaire life, and further reducing operating costs. The following are benefits of incorporating lighting control systems with LED lighting technology include:

- **Dimming of Lighting Circuits after Hours:** This can be based on time of day or traffic volumes. Dimming of luminaires can provide reduced energy costs and prolong the life of the luminaire.

- **Step Dimming or Continuous Dimming:** Lighting systems are designed to meet standard illuminance levels at a future year with a given amount of lumen and dirt depreciation incorporated into the design. This means at initial installation, more lumens are being produced than required. Step or continuous dimming of a lighting system would reduce the initial lumen output to its design standard by reducing the drive current and then gradually increase that drive current at predefined time intervals to maintain the same lumen output over the life of the system (Figure 2). Based on the higher initial illuminance level value and not a depreciated future value if the extended life is beyond the desired period for luminaire replacement, this would make the lower wattage luminaries likeA4 a viable and economic option.

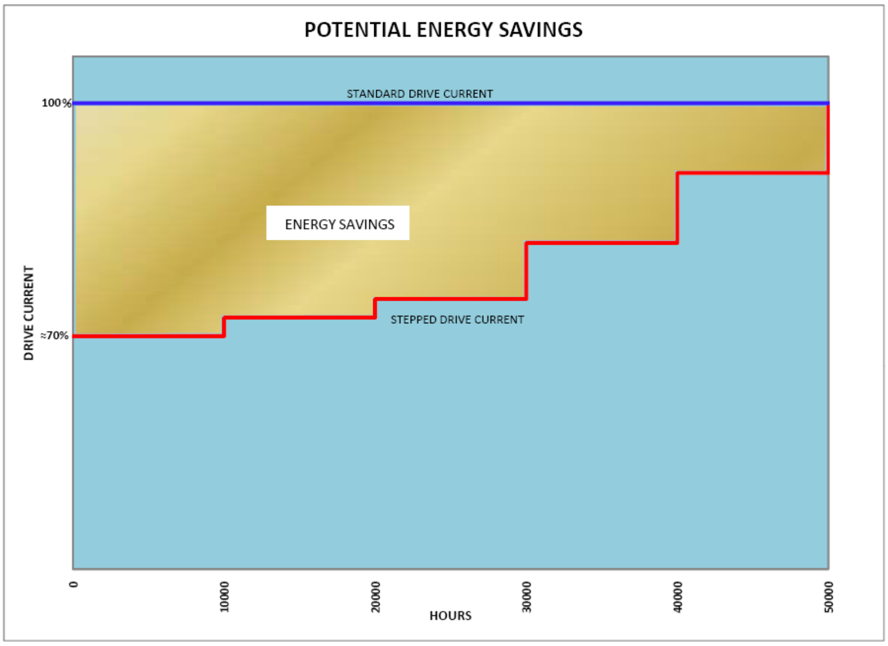

Figure 2 – Diming energy savings

- **Emergency Services Support:** If tied into traffic operations centers, emergency management centers, or electric utility operations centers lighting control systems can increase illuminance levels at select locations to facilitate emergency services and then be reduced back to normal levels when the emergency is over.

- **Pedestrian or Vehicle Activated Lighting Circuits:** Lit corridors with motion sensors incorporated into the luminaire, can be turned off or dimmed until a person or vehicle is in the vicinity. Dimming of luminaires can provide reduced energy costs and prolonged life.

- **Luminaire Health Monitoring:** Control systems can monitor the health of luminaire components such as LED drivers. Many benefits are available through luminaire monitoring:
    - Luminaires can be GPS located to provide maintenance with exact geographical locations reducing time in locating outages,
    - Maintenance can respond in a more efficient manner reducing the number of system wide outages and down times, improving customer service,
    - Outage patrols can be reduced, and
    - Trend analysis can be conducted from information received from the field.

There are many new light control systems on the market today. Just as with LED luminaires, care needs to be taken to select the correct system to meet agency needs. There are many different items that need to be considered both for the control system itself and the infrastructure needs to support that system. Further evaluation of lighting control systems and their potential benefits for Seattle City Light is recommended.

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End Notes

[1] Light pole spacing is an important factor since the general practice on residential streets is to place light poles on every third property line giving typically 150 foot spacing between light poles. Mounting heights of luminaires were simulated at 30 feet. It was assumed this would provide the worst case illuminance values.

[2] The RP-8-00 standards for a residential street with low pedestrian volumes are an average maintained illuminance level of 0.4fc and uniformity ratio of 6:1. Seattle's average illuminance requirement is 0.7fc.

Cool Pavements as a Sustainable Approach to Green Streets and Highways

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Abstract

The urban cityscape is covered with man made materials that absorb the suns light. Darkly colored roads and roofs have replaced surface area which was once predominantly vegetated lands. For these reasons summertime ambient temperatures in cities are typically warmer than those of rural areas. This phenomenon is known as the heat island effect. Heat islands lead to increased air conditioning use which puts a strain on a cities energy grid. To supply this extra wattage municipal power plants must work harder and as a result emit more carbon. Therefore, the heat island effect contributes to environmental problems including air quality and climate change. Dark impervious pavements cover a large amount of urban surface area, typically 30-45%. One solution to this problem is the implementation of cool pavement technologies in pavement areas of less stringent structural requirements such as parking lots and low volume roads. Cool pavements are a class of materials that exhibit enhanced cooling by means of increased reflectivity or increased convection. This study correlates heat island effect to climate change as well as outlining the different cool pavement technologies which may help to mitigate climate change effects.

Introduction

During the summer the average US metropolis experiences increased ambient temperatures in the afternoon and night compared to rural areas. To compensate for these increased temperatures people utilize air conditioning units which consume huge amounts of electricity. In order to cover the surplus wattage demand municipal power plants must pump out more energy, burn more fossil fuel, and emit more carbon dioxide. One reason for this increased temperature in urban regions is the composition of the surface area. Land which was once with vegetation is now inhabited by humans and blanketed with our infrastructure. Cityscapes are made up of darkly colored materials capable of absorbing the sun's energy. Asphalt paves our streets and tar covers our roofs. During summer months these dark surfaces contribute to increased ambient temperatures in the late afternoon and at night. This creates larger demand for cooling which strains the energy grid and raises emission outputs from fossil fuel based power plants. Increasing the cooling of paved areas in cities can serve as a transitive means of reducing carbon dioxide emissions and mitigating climate change. More specifically, rethinking approaches to parking lot and low volume road design is one method to potentially mitigate carbon emissions. Generally speaking, some parking lots may be over designed for the low volume of traffic they experience. The use of specially engineered paving materials can reduce the amount of heat absorbed by parking lots and in turn decrease air temperatures, energy use, and greenhouse gas emissions.

This study correlates heat island effects with US emissions to provide a better understanding of seasonal urban emissions. Also, an overview of different cool pavement technologies is included as means of climate change mitigation.

Heat Island Effect

Heat island effect describes the lingering increased ambient temperatures in cities during warmer months. Perhaps the best way to begin describing the heat island effect is to discuss the thermodynamic relationship between a material surface and the suns rays. The sun imparts energy onto the earth in the form of electromagnetic radiation. Once this radiation is filtered through the atmosphere it reaches the earth's surface. From there, objects absorb a percentage of that energy and store it usually in the form of heat. The energy that can not be absorbed is reflected. This ability of a material to reflect or absorb the sun's light is measured in a unitless parameter known as albedo. Theoretically, albedos can range from 0 for very dark energy absorptive surfaces to 1 for lightly colored reflective surfaces. No objects can absorb or reflect 100% of the suns energy radiated upon them, therefore, an albedo of 0 or 1 is never seen on an earthly object. Fresh asphalt concrete has an albedo of 0.04 because of the dark black viscous bituminous material used to bind aggregates (Akbari 2000). Albedo is a parameter that can be indirectly computed from a device known as a pyranometer. This device measures electromagnetic radiation in units of energy per square length. Albedo is the ratio of total reflected electromagnetic radiation to electromagnetic radiation delivered at the time of incident.

As previously mentioned fresh asphalt concrete has an albedo of 0.04 meaning it absorbs a huge amount of the suns radiation compared to the amount it reflects. Typical parking lots have about 4 inches of asphalt concrete covering compacted earth (AI 1981). Therefore, the capacity to store heat in a sprawling asphalt parking lot is huge. During the hottest hours of the day, around noon, asphalt concrete stores the sun's energy in the form of heat. During cooler times such as the late afternoon and night asphalt concrete releases that heat to keep in equilibrium with the surrounding air. This idea of equilibrium is consistent with the 0^{th} law of thermodynamics. Since dark surfaces, such as asphalt concrete, are abundant in cities there is more heat stored which has the potential to be released. This forces ambient temperatures to be elevated at times during the day when solar radiation is less significant. This phenomenon is known as the heat island effect. Rural areas have a greater percentage of their surface covered in vegetation and highly reflective materials. This is why heat islands are less pronounced or non existent in these regions. After a sunny summer day city temperatures can be up to 5°C, 8°F, higher than rural areas (Akbari 2000).

Dark surfaces like asphalt pavement have several consequences associated with them. One such consequence is elevated temperature of stormwater runoff. Hotter runoff can be detrimental to aquatic life and ecosystems. For example, asphalt pavement with a surface temperature of 38°C (100°F) is able to heat rainwater from 21°C (70°F) to 35°C (95°F) (EPA 2009). Hotter runoff can also alter the fate and transport of urban contaminates by affecting hazardous compound aqueous solubility and rate of volatilization. As previously stated heat island effect increases ambient temperatures creating an increased demand for cooling. This increased demand for cooling can amount to a 5-10 % increase in peak electricity (Akbari 2005). One estimate shows that the temperature increase from the heat island effect in Los Angeles can account for up to 1.5 gigawatts of energy (Akbari 2000). This increase causes additional emissions from municipal power plants. Therefore, the heat island effect contributes to problems with air quality including smog formation. However, the biggest consequence of dark pavements and heat islands may be their contribution to climate change.

Heat Island and Climate Change

Climate change is a pressing topic; it makes headlines daily ranging from legislative initiatives to scientific studies. The anthropogenic release of gas, such as CO_2, is repeatedly cited as the reason climate change is occurring (EPA 2010). Since there are many gases besides CO_2 that contribute to climate change they are ranked in terms of equivalents of CO_2. For example, 1 part methane [CH_4] converts to 21 CO_2 equivalents. In the US the predominate source of CO_2 equivalent emissions stems from fossil fuel combustion. Fossil fuel combustion totaled 85.1% or 5,573 teragrams of CO_2 equivalents in 2008 as seen in Figure 1 (EPA 2010).

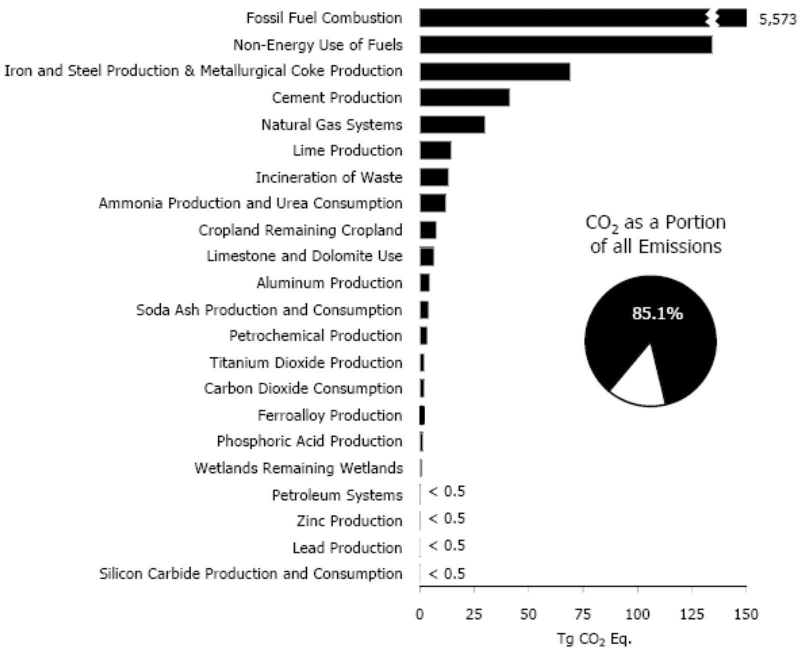

Figure 1. Sources of US CO_2 equivalent emissions in 2008 (EPA 2010)

Out of fossil fuels combustion's 5,573 equivalents 2,636 are used for electricity generation, see Figure 2. This yields about 36 % of total US greenhouse gas emissions, which is a considerable portion.

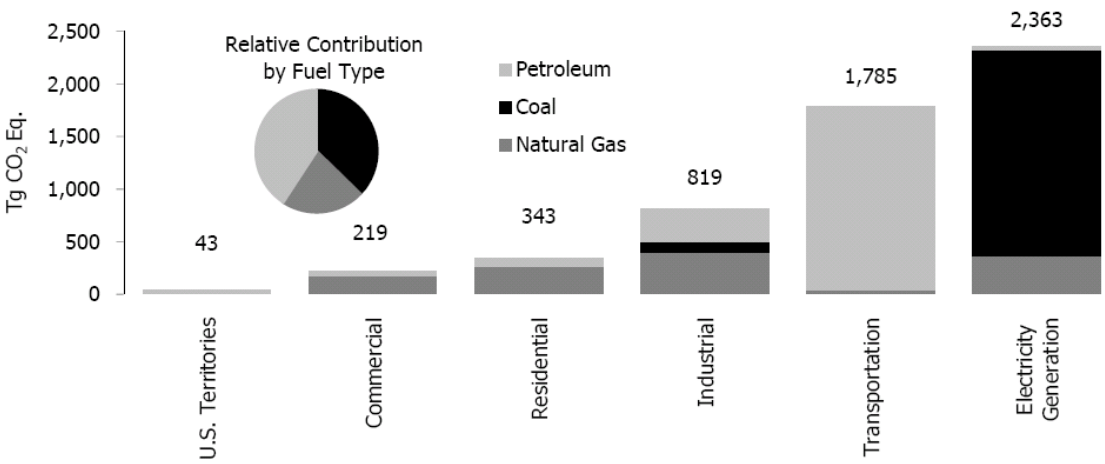

Figure 2. US 2008 fossil fuel combustion breakdown (EPA 2010)

Without any doubt electricity generated through the burning of fossil fuels is the number one emitter of greenhouse gases in the US. It is also noticed from Figure 2 that coal is the fuel that comprises the greatest percent of electricity generated. Unfortunately, coal also has the greatest potential for carbon emissions per unit power created. In order to judge the potential for emissions reductions it may be noted that one estimate shows in Los Angeles heat island effects may account for up to 1.5 gigawatts of energy (Akbari 2000). Through examining the mix of fossil fuels burned to create these superfluous 1.5 gigawatts of energy the potential for emissions reductions can be calculated if heat island effect is mitigated in LA. Figure 3 shows the correlation between fossil fuel type and carbon dioxide emitted.

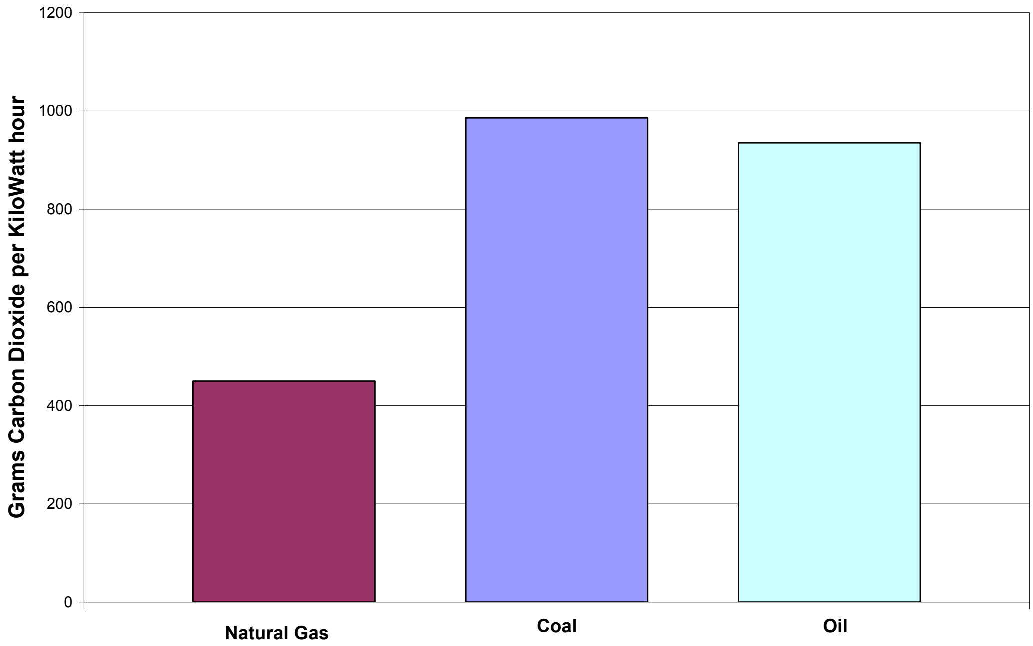

Figure 3. Average emissions dependant on fuel type (UK DECC 2009)

It's clear that targeting reductions in electricity consumption from cooling stands to significantly reduce anthropogenic gas emissions. Electricity reductions can further decrease total US emissions because coal comprises such a large percentage of fuel used to generate the electricity (Figure 2). Coal also has one of the highest emissions to power ratio. Therefore, reducing cooling electricity peaks can assist in the mitigation of climate change effects for future generations especially at coal based power plants.

Urban Surfaces

Percentages of urban surfaces covered by pavement can be identified through Geography Information System (GIS) techniques. In a typical US city paved surfaces make up 30-45% of the total area (Wong 2005). That amount can be further dissected to determine the percentage of the area covered by parking lots through spatial GIS and aerial satellite photograph. Table 1 shows the percentage of four major US cities covered by parking areas. This data was extrapolated from several figures in the EPA's *Reducing Urban Heat Islands: Compendium of Strategies* document (Wong 2005).

Table 1. Parking lot coverage in US cities (Wong 2005)

City	Paved Area *[%]*	Parking Coverage *[%]*
Salt Lake City	36	11.6
Sacramento	45	12.4
Chicago	37	15.2
Houston	29	15.9

Judging from the above table about 10-15 % of most major cities are covered by parking areas. Very few lots are known for their pavement aesthetics. Also, compared to roads lots experience less traffic volume and lower speeds which can loosen design requirements. When designing parking areas, the primary concern is cost. There are an estimated 254.4 million registered passenger vehicles in the US and as the population increases this number will continue to grow (BTS 2007). Parking lots will need to be larger and more numerous which will exacerbate heat island effects. To address these problems new cool pavement materials should be implemented.

To review, new parking lot materials might be beneficial because of the following:

1. Parking comprises growing amount of urban/suburban surface area
2. Parking areas have reduced design requirements compared to roads
3. Parking areas have potential for pollution reduction in:
    - Greenhouse gases – heat island effect
    - Contaminated runoff – runoff with increased temperature and contaminants

Cool Pavement Technologies

Cool pavements are a class of pavement technologies which can be used to mitigate urban heat island effects. They reduce heat being released later in the day and at night by two main principals; increased reflectivity and increased convection. Some cool pavement technologies utilize both principals. By increasing the reflectivity of pavements less of the suns energy can be absorbed leading to less heat being available for later release. Convection is the main heat transfer principal that allows energy to move between a solid and gas (Kreith 1976). Therefore, energy moving from hot pavements to ambient air is controlled by temperature gradients and convection. Allowing more convection to take place at a faster rate will effectively allow pavements to reach equilibrium with cooler ambient air sooner. Additional pavement convection is produced by increasing contact of the pavement with surrounding air. This is accomplished by making pavements permeable. In this scenario more air comes in contact with a greater pavement surface area and in turn cools faster. Cool pavement technologies will now be discussed based on the thermodynamic principal they employ to cool.

Increased Reflectivity

Modified Asphalt Pavements

As asphalt ages it typical becomes more reflective due to the wear of the black bituminous over time. If the asphalt is mixed with lightly colored aggregate it will be able to reflect 15 to 20 % of sunlight compared to the 4% in its newly laid state (Wong 2005). Another modified asphalt option is to add a pigmentation step into the asphalt mix process. This allows for the creation of colored pavements. Some successes have been reported with this process, e.g., a children's park plaza in Seoul, Korea where pavements were modified with ultramarine blue color (Lee *et al.* 1988). The effects of modified asphalt on heat island effect are currently minor and more effective options should be considered especially for parking lots. This will allow for more substantial emission reduction.

Modified Portland Cement Concrete

Without any modifications Portland cement concrete is a moderately reflective surface. Typical mixtures of concrete containing aggregate, grey cement and water can reflect up to 40% of the suns light. However, by using lightly colored aggregate and white cement reflectivity can be increased up to 70% (Wong 2005). The cement industry in the US is another large producer of CO_2 emissions, about 41.1 Tg CO_2 eq in 2008 as seen in Figure 1 (EPA 2010). These emissions originate from the kiln firing in cement production which requires temperatures of almost 3,000°f (PCA 2010).

White cement is very similar to grey cements with a number of different manufacturing steps involved. Unfortunately one of these differences is an increased kiln temperature (LePiver 2010). Increased kiln temperature leads higher fuel consumption and more emissions. By using white cement, emissions that are saved through heat island cooling electricity reductions may be reallocated to the manufacturing process emissions. This could be moving around the CO_2 emissions rather than reducing them. To determine if the emission reductions from white cement outweigh the extra emissions from the manufacturing, more detail about specific mix designs and thermodynamics must be researched.

Chip Seals

Chip seals are created by binding a layer of lightly colored aggregate to the top of asphalt concrete. This technology is typically used to resurface low volume roads. One type of chip seal is micro surfacing. This refers to binding a thin layer of lightly colored aggregates to the surface of asphalt pavements with materials different from concrete cements. Polymers, emulsion, and resins are all considered as means of binding a thin layer of aggregates to raise reflectivity (Wong 2005)

Whitetopping and Ultra Thin Whitetopping

White topping is accomplished by placing a layer of concrete on top of asphalt pavements. This raises the reflectivity of a surface that from about 4% to approximately 40% (Wong 2005). The thickness of this top concrete layers differs by technology name. Whitetopping usually refers to four or more inches of concrete laid upon the asphalt and ultra-thin whitetopping refers to two to four inches (Chango 2009).

Resin Based Pavements

Resin based pavements are a flexible pavement that utilize a tree based resin to bind aggregate in lieu of traditional petroleum based products. The reflectivity of these pavements is directly dependant on the aggregate used because the resin is clear. An initial resin layer is applied to the base course then the mixture of aggregate and resin is placed on top. Next, a final layer of resin is sprayed on to insure cohesion of materials. Resin based pavements can be aesthetically pleasing for walkways, bike paths, and parking lots as seen in Figure 4.

Figure 4. Resin based pavement path (McCormack 2010)

Increased Convection

Porous Asphalt Pavements

Porous asphalt cools through an increased surface area in contact with the ambient air. If properly designed this system allows for contaminant removal and is recharging of the groundwater. Porous asphalt is composed of an openly graded mix of larger aggregates bound together with liquid bituminous material. This layer is laid on a one inch choker course of crushed stone. Below the choker layer is several feet of crushed stone that serves as a reservoir for infiltrating runoff. A minimal slope is provided to allow for infiltration of stormwater. These systems are typically designed with respect to a historically high water table and greater than the 100 year storm event (DCCD 2009). This prevents flooding and contaminants from being smeared through the soil profile during large storm events. Also ample drainage helps protect the pavement from freeze thaw cycles during winter months. It is possible for pores of the asphalt concrete to become clogged with sand, salt, and other debris. Therefore, it is important annual maintenance steps are executed to ensure runoff continues to drain.

Porous Concrete Pavements

Porous concrete cools and works under a very similar system as porous asphalt. The top layer is an open graded aggregate bound with cement paste (Figure 5). Water to cement ratios for porous concrete range from 0.27 to 0.30 (NRMCA 2009). Below the concrete layer there is a layer of crushed stone to serve as a reservoir as rain water waits to drain into the *in situ* vadose zone. There is typically no choker course in this system because the concrete can be laid directly upon the large crushed stone. Flow rates for pervious concrete can reach up to 5 gal/ft^2/min for certain mixes (NRMCA 2009).

Figure 5. Porous concrete
[*Courtesy of Gaia Engineering*]

Solar Energy Harvesting

The concept of harvesting solar energy from asphalt pavement is enticing because it offers a way to collect solar energy by utilizing an existing infrastructure. Thus, there is a need to investigate novel methods for solar energy harvesting and conversion with potential economic efficiency substantially beyond that of current technology.

A practical method to harvest solar energy would be embedding highly conductive water pipes underneath asphalt pavements, and taking advantage of their untapped solar potential. Once heated, this water can be used as-is to heat buildings or can be passed through a thermoelectric generator to produce electricity. Since the temperature would be already about 60^{o}C (140^{o}F), it may require a little electricity to produce vapor initially. However, if the vapor makes turbines spin to generate electricity, it will become self-sufficient system (Lee *et al.* 2010).

Increased Reflectivity and Convection

Grass Paving

Grass paving is a unique technique that can help to mitigate urban heat island. A specialized grid of plastic material is placed upon engineered fill. The spaces in between the grid are filled with grass seed. The system is highly reflective and also allows for increased convection due to permeability. Some systems claim compressive strengths of up to 40 MPa, 5731 psi (ISI 2010).

Figure 6. Grass Pave reinforcement grid (Invisible Structures Inc. 2010)

The drawbacks of these pavements are increased costs and problems with winter maintenance across the board. Many of these technologies do not take well to the plowing of snow and application of de-icing salts. Deicing salts can clog permeable lots and plows can destroy the top layer of pavements.

Summary

EPA published a compendium of strategies on reducing urban heat islands. It has been modified through this study as shown in Table 2 containing important information regarding important characteristics such as degree of heat island reduction impact, relative cost, relative durability etc.

Table 2. Pavement Technologies Summary Modified from EPA's
Reducing Urban Heat Islands: Compendium of Strategies

Technology	Heat Island Contribution	Approximate Cost *[$/square foot]*	Life *[Years]*	Co-Benefits	Weaknesses
Conventional Asphalt	High	$0.10 - $1.50	7–20	Cost	Heat Island Effect
Conventional Concrete	Medium	$0.30 - $4.50	15–35	Cost	--
Modified Asphalt Pavements	Medium	$0.10 - $1.50	7–20	--	--
Modified Portland Cement Concrete	Medium	$0.30 - $4.50	15–36	Cost	White Cement Emission
Chip Seals	Low	$0.10 - $0.15	2–8	Resurfacing Ability	Service Life
Ultra Thin Whitetopping	Low	$1.50 - $6.50	10–15	Resurfacing Ability	Debris Covering Reflectivity
Resin Based Pavements	Low	$2.50 - $3.50	6–10	Improved Asthetics	Solvents Used
Porous Asphalt	Medium	$2.00 - $2.50	7–10	Stormwater Control	Cost
Porous Concrete	Low	$5.00 - $6.25	15–20	Stormwater Control	Cost
Grass Paving	Low	$1.50 - $5.75	>10	Stormwater Control	Winter Conditions

Conclusion and Recommendations

Vast areas of dark pavements in urban areas are one contributing factor to increased ambient temperatures from the heat island effect. This is especially significant during summer months at times when solar radiation is less important such as the late afternoon and night. The increased ambient temperatures create a larger demand for cooling and electricity from municipal power plants. The generation of more electricity from these plants produces more greenhouse gases. Therefore, addressing urban heat island effects has the potential to reduce greenhouse gas emissions.

Scanning urban areas shows parking lots comprise about 10-15% of the total surface area in many US cities. Also, design requirements for parking lots are not a stringent because they experience less traffic volume at lower speeds. Targeting parking lots with cool pavement technologies can be used as a transitive means of reducing greenhouse gas emissions. As the effective service lives of parking lots expire cool pavement options should be implemented.

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Durability of Sustainable Concrete Mixtures

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Abstract
Use of fly ash in concrete reduces the use of natural raw materials, offers benefits of landfill and CO_2 emissions avoidance and therefore contributes to industrial sustainability. This paper presents the results of investigations to determine the various durability aspects of high volume fly ash concrete mixtures, made with ASTM Type I cement and Class C fly ash, yielding a similar 28-day compressive strength to that of Colorado Department of Transportation (CDOT) Class D structural concrete. The durability aspects investigated included the resistance to the chloride-ion penetration (ASTM C 1202), the resistance to the repeated cycles of freezing and thawing (ASTM C 666 Procedure A), and the resistance to the sulfate attack (Mortar bars, ASTM C 1012). It is concluded that the high volume fly ash concrete mixtures are able to exhibit excellent durability characteristics with increased curing time. A concrete mixture with a cementitious material content lower than the CDOT specification and a fly ash content greater than the current CDOT limit, was able to meet Class D structural concrete requirements.

Introduction
Concrete is the dominant material used in construction, both in terms of gross mass of material used as well as the energy consumed and the pollution released from cement manufacture. Fly ash is a by-product of heat generation from thermal coal-fired power plants, which can replace portland cement on a one-to-one mass basis (Reiner, 2007). Fly ash concrete can provide equal or superior performance up to certain replacement limits. Use of fly ash in cement and concrete reduces the use of natural raw materials and therefore contributes to industrial sustainability. Blended cements and concrete containing large proportions of fly ash offer the benefit of CO_2

emissions avoidance (Liu et al, 2009). Fly ash used as an additive to cement and concrete is the greatest utilization of the coal by-product in the United States. Annually, about 60% of all re-utilized fly ash was used for this purpose (Liu et al, 2008). However, fly ash use in concrete is practiced and accepted at low replacement levels. The majority of engineers, architects, and contractors are not comfortable with specifying higher percent replacement of portland cement with fly ash, e.g. 20% or greater, without incentive or mandate (Reiner, 2007). One of the barriers is the impact of high volume fly ash on the durability of the concrete.

This paper studies the various durability aspects of fly ash concrete mixtures, made with ASTM Type I cement and Class C fly ash, yielding a similar 28-day compressive strength to that of Colorado Department of Transportation (CDOT) Class D structural concrete. Class D concrete is a widely used dense medium strength structural concrete (CDOT, 2008). Required field compressive strength is 31 MPa (4500 psi) at 28 days; the cementitious content ranges between 365 to 392kg/m^3(615 to 660 lbs/cy); air content ranges between 5-8% and the maximum water/cementitious material ratio is 0.44. The durability aspects investigated included the resistance to the chloride-ion penetration at 28 days, 56 days and 90 days of curing (ASTM C 1202), the resistance to the repeated cycles of freezing and thawing after 28 days of curing (ASTM C 666 Procedure A), and the resistance to the sulfate attack (Mortar bars, ASTM C 1012).

Materials

An ASTM Type I portland cement was used for this study. The specific gravity of this cement was 3.15; the fineness (Blaine) was 398m^2/kg, and the setting time (Vicat), initial 134 min.

The chemical analysis of the Class C fly ash used in this study is shown in Table 1.

Table 1 Chemical Analysis of Class C Fly Ash Sample

CHEMICAL TESTS	Fly Ash	ASTM C 618 CLASS F/C
Silicon Dioxide (SiO_2), %	33.14	
Aluminum Oxide (Al_2O_3), %	15.65	
Iron Oxide (Fe_2O_3), %	7.14	
Sum of SiO_2, Al_2O_3, Fe_2O_3, %	55.93	70.0/50.0 min.
Calcium Oxide (CaO), %	28.6	
Magnesium Oxide (MgO), %	6.81	
Sulfur Trioxide (SO_3), %	2.47	5.0 max.
Sodium Oxide (Na_2O), %	1.95	
Potassium Oxide (K_2O), %	0.32	
Loss on ignition, %	0.89	6.0 max

Coarse and fine aggregate were obtained from a representative source within Colorado. The coarse aggregate met ASTM C33 Size Number 57 and 67 gradation requirements. The graded coarse aggregate had a maximum aggregate size (MAS) of

25.4mm (1.0in.) and a nominal maximum aggregate size (NMAS) of 19mm (0.75 in.). The fine aggregate met ASTM C33 gradation requirement for concrete fine aggregate.

A commercially available sulfonated, naphthalene formaldehyde condensate high range water reduce agency (HRWRA) was used. The product manufacturer recommends addition rates from 390-1300 mL/ 100kg (6 to 20 fl oz/cwt) of cementitious material.

The air entraining admixture used in all the fly ash concrete mixtures contains a blend of high-grade saponified rosin and organic acid salts. Addition rates range from 15 to 200 mL/100kg (3/4 to 3 fl oz/cwt) of cementitious material.

Mixture Proportions

Nine concrete mixtures and seven mortar mixtures were tested in this study. Concrete mixtures included one control mixture with a cementitious material (CM) content of 377 kg/m^3 (635 lb/cy) and 15% fly ash. Two concrete mixtures were made with a CM content of 338 kg/m^3 (570 lb/cy) and a fly ash content 30% and 50%, two concrete mixtures with a CM content of 392 kg/m^3 (660 lb/cy) and a fly ash content 30% and 50%, three similar mixtures with a CM content of 365 kg/m^3 (615 lb/cy) and a fly ash content of 40% to verify the repeatability of the results, and one mixture with a CM content of 418 kg/m^3 (705 lb/cy) and a fly ash content of 60%. Mortar mixtures were made per the ASTM C 1012 mixture proportion with fly ash contents of 0%, 15%, 30%, 40%, 50% and 60% of the cementitious materials content respectively. The proportions of the concrete mixtures are summarized in Table 2.

Table 2 Mixture Proportions

Mixture Identificatior		W/(C+FA)	Water	Cement	Fly Ash	Coarse Aggregate	Fine Aggregate	AEA
			kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	mL/100kg
0	15Ash_635	0.4	151	320	57	1032	711	98
1	40Ash_615A	0.4	146	219	146	1032	720	98
2	30Ash_660	0.4	157	274	117	1032	674	98
3	40Ash_615B	0.4	146	219	146	1032	720	98
4	30Ash_570	0.4	135	237	101	1032	777	98
5	40Ash_615C	0.4	146	219	146	1032	720	98
6	50Ash_660	0.4	157	196	196	1032	662	98
7	50Ash_570	0.4	135	169	169	1032	767	98
8	60Ash_705	0.4	167	167	251	1032	603	98

Test Methods

The batching followed ASTM C 192 “Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory.” Both fresh and hardened concrete properties were examined for each mixture batched. The fresh and hardened concrete tests in this study are shown in Table 3. DK-4000 Dynamic Resonance Frequency Tester and E-METER Resonant Frequency Tester were used to measure the resonant frequency of concrete prisms. Both of the two equipment comply with ASTM C 215.

Table 3 Test Methods

Fresh Concrete Tests	Standard	Time of Test
Slump	ASTM C 143	At Batching
Unit Weight	ASTM C 138	At Batching
Air Content	ASTM C 231	At Batching
Hardened Concrete Tests	**Standard**	**Time of Test**
Compressive Strength	ASTM C 39	1,3,7,28,56,90 days
Freeze-thaw Resistance	ASTM C 666	28 and Subsequent days
Rapid Chloride Ion Penetrability	ASTM C 1202	28, 56, 90days
Sulfate Attack Resistance	ASTM C1012	7 days and Subsequent days

Test Results and Discussion

Fresh Concrete Properties

Fresh concrete properties for the nine mixtures are given in Table 4. The AEA and HRWRA were used to obtain 5-8% air content and a 102 ± 25 mm(4 ± 1 in) slump.

Table 4 Fresh Concrete Properties

Mixture Identification		Slump		Unit Weight		Air Content	HRWR	
		cm	in.	kg/m3	lb/cf	%	L/100kg	fl oz/cwt
0	15Ash_635	10.2	4	2291	143	7	1.25	19.2
1	40Ash_615A	9.5	3.75	2265	141.4	8	0.47	7.2
2	30Ash_660	10.2	4	2239	139.8	9	0.44	6.7
3	40Ash_615B	9.5	3.75	2262	141.2	9	0.47	7.2
4	30Ash_570	8.3	3.25	2278	142.2	8	1.14	17.5
5	40Ash_615C	7.6	3	2275	142	7.4	0.47	7.2
6	50Ash_660	9.5	3.75	2214	138.2	9	0	0
7	50Ash_570	7.6	3	2294	143.2	7	0.51	7.8
8	60Ash_705	19.1	7.5	2220	138.6	8	0	0

The slump for mixtures 0-8 ranged from 7.6 – 10.2cm (3 – 4in). Mixture 9 experienced a slump of 19.1cm (7.5in). This is due to the increased cementitious content and fly ash percentage.

Three mixtures' air contents exceeded 8%. Reduction of the air content is expected with lower dosage of AEA. 40Ash_615A, B, and C had similar fresh concrete properties with the same amounts of HRWRA and AEA.

Compressive Strength

The compressive strength values at 1, 3, 7, 28, 56, and 90 days of age are shown in Table 5 and Figure 1. CDOT Class D structural concrete requires 31MPa (4500 psi) compressive strength at 28 days of age. The 60Ash_705 failed in this requirement. The strengths of Mixture 1,2 and 6 at 28 days were lower than 31 MPa (4500 psi), but were similar to this criteria. Based on the 28-day strength requirements, the substitution levels of cement by this Class C fly ash should be limited to 50%.

Table 5 Compressive Strength

Mixture Identification		1-day	3-day	7-day	28-day	56-day	90-day
		MPa	MPa	MPa	MPa	MPa	MPa
0	15Ash_635	24	32.3	36.7	43.1	42.3	48.2
1	40Ash_615A	12.6	20.5	24.6	30.4	34	35.9
2	30Ash_660	12.9	21.1	23.9	30.9	33.4	35.4
3	40Ash_615B	10.4	21.7	26.2	32.7	34.1	35.8
4	30Ash_570	16.4	29.8	35.1	41.4	45	47.7
5	40Ash_615C	13	24.4	28	35.4	39.8	40.2
6	50Ash_660	5.4	18	21	29.6	31	34.5
7	50Ash_570	6.3	20.3	24.5	32	35.5	39.2
8	60Ash_705	2.5	14.3	18.6	24.9	29.4	32.4

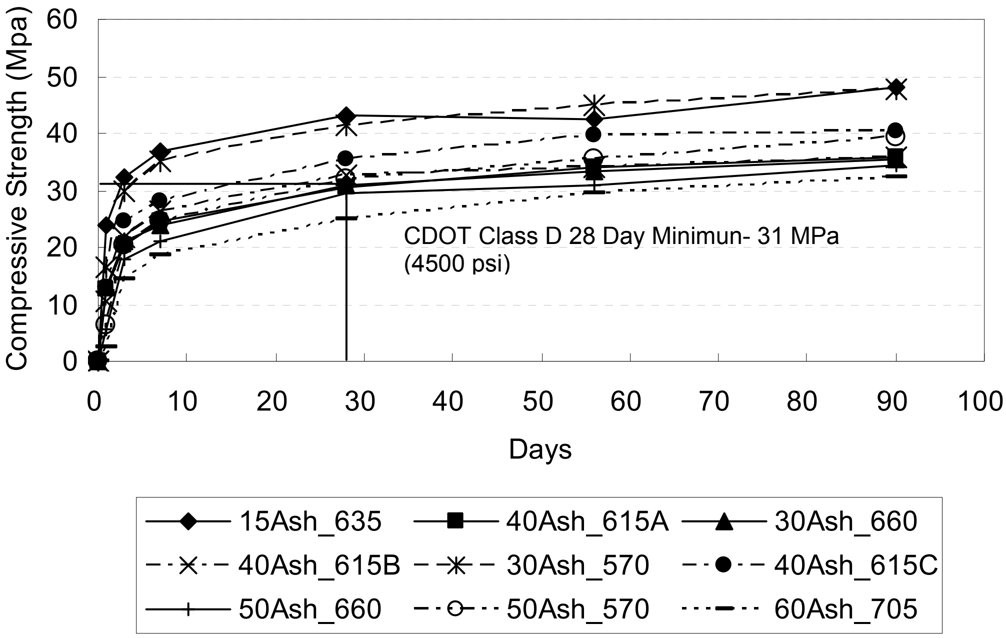

Figure 1 Compressive Strength Versus Time

<u>Resistance to Chloride-Ion Penetration</u>

The fly ash concrete mixtures exhibited excellent resistance to chloride ion penetration at later ages, shown in Table 6 and illustrated in Figure 2. The total charge passed for the fly ash concrete mixtures ranges from 999 to 1611 coulombs at 90 days of age. The total charge passed ranges from 1578 to 4222 coulombs at 28 days of age. The improvement in the resistance to chloride-ion penetration as the testing age increases is due to the reduction in the porosity of the concretes as a result of the continued cement hydration and pozzolanic reaction of the fly ash.

Table 6 Rapid Chloride Ion Penetrability

Mix Identification		28-day (Coulombs)	56-day (Coulombs)	90-day (Coulombs)
0	15Ash_635	1650 (low)	1330 (low)	1104 (low)
1	40Ash_615A	2481(Moderate)	1616 (low)	1080 (low)
2	30Ash_660	2372(Moderate)	1713 (low)	1274 (low)
3	40Ash_615B	2189(Moderate)	1677 (low)	1248 (low)
4	30Ash_570	1578 (low)	1395 (low)	1089 (low)
5	40Ash_615C	2684(Moderate)	1394 (low)	1098 (low)
6	50Ash_660	3435(Moderate)	2108(Moderate)	1295 (low)
7	50Ash_570	2777(Moderate)	1481 (low)	999 (very low)
8	60Ash_705	4222 (High)	2326(Moderate)	1611 (low)

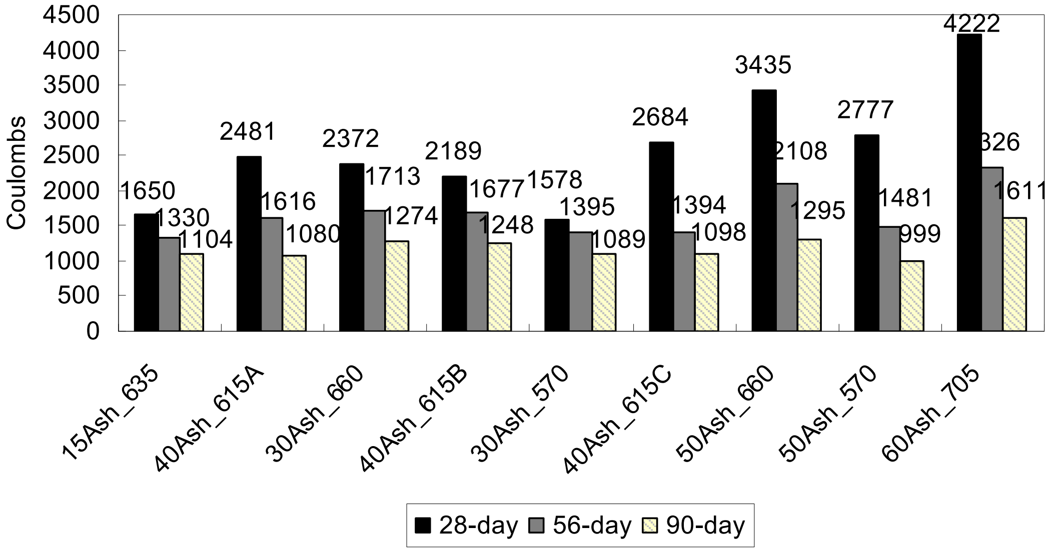

Figure 2 Rapid Chloride Ion Penetrability Tests Results

The three mixtures 40Ash_615A, B and C used for repeatability exhibited similar resistance to chloride ion penetration at different ages. The total charges passed for the three mixtures range from 2189 to 2684 Coulombs, 1394 to 1677 Coulombs, and 1080 to 1248 Coulombs at 28, 56 and 90 days of age, respectively. According to the ASTM C 1202, the chloride ion penetrability of the three mixtures is moderate at 28 days, low at 56 days and low at 90 days. The test results show the repeatability of the resistance to chloride-ion penetration test.

The total charge passed for the concrete mixtures with the same cementitious content increases as the fly ash content increases, comparing the two mixtures 30Ash_660 and 50Ash_660 or the two mixtures 30Ash_570 and 50Ash_660 at 28 days and 56 days. This is due to the fact that higher percentage of fly ash increases the porosity of the hardened cement paste. However, at 90 days, the charge passed for the mixture

30Ash_660 is close to that of 50Ash_660, which are 1274 and 1295 Coulombs respectively. The charge passed for mixture 30Ash_570 is slightly higher than that of 50Ash_570, 1089 and 999 Coulombs respectively. This is a result of the reduction of the hardened cement paste's porosity resulting from the continued cement hydration and pozzolanic reaction of the fly ash.

The total charge passed for the concrete mixtures with the same fly ash content decreased as the cementitious content decreased, comparing the two mixtures 30Ash_660 and 30Ash_570 or the two mixtures 50Ash_660 and 50Ash_570 at different ages. The total charge passed for the mixture 60Ash_705 is the highest at each testing age due to its high fly ash content. This is explained by the "fill-out" effect of the fly ash. In all the mixtures, the coarse aggregate contents and the w/cm were kept constant. The increase in cementitious material content decreased the fine aggregate content. A portion of the fly ash in the higher cement replacement levels, acts as a filler material in the concrete mixture.

Resistance to Freeze/Thaw Cycling
The fly ash concrete mixtures performed excellent during the freeze/thaw testing. Each of the concrete specimens reached 300 freezing and thawing cycles, with durability factors equal to or greater than 91. The test results are shown in Table 7 and Figure 3.

Table 7 Durability Factors

Mix Identification		Resonant frequency				Durability Factor	
		DK-4000(HZ)		E-METER(HZ)			
		Initial	Final	Initial	Final	DK-4000	E-METER
1	15Ash_635	2100	2070	2050	2063	97	101
2	40Ash_615A	2002	1963	1941	1957	96	102
3	30Ash_660	1963	1963	1880	1958	100	108
4	40Ash_615B	2031	2012	1932	1931	98	100
5	30Ash_570	2119	2090	2032	2068	97	104
6	40Ash_615C	2051	2031	2063	2014	98	95
7	50Ash_660	1934	1934	1939	1930	100	99
8	50Ash_570	2061	2021	2023	1979	96	96
9	60Ash_705	1904	1826	1946	1860	92	91

The excellent resistance to freezing and thawing cycles was due to the 7%-9% air contents in the concrete mixtures. However, by comparing the durability factors of 30Ash_660 and 50Ash_660, as the fly ash content increased, the durability factor decreased. The same conclusion is found by comparing the two mixtures 30Ash_570 and 50Ash_570. The mixture 60Ash_705 had the highest cementitious material and fly ash contents, but lowest durability factor. The prisms were placed in the freeze-thaw chamber after 28 days of curing. The improvement of the resistance to freeze/thaw cycling of the fly ash concrete mixtures is expected if the curing age is extended. However it might not be obvious due to the "fill-out" effect of the fly ash in the concrete mixtures as discussed in the previous sections.

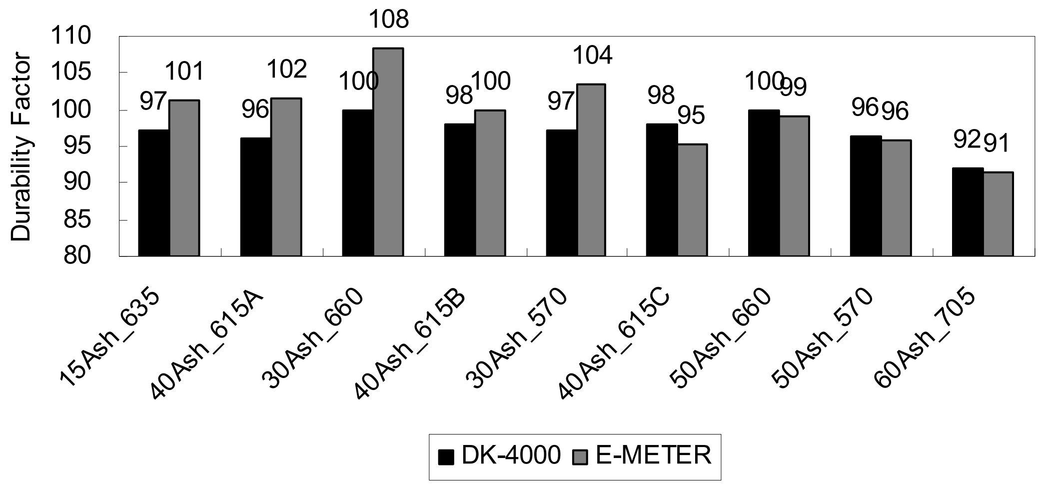

Figure 3 Durability Factors

<u>Resistance to Sulfate Attack</u>

Four levels of sulfate exposure are presented in the ACI 318-08 Table 4.2.1 based on the concentration of water soluble sulfate in the soil by weight or in water (ppm) anticipated to be in contact with the concrete. For the ASTM C 1012 testing, a S3 exposure (very severe) was used to evaluate the sulfate resistance of the fly ash mortar mixtures compared to the control mixtures. For this test, the samples used Type I cement in order to better evaluate the effect of the presence of the fly ash.

The data in Table 8 shows expansions of different mortar mixtures due to sodium sulfate from 7 days to 6 months. Two control mixtures were created (0Ash_0 and 0Ash_1.5). The mixture 0Ash_0 was made with 100% portland cement without AEA addition. The water/cement ratio was 0.485. In addition, the 0Ash_1.5 mortar mixture consisted of 100% portland cement and a 98 mL/100kg (1.5 fl oz/cwt) AEA dosage with 0.46 water/cement ratio. Other mixtures were made with fly ash contents of 15%, 30%, 40%, 50% and 60% of the cementitious materials content respectively and 98 mL/100kg(1.5 fl oz/cwt) AEA. The water/cementitious material ratios were 0.46. The length change trend lines are shown in Figure 4.

Table 8 Length Changes (Expansion %) of Mortar Bars

Mix Identification	1 week	2 week	3 week	4 week	8 week	13 week	15 week	4 month	6 month
0Ash_0	-0.0013	0.0017	0.0068	0.0056	0.019	0.0234	0.0308	0.032	0.0448
0Ash_1.5	-0.0007	-0.003	0.0056	0.0077	0.0113	0.0144	0.0234	0.0227	0.0351
15Ash_1.5	0.0024	0.0001	0.0063	0.0091	0.0114	0.0211	0.0204	0.0246	0.0319
30Ash_1.5	0.0028	0.003	0.0109	0.0141	0.023	0.0334	0.0295	0.035	
40Ash_1.5	-0.0003	0.0094	0.0097	0.0137	0.0242	0.0386	0.0406	0.0426	
50Ash_1.5	0.0058	0.013	0.0132	0.0173	0.033	0.0434	0.05	0.0533	
60Ash_1.5	0.0004	-0.0211	0.0073	0.0129	0.0377	0.0417	0.0455		

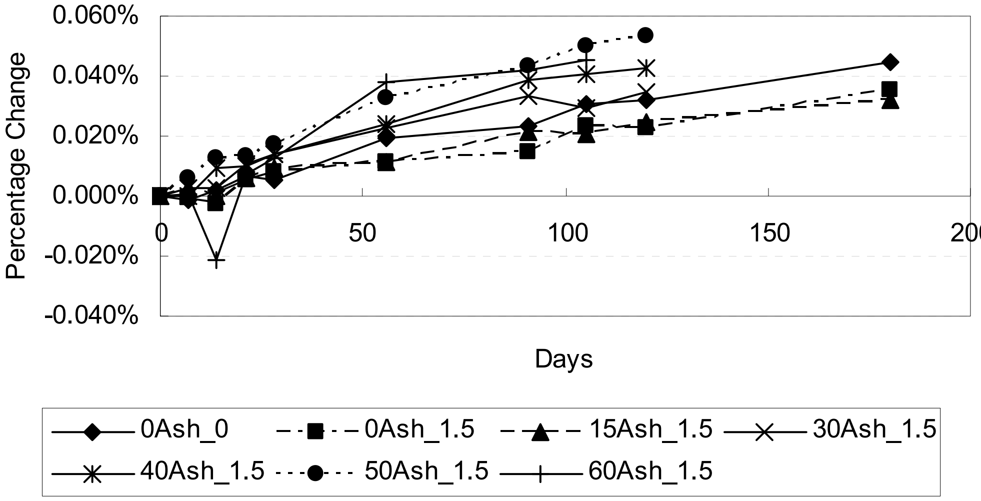

Figure 4 Length Change Percentage of Mortar Bars

The data in the Table 8 and Figure 4 indicate that as the fly ash content increased, the mortar mixtures experienced increased length changes due to the sulfate attack. The CaO content in this Class C fly ash was 28.6%. Therefore gypsum corrosion governed the sulfate attack, which can be described by the reaction between sulfate ions and calcium hydroxide: $CH + SO_4^{2-}(aq) \rightarrow C\bar{S}H_2 + 2OH^{-}(aq)$. This reaction can cause an expansion in solid volume of approximately 120%. However, the length change of the mixture 60Ash_1.5 was less than 50Ash_1.5 at all ages. The compressive strength of this mixture increased slowly. The ASTM C 1012 requires the mortar bars be placed into the sulfate solution when the strength of the 50cm × 50cm × 50cm (2 in. × 2 in. × 2 in.) mortar cubes reach 20MPa (2800 psi). The strength did not reach 20 MPa (2800 psi) until they were placed in the standard curing tank for 7 days. During these days, a portion of the calcium hydroxide produced from the cement hydration and lime reaction might be reduced, which is responsible for the less length change of the mixture 60Ash_1.5. Due to its low early strength, the substitution level of the cement for the Class C fly ash should be limited to 50%.

The test also indicates that the use of Class C fly ash did not improve the sulfate resistance of concrete, but the data collected for the fly ash mixtures are close to the control mixtures. Generally, the Class C fly ash is not used in very severe sulfate exposure environment. If these fly ashes are to be used in these environments, the amount shall be determined by sulfate resistance tests when mixed with Type V cement. Class C fly ash was used in this study as part of an ongoing research study at the University of Colorado Denver.

Conclusion

The test results show that the three mixtures 40Ash 615A, B and C had similar fresh and hardened concrete properties, which proved the repeatability of the experimental testing.

The substitution level of the cement with Class C fly ash should be limited to 50% according to the CDOT Class D structural concrete 28 day compressive strength requirements. The optimized concrete mixture with the highest possible fly ash content was selected and reported in Liu (2010)'s dissertation.

All fly ash concrete mixtures demonstrated excellent resistance to chloride-ion penetration with values of less than 1611 Coulombs after 90 days of moist-curing. The data showed the replacement of cement with fly ash increased the porosity of the hardened cement paste. The "fill-out" effect of the Class C fly ash was observed in when testing the concrete mixtures for permeability. Therefore, the fly ash can be designed to replace fine aggregate to increase the beneficial use of this by-product in concrete. The durability factors of the fly ash concrete prisms after 300 cycles of freezing and thawing in ASTM C 666 were excellent. The improvement of the resistance to freeze/thaw cycling of the fly ash concrete mixtures is expected if the curing age is extended.

The sulfate attack tests indicated that the Class C fly ash did not improve the sulfate resistance of the mortar mixtures when compared to the control mixtures. However, the Class C fly ash is not used in very severe sulfate exposure environment.

The concrete mixture 50Ash_570 yields a 28 day strength higher and a better durability (resistance to chloride ion penetration and freeze/thaw cycling) than that required by the CDOT Class D structural concrete. This concrete mixture was made with 338 kg/m^3 (570 lbs/cy) cementitious material, which is lower than the current CDOT specification, and 50% cement replacement percentage with fly ash, which is greater than the current CDOT limits (20% Class C).

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Carbon Nano Fiber Reinforced Cement Composite for Energy Harvesting Road

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ABSTRACT

Energy harvesting (also known as power harvesting or energy scavenging) technology allows capturing unused ambient energy such as solar, wind, thermal, strain and kinetic, energy of gas and liquid flows and converting the energy into another form of usable energy. One form of ambient energy available from pavements is thermal energy derived from natural heating of pavements. The goal of this study was to determine if there is a possibility of capturing thermal energy from pavements and storing the energy and using it as alternative power source to other devices. In this paper, a smart material based on regular available Portland cement has been developed which can capture ambient thermal energy available from pavements. The cement composite material acts as a pyroelectric material. The characteristic of pyroelectric material is that a change in temperature creates current flows in the material. Specimens of Portland cement with and without carbon nanofibers have been prepared in the laboratory and tested for various properties, such as, pyroelectric coefficient and dielectric constant. It has been found that plain Portland cement acts as pyroelectric material. Addition of carbon nanofibers increases the pyroelectric behavior of cement. Both dielectric constant and pyroelectric coefficient increase with increase in temperature. The present research indicates that simple material such as Portland cement can be used to capture heat energy from pavements, which can be stored in capacitor for the use of power source to other sensor electronics.

Key words: Cement-Carbon nano-composites, Electrical properties, Pyroelectric coefficient, Pavement Energy Harvesting

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1.0 INTRODUCTION

Energy harvesting (also known as power harvesting or energy scavenging) technology allows capturing unused ambient energy such as vibration, strain, light, temperature gradients, and/or changes, energy of gas and liquid flows and converting into usable electrical energy which is stored for performing sensing and actuation and other applications. Energy harvesting is a perfect match for wireless devices and wireless networks which otherwise depend on battery power and other maintenance-free systems. Thus, providing cost-effective and environment friendlier solutions for various applications.

With the high price of fossil fuels, there is a renewed emphasis on energy conservation and development of alternative energy resources and systems. As a result, there is emphasis on low cost energy conversion materials. Due to recent advances in low-power portable electronics and the fact that batteries in general provide a finite amount of power, attention has been given to explore methods for energy harvesting and scavenging. Energy can be recovered from mechanical vibration (Sodano et al2004), light, and spatial and temporal temperature variations (Roundy et al 2003, Paradiso and Stamer 2005).

Thermal energy in the environment is a potential source of energy for low-power electronics. The pyroelectric effect converts a temperature change into electrical current or voltage. In pyroelectric materials, the thermal energy is converted to electrical energy. Electric dipoles are present in the materials due to the presence of ionic bonding. Pyroelectric materials are mainly used as sensors. One popular application of pyroelectric sensors is in the regular household motion sensors, where slight change in temperature from infrared radiation from human bodies can produce electrical charges which can trigger alarm. In particular, charge is produced when the material's temperature is altered as a function of time.

Several factors must be considered to optimize the performance of such materials for a given application such as material's geometry, boundary conditions, and even the circuitry used to harvest power must be carefully considered (Sebald et al 2008). Recent work was presented on using Lead Zirconate Titanate (PZT), PMN-PT, Polyvinylidene Fluoride (PVDF) and other pyroelectric materials for energy harvesting and storage (Bauer 2006).

Recently, focus has been put on pyroelectric materials as energy harvester (Buchanan and Huang 1999). If such electric energy can be trapped, it can be used for potential energy harvesting purposes. There have been several studies performed in this emerging field recently. In a recent paper Cuadrasa et al (2010) have showed the potential of using pyroelectric materials as energy harvester. The authors tested several PZT and PVDF as potential pyroelectic material under various temperature conditions. The research results indicate that both PZT and PVDF can be used as pyroelectic material.

Novel applications require diverse and specific properties in materials which cannot be met in single-phase materials. The composites contain two or more chemically different materials or phases. In these materials, it is possible to tailor electrical, piezoelectric, pyroelectric, optical, and mechanical properties catering a variety of applications in civil engineering. The composites show properties derived from individual components. Recent studies on new cement based composites show potential usefulness in structural health monitoring and other applications. Several researches have shown the potential of using nano-composites. Han et al (2009) have fabricated nickel powder-filled cement-based composite piezoresistive sensors. The gauge factor of piezoresistive sensors is higher than 895.45 and goes up to 1929.5 maximum with the compressive strain in the range from 0 to 125689 με. Chaipnaich (2007) investigated the PZT particle size on dielectric and piezoelectric properties of PZT-cement composites. The author proposed that the enhancement in dielectric and piezoelectric properties was due to the lesser contacting surfaces between the cement matrix and the PZT particles. Wen and Chung (2000) presented damage monitoring of cement paste by electrical resistance measurement. Gong et al (2009) exploited piezoelectric and dielectric behavior of 0-3 cement–based composites mixed with carbon black for civil engineering applications. The authors showed that piezoelectric sensitivities of the composites can be enhanced dramatically with incorporation of small amount of carbon black.

Wen and Chung (2003) investigated the pyroelectric behavior of cement-based materials. They showed that the steel/carbon-nanofibers increase the dielectric properties of cement composites. However, there are limited studies on the pyroelectric and dielectric properties of cement-based nano-composites for infrared sensing and energy harvesting and other civil engineering applications. Therefore further electrical and pyroelectric investigations in cement-based composites, including nano-composites, are warranted for the purpose of fundamental understanding of their behavior.

Specially, use of pyroelectric materials in energy harvesting from pavements is missing in current literature. If the pavement temperature can be converted into electrical current, it would be ideal choice for using alternative sustained power source to wireless sensors and other devices which require low but sustain power. This would ensure sustained and uninterrupted power supply to pavement management system hardware and will contribute to the energy conservation. In this paper, the pyroelectric properties of cement composites with carbon nano-fibers and Polyvinyl Alcohol (PVA) consisting of ordinary Portland cement as matrix are reported. The influence of carbon nano-fibers on the dielectric and pyroelectric properties of the composite has been examined for admixtures prepared under identical temperature and humidity conditions. The possibility of harvesting electrical energy from pavement temperature variation is also discussed.

2.0 MATERIAL AND TEST METHOD

To prepare the composite specimens, the plain Portland cement, PVA and carbon nanofibers were mixed thoroughly. The PVA acts as a binder within the cement. No aggregate was added. The carbon nanofibers (PR-19-XT-LHT) with following characteristic were obtained from Pyrograph Products, Inc Cedarville, OH 45314:

Fiber diameter, nm (average):	150
CVD carbon overcoat present on fiber:	no
Surface area, m^2/gm:	20-30
Dispersive surface energy, mJ/m^2:	120-140
Moisture, wt%:	<5
Iron, ppm:	<14,000

The weighted mixture was mixed in water to make a paste of suitable viscosity. The paste was compressed in a steel mound to form discs of diameter 10 mm and thickness 2.0 mm approximately. The discs were then cured at 25°C under 100% humidity for 24 hours to speed up the hydration process of cement matrix. After drying the samples, silver electrodes were coated on both sides of the discs to form full-face electrodes. Finally, to make the samples functional, the electroded samples were poled at 50^0C with 75 kV/cm electric field for 1 hour and then cooled to room temperature with applied field. After the poling process the samples were short-circuited to remove any extrinsic charges on the sample. The detailed descriptions of samples' composition are given in Table 1. There is a limitation of adding carbon nanofibers; too much nanofibers can make the material highly conducting and thus invalidate the electrical measurements. Two electrical parameters were calculated which were relevant to the materials potential application of charge storage capacity: the real (ε') and imaginary (ε'') parts of dielectric constant and dielectric loss ($\tan \delta$) and they are defined as:

$$\varepsilon' = \frac{C_p d}{\varepsilon_0 A} \qquad \varepsilon'' = \varepsilon' \tan\delta \tag{1}$$

where A is the electrode area (identical areas for the opposite electrodes were used in each sample), d is the thickness of the sample, $\omega=2\pi f$ is the frequency of ac measurement, $\varepsilon_0 = 8.854\text{x}10^{-12}$ F/m is the permittivity of vacuum. A series of ac frequency was selected from very low (10 Hz) to as high as 1 MHz to obtain a wider spectrum. To measure the dynamic relative pyroelectric current, direct method of Byer and Roundy (1972) was used. The detailed measurement procedures of these parameters are described in earlier publication (Batra et al 2009). The pyroelectric current I_p was also measured at various temperatures and the pyroelectric coefficients (p) were calculated using the relationship:

$$p = \left(\frac{I_p}{A}\right) / \left(\frac{dT}{dt}\right) \tag{2}$$

where A is the electrode area and dT/dt is the rate of change of temperature which was kept constant throughout the measurement. The change in pyroelectric coefficient will indicate the change in dipole orientation inside the material; higher the coefficient, better the material is for converting temperature change in electrical charge. The additional charge generated via heating or cooling within a temperature change dT can be calculated as:

$$dQ = dI_P dt = pA\frac{dT}{dt}dt = pAdT \tag{3}$$

where, the pyroeletric coefficient p could be constant or as a function of temperature.

3.0 ELECTRICAL MEASUREMENT RESULTS

Figure 1 and Figure 2 show the frequency dependence of dielectric constant (ε') and loss (ε") respectively for cement composites reinforces with carbon fiber. All of the composites show a decrease sharply in dielectric constants (ε' and ε") with increasing frequency increasing in the range from 100 Hz to 10 kHz. This is mainly attributed to interfacial polarization of the composites and polarization in cement matrix. When frequency is larger than 10 kHz, the composites exhibit relatively good frequency stability. However, the behavior of the parameters studied can be better explained by knowing the porosity and the moisture content of the composites below percolation. However, the pyroelectric behavior of the cement composite is very similar to the ones observed in other materials (Batra et al 2009, Wen and Chung 2003).

Figure 3 and Figure 4 show the typical characteristics of temperature dependence of dielectric constants (ε') and pyroelectric coefficient of cement composites respectively. As the figures indicate, these parameters increase with increase in temperature. The observed increase in dielectric constant can be attributed to the increase in mobility of ions as the temperature increases. The influence of carbon fiber content on the dielectric constant and pyroelectric coefficient at 1 kHz frequency and $40^{o}C$ are plotted in Figure 5 and Figure 6 respectively. It can be seen that the dielectric constant values increase with the increase in nano carbonfiber content. The enhancement of ε" with carbon content is related to increase in the AC conductivity of the composite as depicted in Figure 7, which involves electrons and ions.

4.0 ENERGY STORAGE VIA PYROELECTRIC EFFECT

The conversion of thermal energy into electrical energy is essential in pyroelectric sensors. A large amount of heat absorbed by the pavement is radiated to the atmosphere. It was the goal of this initial study to demonstrate the feasibility of capturing the thermal energy from pavement via pyroelectric effect. The idea explored in this section has been proposed by Cuadras et al (2010) for pyroelectric energy harvesting. To achieve this, the pyroelectric sensor is modeled as a capacitor and resistor in parallel with a current source (Figure 8). The current is generated within the cell with the change in temperature. Eq. 1 indicates that the pyroelectric current is directly proportional to the rate of change of temperature. However, one problem with this behavior is that the current will flow in opposite direction when the rate changes from positive to negative or from negative to positive. In other words, a heating followed by cooling or cooling followed by heating will produce charge accumulation in different direction. However, to charge an external capacitor it is essential that the capacitor be charged continuously.

To mitigate the problem, a full bridge diode rectifier circuit, as shown in Figure 9, can be used. There are two pairs of diodes; one pair is used for each direction of currebt flow. Diodes D_1-D_2 are used when current is flowing in one direction and D_3-D_4 are used when the current flows in other direction. At each time only the forward biased diodes work, the other two pairs blocks current flow under reverse biased condition. As it can be seen, in both cases, the external capacitor is charged via charge flow in one direction and that causes the voltage to increase across the external storage capacitor.

The charge flow in the two-capacitor system can be modeled as follows: When the new charge is accumulated, it is distributed in both capacitors and the charge balance equation can be written as (Cuadras et al 2010):

$$\Delta Q_n = Q_{E,n} - Q_{E,n-1} + Q_{P,n} \pm Q_{P,n-1} \tag{4}$$

$$\begin{aligned} Q_{P,n} &= V_n C_P \\ Q_{P,n-1} &= V_{n-1} C_P \\ Q_{E,n} &= V_n C_E \\ Q_{E,n-1} &= V_{n-1} C_E \end{aligned} \tag{5}$$

where C_p and C_E are pyroelectric cell capacitance and external charging capacitance respectively, V_n and V_{n-1} are voltage at temperature data points n and n-1 respectively, Q_p and Q_E are charge accumulated in pyroelectric cell and external capacitance respectively, and ΔQ_n is the additional charge generated at n^{th} data point (from heating or cooling). The ± sign in front of the right hand side term indicates that charge stored in pyroelectric cell can be in opposite direction if the sign of the rate of change of temperature changes from $(n\text{-}1)^{th}$ data point to n^{th} data point.

Substitution of Eq. 5 into Eq. 4 results the following recurrence equation, from which the voltage across the external capacitance can be calculated at a given temperature data point:

$$V_n = \frac{\Delta Q}{C_P + C_E} + \left(\frac{C_E \pm C_P}{C_E + C_P}\right) V_{n-1} = \frac{pA\Delta T}{C_P + C_E} + \left(\frac{C_E \pm C_P}{C_E + C_P}\right) V_{n-1} \tag{6}$$

Once the voltage is determined, the energy stored at n^{th} data point can be calculated from the following equation:

$$E_n = 0.5 C_E V_n^2 \tag{7}$$

Eq. 6 has been used to simulate the voltage produced from a measured temperature profile of actual pavement temperature (shown in Figure 10). Figure 10 shows the temperature profile between May-Oct at a station location in Huntsville, Alabama. The temperature profile was obtained from the Environmental and Climatic Database of Mechanistic Empirical Pavement Design Guide (MEPDG) (NCHRP 2004). The simulated voltage is shown in Figure 11. The circuit is simulated with the following values: $C_P = 3.761\text{x}10^{-12}$ F, $C_E = 10\text{x}10^{-6}$ F, $p = 1.5\text{x}10^{-9}$ C/cm^2/^{o}C, $A = 0.907$ cm^2. When $C_E >> C_P$, Eq. 6 becomes: $V_n \approx (pA\Delta T)/C_E + V_{n-1}$. This is the simplified version of Eq. 6; when storing energy from temperature fluctuations, the values of C_P and C_E should be optimized for highest energy storage. Figure 11 shows that the accumulated voltage increases as the summer months go by. The maximum voltage accumulated at the end of October is around 0.55 V. It should be noted that this maximum voltage can be controlled by choosing suitable value for external storage capacitor, C_E.

Assuming that one single device will produce 10 μW/cm^2 of energy, this converts to $10 \times (12 \times 2.54)^2$ μW/ft^2 ≈ 10 mW/ft^2. Most of the wireless devices use energy in the range of several mW, therefore, even one single device will be sufficient to produce power for the wireless sensors. To check how many devices will be required to produce a power of 10 W, which is typical for a street intersection LED signal, the area required = $10/(10 \times 10^{-3})$ ft^2 = 1000 ft^2, i.e., for a 10 ft wide lane, 100 ft length of the lane need to be covered by the sensors.

It is possible to increase the voltage by placing several of the pyroelectric cells in parallel. The current would increase and hence charge accumulation will be algebraically added. Currently, the authors are testing the methodology by using several of these sensors in real pavement and monitoring the voltage generated. The present experimental results are in agreement with the predicted results.

5.0 CONCLUSIONS

In this study cement-based pyroelectric nano-composites have been fabricated and their electrical and pyroelectric properties have been measured. The material data has been used to perform simulation with real pavement temperature data obtained from climatic database of MEPDG. The preliminary experimental results obtained from composite samples can be summarized as follows:

1. Cement-Carbon nano-composites can be fabricated using normal mixing and compaction method.
2. The dielectric constants of composites increase as the carbon fiber content increases.
3. The pyroelectric coefficients of composites also increase as carbon fiber content increases. Higher content of carbon fiber in the cement nano-composites is beneficial for pyroelectric energy conversion devices
4. The simulation result with the real time pavement temperature data indicates that the methodology is a sound one and should be explored further with real time pavement experimentation.

Further work is in progress to characterize piezoelectric properties of the fabricated nano-composites so as to find potential use in piezoelectric micro-energy converters. The combination of piezoelectric and pyroelectric sensors will be ideal for energy harvesting from pavements.

6.0 ACKNOWLEDGEMENTS

The partial financial support for this work through NSF-RISE grant ID 0927644 is gratefully acknowledged. Special thanks to Drs. Mohan Aggarwal and M. A. Alim for support in our work.

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Table 1: Composition of nanocomposites fabricated

Simple Name	nano Carbon (% by mass)	PVA (% by mass)	Cement (% by mass)
SSS3	0.070	0.513	99.417
SSS5	0.246	0.500	99.254
SSS7	0.490	0.508	99.002
SSS8	0.629	0.508	98.863
SSS9	1.173	0.509	98.318

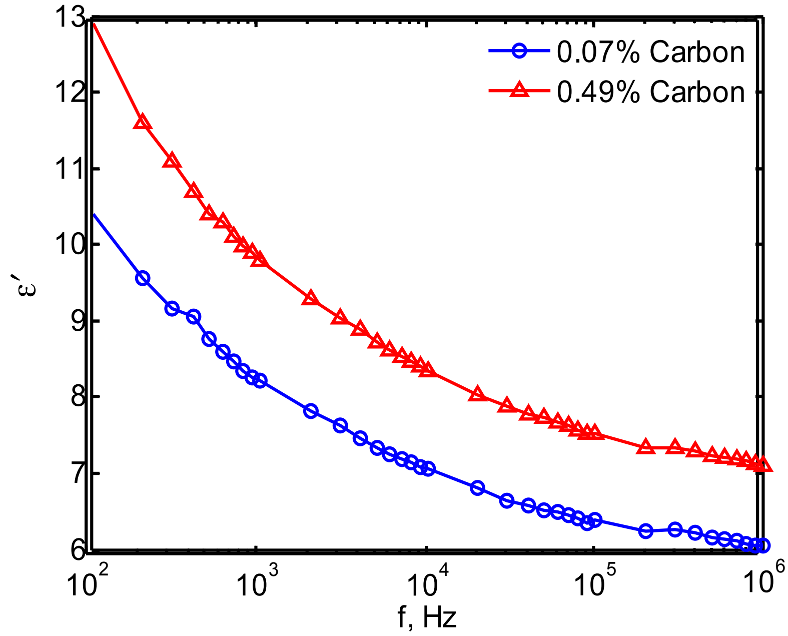

Figure 1: A typical dependence of dielectric constant (ε') of cement:carbon nanocomposites on frequency (40 °C).

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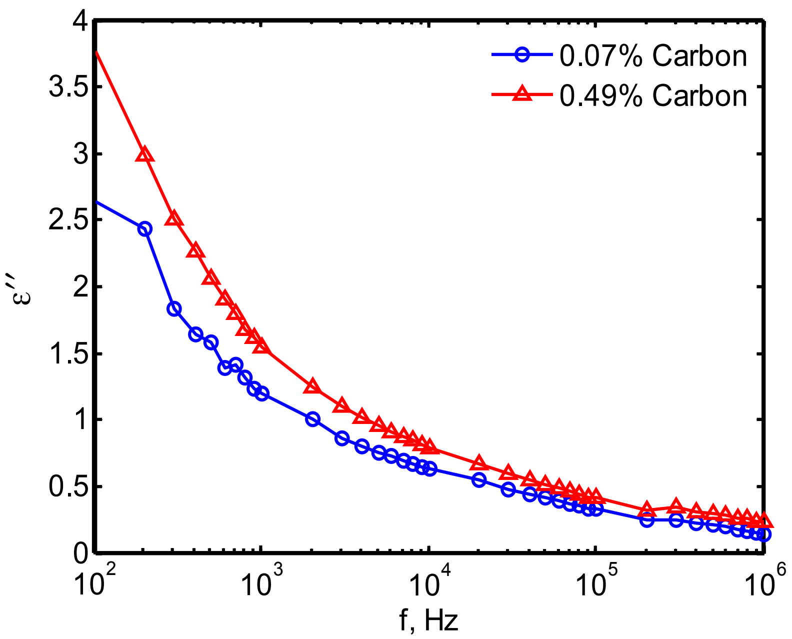

Figure 2: A typical dependence of dielectric loss (ε'') of cement:carbon nanocomposites on frequency (40^{o}C).

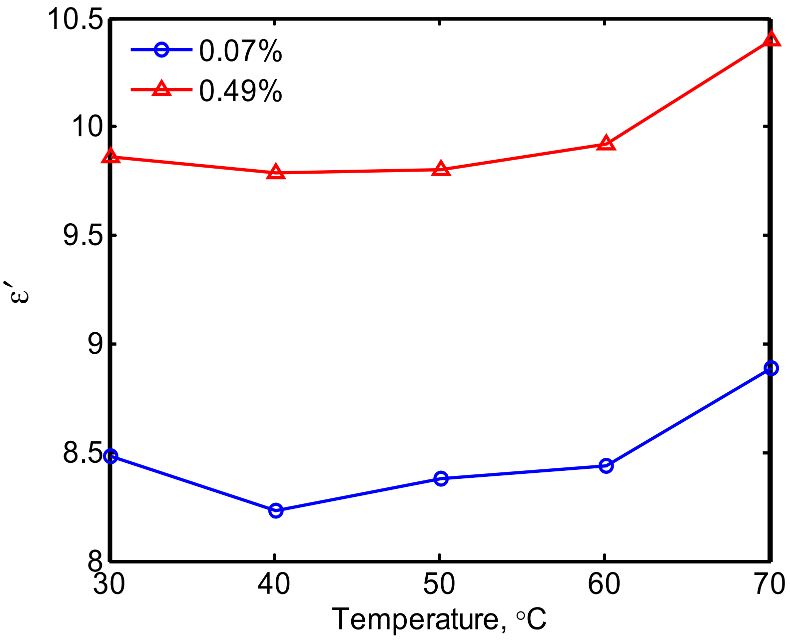

Figure 3: A typical dependence of dielectric constants (ε') of cement-carbon nano-composites on temperature.

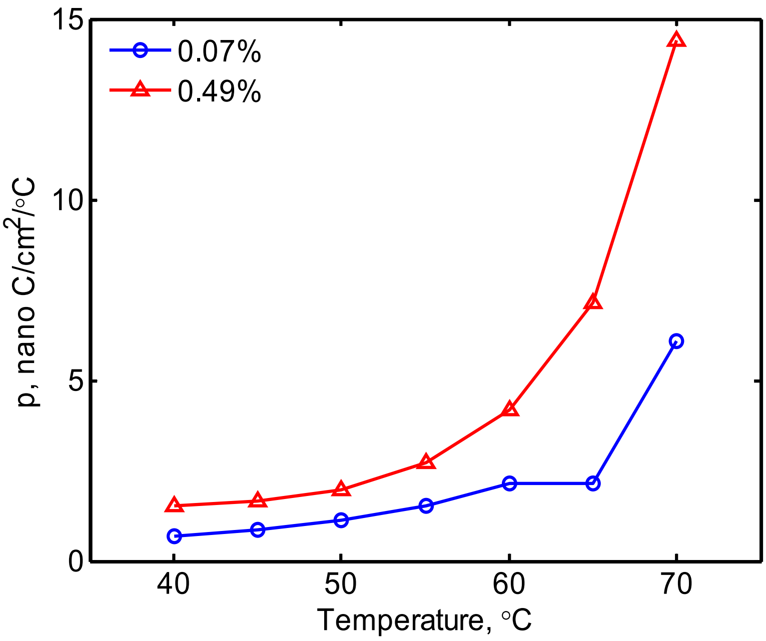

Figure 4: A typical dependence of pyroelectric coefficient of cement-carbon nano-composites on temperature.

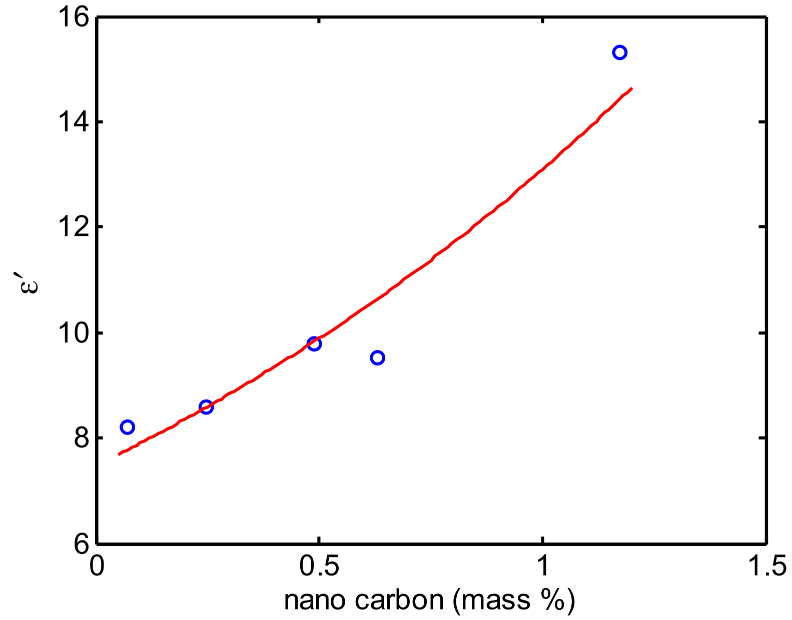

Figure 5: Dependence of the dielectric constants (ε') of cement-carbon nano-composites on the carbon content (40 °C and 1 kHz frequency).

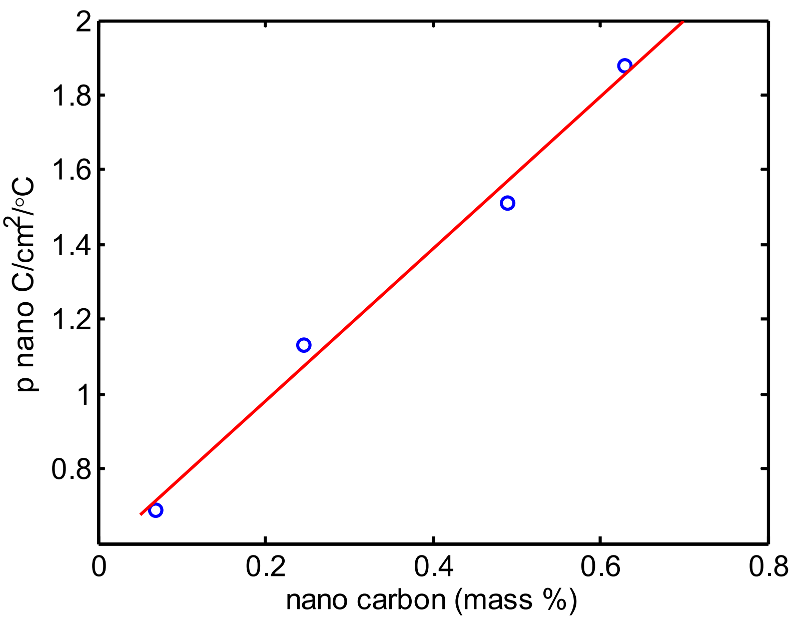

Figure 6: Dependence of the pyroelectric coefficients of cement-carbon nano-composites on the carbon content (40 °C and 1 kHz frequency).

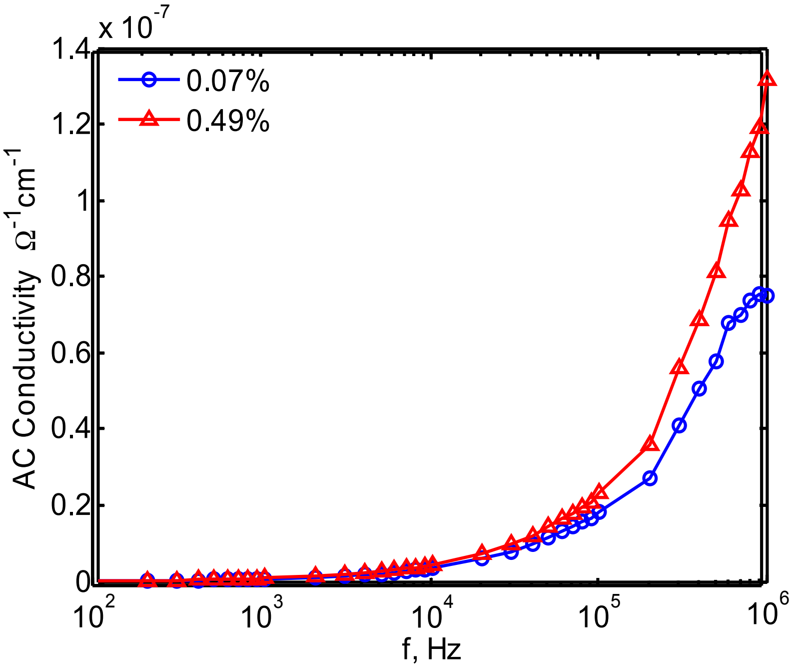

Figure 7: A typical dependence of AC conductivity of cement-carbon nano-composites on frequency (40°C).

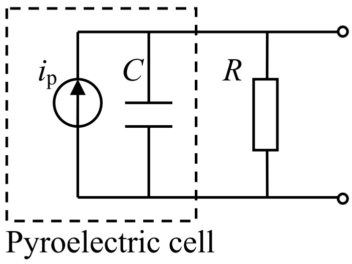

Figure 8: Pyroelectric material model; I_p = current generated, C_P = internal capacitance of the cell, R = internal resistance of the cell.

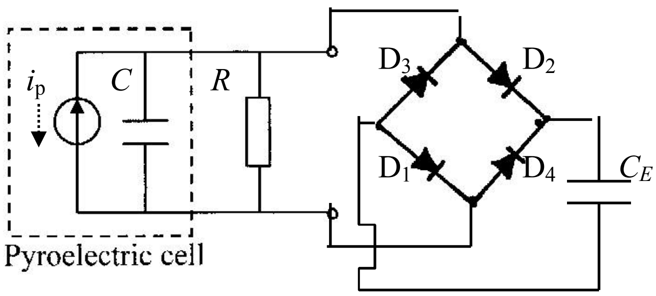

Figure 9: Pyroelectric cell with full bridge rectifier circuit for charge storage; D_1-D_2 are used in one direction of current flow (solid arrow), D_3-D_4 are used in other direction of current flow (dotted arrow) (Cuadras et al 2010).

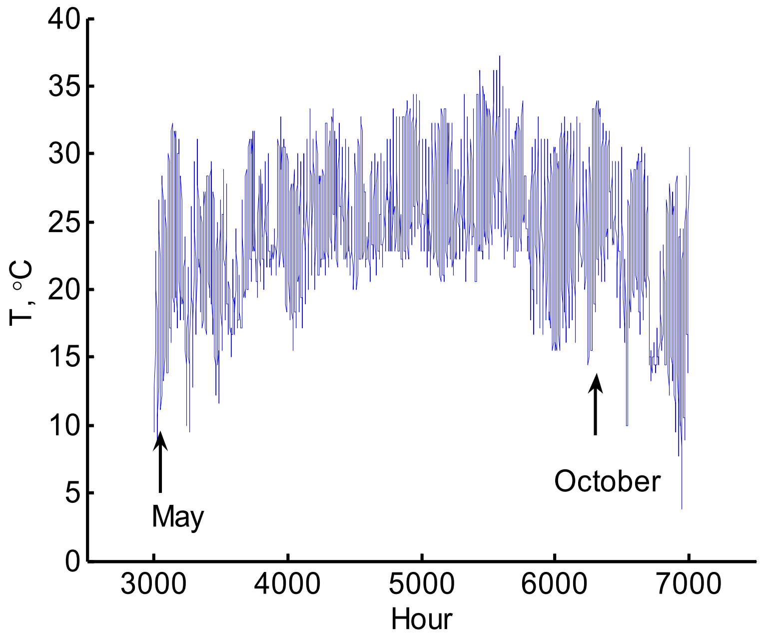

Figure 10: Temperature profile at Huntsville, AL, May-Oct, Station ID = 03856.

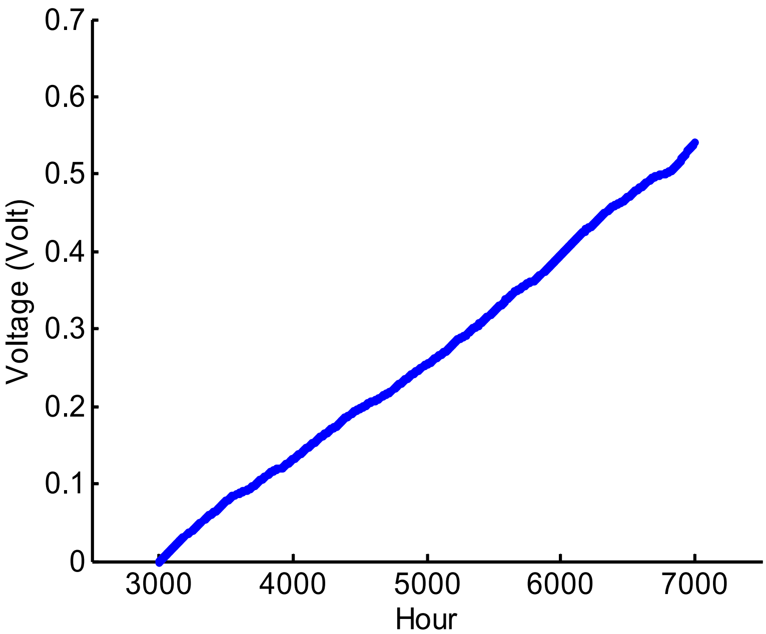

Figure 11: Generated voltage across the external storage capacitor.

TRACE ELEMENT LEACHING FROM RECYCLED PAVEMENT MATERIALS STABILIZED WITH FLY ASH

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ABSTRACT

Percolation rates and concentrations of trace elements are presented from leachate collected in pan lysimeters installed beneath roadway sections where fly ash was used to stabilize subgrade or base course. Data from control sections are also presented. Percolation rates from the base of a pavement profile vary seasonally in response to seasonal variations in meteorological conditions. Percolation rates typically range between 0.1-0.5 mm/d, with the average percolation rate falling between 0.1-0.2 mm/d depending on site conditions. Concentrations of six elements (B, Cd, Cr, Cu, Mo, and Zn) in leachate from roadway sections stabilized with fly ash have been elevated compared to concentrations from control sections at all field sites with control sections. Four elements from fly-ash-stabilized materials have been elevated in concentration relative to control section at some sites (As, B, Cd, Cr, and Mo) and have also exceeded MCLs. Both B and Mo persistently exceed MCLs. In contrast, concentrations of Cd and Cr have only exceeded MCLs in the first samples collected (PVF < 0.25), and then have remained well below MCLs.

INTRODUCTION

Approximately 63.5 million Mg of fly ash was produced in the US in 2007, of which 45% was used in beneficial applications including roadway stabilization [ACAA 2008]. The primary limitation to greater use of fly ash in road construction is concern about environmental impacts to soil and groundwater from potentially toxic elements present in the ash [US DOE 2009]. Fly ash contains trace amounts of many metals and metalloids present in the coal, including As, B, Ba, Be, Cd, Cr, Co, Cu, Pb, Mn, Ni, Se, Sr, Tl, V, and Zn [NRC 2006].

Over the past decade, we have installed 10 large pan lysimeters beneath sections of roadway where the base or subgrade was stabilized with cementitous coal fly ash during construction. The purpose of the lysimeters was to monitor the temporal variation in percolation from the base of the roadway and the type, concentration, and pattern of trace elements in the percolate. These two quantities yield the mass flux discharged from the base of the pavement profile, which is a key factor affecting risk assessments for groundwater beneath pavements. This paper provides a summary of the data from the pan lysimeters.

FIELD SITES

Five field sites constructed using fly-ash-stabilized base course or subgrade are being monitored (Table 1). These sites are Wisconsin State Highway 60 (STH60) in Lodi, WI; US Highway 12 (US12) in Fort Atkinson, WI; the Scenic Edge subdivision (Scenic Edge) in Cross Plains, WI; 7th Avenue in Waseca, MN; and the Minnesota Department of Transportation's full-scale highway testing facility (MnROAD) in Albertville, MN, USA.

Table 1: Properties of Stabilized Layers and Lysimeters

Site	STH60	US12	Scenic Edge	MnROAD	Waseca
Layer Stabilized	Subgrade	Subgrade	Subgrade	Base Course	Base Course
Material Stabilized	Soil	Soil	Soil	Recycled Paving Material	Recycled Paving Material
USCS and AASHTO Classification	CL A-6	CL or SC A-6	CL A-7-6	GW-GM A-1-a	GW-GM A-1-a
Fly Ash Type	Columbia	Columbia	Columbia	Riverside 8	Riverside 7
% Fly Ash by Mass	10	12	12	14	10
Compacted Dry Density of Stabilized Layer (kN/m^3)	15.4	18.9 - 20.0	15.9	19.6	15.9
Stabilized Layer Thickness (mm)	300	300	300	203	150
Lysimeter Dimensions (m)	3.75 x 4.75	3 x 3	3.75 x 4.75	3 x 3	4.0 x 4.0

During construction at least one pan lysimeter was installed at each site immediately below the stabilized materials to collect leachate discharging from the bottom of the layer. Lysimeters were also installed beneath control materials at STH60, US12, and MnROAD.

METHODS AND MATERIALS

Fly Ashes

Fly ash is classified based on chemical composition by ASTM C 618 as either Class C or Class F. Fly ash that does not meet the requirements of Class C or F is often referred to as "off-specification." The composition within a class can vary significantly [US EPA 2008].

The majority of the fly ash that is recycled in the US is used in concrete and classifies as Class C or F. Off-specification ash with higher carbon content often cannot be used in Portland cement concrete due to effects on strength and longevity and therefore is not used at the same frequency as Class C and F ashes. However, off-specification ashes can be used in non-concrete applications such as roadway stabilization [US EPA 2008]. Two of the ashes used in this study were Class C ashes; the other ash was an off-specification ash.

The field sites in this study employed three cementitious fly ashes for stabilization of base course or subgrade: Columbia, Riverside 7, and Riverside 8. Columbia fly ash is from Alliant Energy's Columbia Power Station in Portage, WI, USA, whereas the Riverside 7 and Riverside 8 fly ashes are from Xcel Energy's Riverside Power Plant in Minneapolis, MN, USA. Columbia ash was used at the STH60, Scenic Edge, and US12 sites. The Riverside ashes were used at the MnROAD and Waseca sites. Columbia ash classifies as Class C. Riverside 7 is classified as Class C, whereas Riverside 8 is an off-specification ash due to its high carbon content (>5%).

Leachate Monitoring

The pan lysimeters were constructed with 1.5-mm-thick linear low-density polyethylene (LLDPE) geomembrane overlain with a drainage layer comprised of a geonet between two layers of geotextile. Leachate collected in each lysimeter is routed to a 120-L high-density polyethylene (HDPE) leachate collection tank via polyvinyl chloride (PVC) pipe. The tanks are buried approximately 2 m deep along the shoulder of the roadway.

Leachate in the tanks is pumped and sampled periodically. Volume of leachate discharged from the layer is recorded and total pore volumes of flow (PVF) are calculated. Samples are collected from the pumped leachate for chemical analysis in HDPE sample bottles with zero headspace. Within 24 hr of sampling, pH and oxidation-reduction potential (Eh) are measured in the laboratory. The sample is then filtered with a 0.2 μm micropore filter and preserved to pH<2 using trace-metal-grade HNO_3.

Leachate Chemical Analysis

Chemical analysis of the leachate samples has been conducted with several methods over the course of the project due to the availability of equipment and changing requirements for certain analytes. The methods include atomic adsorption (EPA Standard Methods 213.2, 218.2, 270.2, and 272.2), inductively coupled plasma-mass spectrometry (USEPA Method 200.8), inductively coupled plasma-optical emission spectrometry (USEPA Method 200.8), and cold vapor atomic fluorescence spectrometry (USEPA Methods 1631, 1669) for Hg. The elements analyzed are Ag, Al, As, B, Ba, Be, Cd, Co, Cr, Cu, Fe, Hg, Mo, Mn, Ni, Pb, Sb, Se, Sn, Sr, Ti, Tl, V, and Zn. Concentrations of all elements were not measured at all sites or at all times during the study.

RESULTS

Precipitation Patterns and Lysimeter Drainage

Long-term flux of leachate discharged from the fly-ash-stabilized layers has been less than 8% of the local precipitation, and often only 1-3% of precipitation (Fig. 1). Percolation rates typically range between 0.1-0.5 mm/d, with the average percolation rate falling between 0.1-0.2 mm/d depending on site conditions. Regional average groundwater recharge rate for the sites is estimated to range from 19% to 24% of precipitation for the Minnesota sites and from 20% to 21% of precipitation for the Wisconsin sites. This indicates that the recharge rate in areas adjacent to a stabilized roadway may be significantly higher than the rate of leaching from the roadway. This difference in recharge rates will affect subsurface transport by diluting elements discharged from the roadway.

Greater discharge of leachate relative to precipitation occurs in the fly-ash-stabilized base course layers (2.1 to 7.8% of precipitation) compared to the stabilized subgrades (1.8 to 2.4% of precipitation) (Fig. 1). The control base courses also had greater leachate flux than the control subgrades in terms of percentage of precipitation.

Peak fluxes from the layers tend to occur in the spring months when heavy rains and snow melt occur, and again in a period in the late summer and early fall. There is a delay of peak fluxes of one to two months after peak precipitation events. Minimum fluxes tend to occur in the winter when precipitation and pore water are often frozen, and in a period in July or August. Occasionally the flux from the base course layers approaches 15% of precipitation for a period of several months, but the long-term average has never been more than 7.8%.

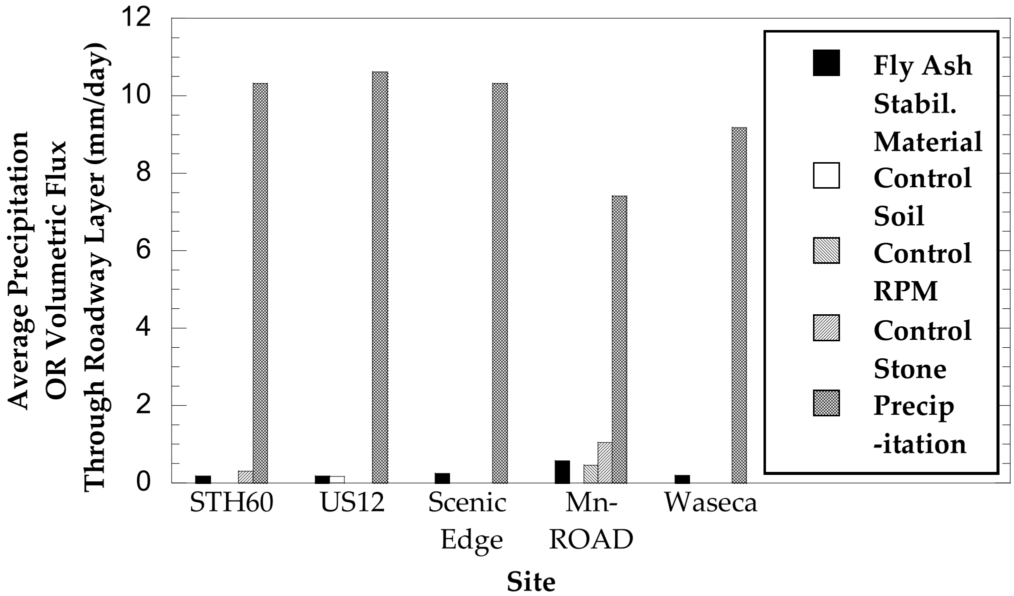

Fig. 1.Comparison of Long-term Volumetric Flux from the Roadway Layers Relative to Local Average Daily Precipitation

Chemical Indicator Parameters

The pH and Eh of leachates collected in the lysimeters are presented in Fig. 2. The pH in field leachate ranges from 6 to 9, with most of the data near neutral (Fig. 2a) for both stabilized and control materials. Only the east stabilized lysimeter at the US12 site regularly has pH greater than 8, possibly because this is the only site with concrete pavement. The leachate Eh generally ranges from +300 to -150 mV, with most data predominantly oxidizing (Eh > 0) and occasional samples in a reducing state (Eh < 0) (Fig. 2b). Only the east lysimeter at the US12 site has Eh less than -150 mV on a regular basis (Fig. 2b). The US12 east lysimeter regularly has leachate that is grey in color and has a strong odor of anaerobic decay. Other field leachates generally are clear to yellow, and have no odor.

Elements Released and Magnitude of Concentrations

Of the twenty-four trace elements considered in the analysis (Ag, Al, As, B, Ba, Be, Cd, Co, Cr, Cu, Fe, Hg, Mn, Mo, Ni, Pb, Sb, Se, Sn, Sr, Ti, Tl, V, and Zn), all except Be were present in detectable quantities in leachate from fly-ash-stabilized layers. Only Mo had a peak concentration greater than 10000 μg/L. Sr, Al, Fe, B, and Mn have maximum peak concentrations between 10,000 and 1000 μg/L; Sn, Ba, V, Se, Zn, As, Cu, Tl, and Ni have maximum peak concentration between 1000 and 100 μg/L; and Pb, Cr, Sb, Ti, Co, Cd, and Ag have maximum peak concentration between 100 and 10 μg/L. Peak concentrations of both Hg and Be have been less than 1 μg/L.

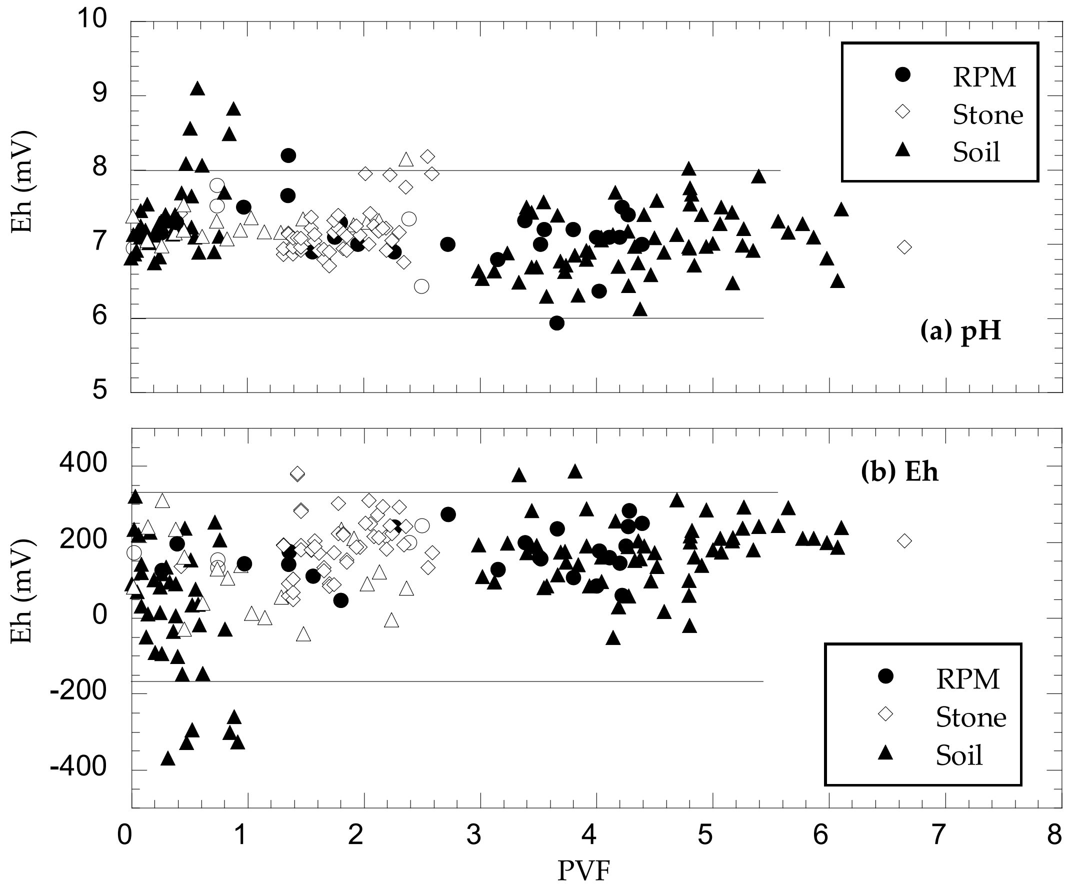

Fig. 2. pH (a) and Eh (b) of Leachate from Lysimeters Beneath Stabilized and Control Materials

Elution Patterns

Leachate concentrations were observed to rise and then fall over time or pore volumes of flow (PVF). Several elements in the leachate were observed to reach peak concentration during the first or second PVF and to remain lower than the peak in all subsequent samplings events (a first-flush leaching pattern). Others would remain relatively constant over time. Examples of these patterns are shown in Fig. 3.

The number of elements at a site with concentrations exceeding maximum contaminant levels (MCLs) typically decreased with increasing PVF, with concentrations typically dropping below MCLs within 2-4 PVF. However, environmental conditions vary in the roadway materials over time scales of hours to seasonally, including temperature, moisture content, precipitation and infiltration rate, pH, biological activity, and freeze-thaw cycles. As a consequence, leaching and mobility of elements may change temporally with changing environmental conditions.

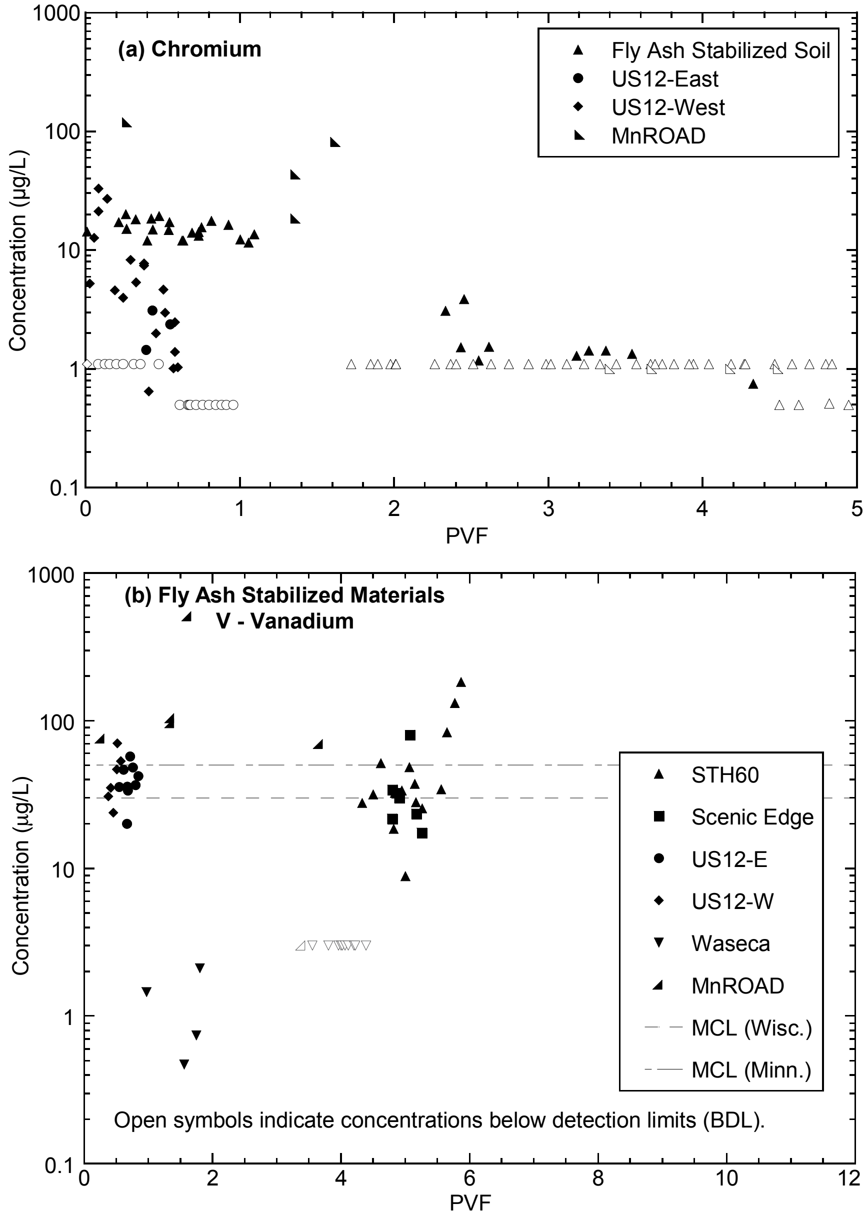

Fig. 3. Examples of elements showing a decrease in concentration with PVF (a) and relatively consistent concentration with PVF (b)

EVALUATION OF LEACHATE CONCENTRATIONS

Field Concentrations Compared to Control Sections

Concentrations of elements in leachate from a material stabilized with fly ash were considered elevated relative to concentrations from control materials if the confidence interval associated with the peak concentration from the material stabilized with fly ash was greater than and did not overlap the confidence interval associated with the peak concentration of the control material. Confidence intervals were computed using coefficients of variation (COV) from 7 replicate analyses of each element tested via ICP-OES.

Nineteen of the 24 elements tested were found to have elevated concentrations relative to control concentrations. Six elements (Mo, B, Cu, Cr, Cd, and Zn) had elevated concentrations at all 3 field sites with control sections. Eleven elements (Sr, Al, Ba, Ti, Co, Fe, Sn, As, V, Ni, and Mn) were elevated at two of the three sites, and both Pb and Ag were elevated at one of the sites. Concentrations of Hg, Be, Se, Tl, and Sb were not elevated in leachate from the stabilized materials.

Elements Exceeding MCLs

Eleven elements in lysimeter leachate were found to exceed MCLs: As, B, Cd, Cr, Mo, Ni, Pb, Sb, Se, Tl, and V. Of these eleven elements, eight were elevated in concentration relative to the control sections (As, B, Cd, Cr, Mo, Ni, Pb, and V). The concentrations of Sb, Se, and Tl in leachate from stabilized materials were found to be equal or less than the concentrations from control materials.

Four of the elements from fly-ash-stabilized materials that exceeded MCLs were elevated at all sites relative to the control section. In order of descending level of elevation, these elements are B, Mo, Cr, and Cd. Molybdenum has no MCL in Minnesota, but the peak Mo concentration at MnROAD was 470 times higher than the Wisconsin MCL. Cd and Cr concentrations only exceeded MCLs in the first samples collected (PVF < 0.25), and then remained well below the MCL in all subsequent samples. In contrast, the B and Mo persist at elevated concentrations.

Four of the elements that exceeded MCLs were elevated in leachate from stabilized materials at only one or two of the three sites with controls. In order of descending level of concentration elevation, these elements are V, Ni, As, and Pb. V continues to leach at concentrations above the MCL at all sites where the concentration has exceeded the MCL. Ni only exceeded the MCL or was elevated relative to the control at the US12 site, which has more acidic and reducing conditions than the other sites.

Both As and Pb have relatively low and constant concentrations that periodically exceed the MCL over many PVF. However, the concentrations of As and Pb from stabilized materials are only slightly elevated relative to control concentrations.

CONCLUSIONS

The field data indicate that the percolation rate from the base of a pavement profile varies seasonally in response to seasonal variations in meteorological conditions. Percolation rates typically range between 0.1-0.5 mm/d, with the average percolation rate falling between 0.1-0.2 mm/d depending on site conditions.

Concentrations of many trace elements, particularly those with relatively low water quality standards, diminish over time as water flows through the pavement profile. For many elements, concentrations below US water drinking water quality standards are attained at the bottom of the pavement profile within 2-4 pore volumes of flow.

Concentrations of six elements (Mo, B, Cu, Cr, Cd, and Zn) in leachate from roadway sections stabilized with fly ash were elevated compared to concentrations from controls at all sites with control sections. Concentrations of four elements from fly-ash-stabilized materials were elevated relative to the control sections at all sites (As, B, Mo, Cr, and Cd) and also exceeded MCLs. Of these elements, both B and Mo have exceeded the MCL for many PVF. In contrast, concentrations of Cd and Cr only exceeded MCLs in the first samples collected (PVF < 0.25), and then remained well below the MCL in all subsequent samples.

ACKNOWLEDGEMENT

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USING FOUNDRY SAND IN GREEN INFRASTRUCTURE CONSTRUCTION

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INTRODUCTION

Foundry sand is a high-quality uniform silica sand that is used to make molds and cores for ferrous and nonferrous metal castings. The metal casting industry annually uses an estimated 100 million tons of foundry sand for production. Over time, foundry sands physically degrade until they are no longer suitable for molds. Consequently, 9 to 10 million tons of sand is discarded each year. However, the discarded foundry sands have remarkably consistent composition and are generally considered a higher quality material than typical bank run or natural sands used in construction. Currently, an estimated 28% of discarded foundry sand is reused, primarily in construction-related applications, while the remaining sand is disposed of in landfills (American Foundry Society 2007). Recycling of foundry sand can save energy, reduce the need to mine virgin materials, and may reduce costs for both producers and end users. Use of foundry sand as a fine aggregate in construction applications offers project managers the ability to enhance green sustainable construction by reducing their carbon footprint, while also qualifying for LEED credits. The U. S. Environmental Protection Agency (EPA) recently estimated that at the current recycling level 20,000 tons of CO_2 emissions are prevented while 200 billion BTUs of energy are saved (US EPA 2008). Support for increased reuse of foundry sand has brought together the U.S. EPA, the Federal Highway Administration, the U. S. Department of Agriculture, the Recycled Materials Resource Center (RMRC), state environmental agencies, the foundry industry and end users to develop the tools and resources needed to increase foundry sand recycling to 50% by 2015.

This paper provides a comprehensive overview of the engineering and construction properties of foundry sand for use in Portland cement concrete, hot mix asphalt, road subbase layers, embankments, and flowable fill. Recent studies addressing environmental concerns of using foundry sand as a construction material are reviewed. With the goal of advancing use of foundry sand in construction application, references to resources and tools, such as web-based training and a foundry locator map module, are made available.

GENERAL FOUNDRY SAND PROPERTIES

Foundry sands consist of green sand and resin sand. Green sands are typically comprised of high-quality silica sand, 5-10 percent bentonite clay, 2 to 5 percent water and less than 5 percent sea coal. The green sand process constitutes upwards of 90 percent of the molding materials used. Resin sands are high-quality silica sand usually held together with organic binder in conjunction with catalysts and different hardening/setting procedures. Resin sands are most often used for "cores" that produce cavities that are not practical to produce by green sand molding operations, primarily due to strength issues.

Physical Properties

Physical properties for foundry sand from green sand systems are listed in Table 1. The grain size distribution of most foundry sand is very uniform, with approximately 85 to 95 percent of the material between 0.6 mm and 0.15 mm (No. 30 and No. 100) sieve sizes. Five to 12 percent of foundry sand can be expected to be smaller than 0.075 mm (No. 200 sieve). The particle shape is typically subangular to rounded.

Foundry sand has low absorption, although reported values of absorption were found to vary widely, which can be attributed to the presence of binders and additives (Javed and Lovell 1994ab). The content of organic impurities (particularly from sea coal binder systems) can vary widely (Emery 1993). The specific gravity of foundry sand has been found to vary from 2.39 to 2.70. This variability has been attributed to the amount of fines and additive contents in different samples (Federal Highway Administration 2004, Javed and Lovell 1994ab).

In general, foundry sands are dry, with moisture contents less than 2 percent. Clay lumps and friable particles are sometimes associated with the molded sand, and are easily broken up. The variation in hydraulic conductivity (Table 1) is a direct result of the fraction of fines in different foundry sands.

Mechanical Properties

Typical mechanical properties of foundry sand are listed in Table 3. Foundry sand has good durability characteristics as measured by low Micro-Deval abrasion (Ontario Ministry of Transportation, 1996) and magnesium sulfate soundness loss tests (ASTM C88-05). Studies have reported relatively high soundness loss, which is attributed to samples of bound sand loss and not a breakdown of individual sand particles. The internal friction angle of foundry sand has been reported to be in the range of 33 to 40 degrees, which is comparable to that of conventional sands (Javel and Lovell, 1994).

Mineralogical and Chemical Properties

Foundry sand consists primarily of silica sand (>80% silcon dioxide), coated with a thin film of burnt carbon and residual binder (Du et al 2002). Loss on ignition in foundry sand has been reported by the American Foundrymen's Association (1991) to be around 5%. Depending on the binder and type of metal being cast, the pH of foundry sand can vary from approximately 4 to 12 (Johnson, 1981, Emery 1992, Bhant and Lovell 1996, Dayton et al 2010). A pH of 5.5 or less in soil is considered a corrosive condition.

Environmental Considerations

Characterization of foundry sand: Foundry sand often contains trace metals and core material containing partially degraded binder. Foundry sand may contain trace amounts of leachable metals and phenols. Many studies have been conducted to characterize the constituents found in foundry sand. The metal type poured can significantly affect metal constituent levels. Foundry sand from brass or bronze foundries may contain high concentrations of metals including cadmium, lead, copper, nickel, and zinc (Javed and Lovell 1994ab). Therefore, unlike sands from ferrous and aluminum foundries, these sands are not typically appropriate for beneficial use in most applications. A study of 43 foundry sands from aluminum, iron, and steel foundries found the total metals concentration in the sand to be similar to the levels found in agricultural soil (Dungan and Dees 2007).

The resin binder systems are the primary sources of organic constituents in foundry sand. Green sand systems have been shown to have lower potential for leaching organic compounds. The primary organic constituents from foundry sand are acetone and 1,1,1-trichloroethane (EPA 2002a). Tikalsky et al (2004) found that most organic compounds are burned out during the casting process. Studies have shown that foundry sands contain polyaromatic hydrocarbons (PAHs) and phenolic compounds (Ji et al 2001, Dungan 2006, Stehouwer et al. 2010) However, the majority of the foundry sands analyzed contained PAHs and phenolics below threshold levels established in state beneficial use regulations.

Evaluation of leaching: Multiple studies have concluded that constituents in leachate from most iron, steel, and aluminum foundry sands fall well below the regulatory limits for determining a hazardous waste (Fox and Mast 1997, Tikalsky et al 2004, Wang and Vipulanandan 2000, Dungan and Dees 2007). Sands from some leaded copper-base facilities, however, may be considered a hazardous waste under EPA rules due to metal content.

Examinations of the environmental effects of ferrous foundry sand have shown that foundry sand did not cause groundwater or surface water contamination and that the measured concentrations were below the U.S. EPA drinking water limits (Lovejoy et al 1996, Naik and Singh 2001, Guney et al 2006, Lee and Benson 2006). Several foundry sand leachate characterization studies suggest that foundry sand is generally safe to reuse in highway applications (Boyle and Ham 1979, Han and Boyle 1981, Ham et al 1993a, Ham et al 1993b).

A study on concentrations of metals in leachate beneath a foundry sand test plot found concentrations comparable to natural soils (Freber 1996). Dungan and Dees (2007) found that waste molding sands have a low metal leaching potential using SPLP and ASTM extraction tests with results falling below the national drinking water standards.

Leaching of metals from flowable fill is a long process due to the low permeability of the material. A study performed by Naik and Singh (2001) showed that concentrations of iron, barium, magnesium, zinc, arsenic, chromium, lead, selenium, cadmium, mercury and chloride in leachate extracted from flowable fill materials containing up to 85% foundry sand were below the enforcement standards of the Wisconsin Department of Natural Resources ground-water quality standards and also met practically all the parameters of the drinking water standards

However, Lee and Benson (2002) and Coz et al (2004) had found leaching concentrations of zinc, lead, chromium, and iron in foundry sand to be above the U.S. EPA drinking water limits, although the difference was within 10 percent. Lee and Benson (2006) conducted water leach tests on 12 green sands from iron casting foundries. Concentrations of constituents of concern barely exceeded Wisconsin's maximum permissible concentrations. Similar concentrations are observed in reactive medium barrier material that is commonly placed below the groundwater table for remediation of contaminant plumes. Sauer et al (2005) performed a laboratory batch water leach test, column leach test, and below subbase lysimeter study to evaluate leachate from gray iron foundry sand. Peak selenium concentrations in the leachate from the field lysimeters exceeded Wisconsin groundwater standard. However, application of dilution factors reduce expected concentrations between the bottom of the pavement structure and the groundwater table. Concentrations would not exceed the groundwater quality standards if the foundry sand layer is at least 1 m above the groundwater table.

Laboratory studies performed by Winkler and Bol'shakov (2000) indicate that organic compounds leach only at low concentrations. Johnson (1981), Emery (1993), and Ham et al (1989) report that with the presence of phenols in chemically bonded foundry sands, there is a possibility that leachate from stockpiles could result in phenol discharges.

Due to the general complexity in composition and character of foundry sand, appropriate leaching tests should be conducted on foundry sand from a particular source before reuse, although recent studies have suggested that it is not necessary to leach and measure the full spectrum of metallic elements in the sand (Tikalsky et al 2004). Foundries interested in beneficially using their sands should refer to their state's testing requirements.

Risk evaluations: Hindman et al (2008) conducted a greenhouse column experiment to evaluate the suitability of using foundry sand from ferrous and aluminum foundries in manufactured soils by measuring plant growth, plant uptake and leaching of

nutrients, trace metals, metalloids, and organics. They concluded that use of foundry sand from ferrous and aluminum foundries in blended soils will not increase risk of trace element or organic contaminant transport to surrounding soils or waters.
Dungan and Dees (2006) conducted a 28-day experiment with the earthworm *Eisenia fetida* and 6 different waste foundry sands to assess the bioavailability of metals in soil blends up to 50% foundry sands. Based upon the earthworm mortality and metal accumulation data, the study suggests that waste sands from the iron, aluminum and steel foundries do not pose an ecotoxicological or metal transfer risk. However, earthworms in soil blends using sands from a brass foundry suffered excessive mortality and metal uptake.

In 2002, a national effort to identify the risks and benefits of using foundry sand from ferrous and aluminum foundries was initiated. Partners in the effort included the U.S. Department of Agriculture-Agricultural Research Service, the Ohio State University, the Pennsylvania State University, and U.S. EPA. Using the metal and organic constituent levels from foundry sands from more than 30 iron, steel, and aluminum foundries, EPA and USDA modeled several exposure pathways associated with the use of foundry sands in a soil blend. Exposure pathways included: inhalation, groundwater ingestion, and ingestion of vegetables grown in a home gardener scenario. The draft study concluded that non-olivine sands from iron, steel, and aluminum foundries do not pose a threat to human health or the environment when used in roadway sub-base or as an ingredient in manufactured soils or soil-less media. The study was submitted for peer review and a final report is pending (US EPA 2010).

Environmental Impact Modeling Tools: Models currently used to simulate leaching from pavement systems and potential impacts to groundwater include STUWMPP (Friend et al 2004), IMPACT (Hesse et al 2000), WiscLEACH (Li et al 2006), and IWEM (EPA 2002b). Examples of models in the public domain include WiscLEACH and IWEM. WiscLEACH combines three analytical solutions to the advection–dispersion–reaction equation to assess impacts to groundwater caused by leaching of trace elements from materials used in highway subgrade, subbase and base layers. WiscLEACH employs a user friendly interface and readily available input data along with an analytical solution to produce conservative estimates of groundwater impact.

The U.S. EPA's Industrial Waste Management Evaluation Model (IWEM) can be used to determine whether leachate will negatively affect groundwater. IWEM inputs include site geology/hydrogeology, initial leachate concentration, metal parameters, and regional climate data. IWEM includes a roadway nodule that evaluates industrial material resources as a contaminant source. Given a length of time, the program will produce a leachate concentration at a control point that is a known distance from the source. Monte Carlo simulations can provide worst-case scenarios for situations where a parameter is unknown or unclear. Melton et al (2006) and Li and Benson (2009) compared IWEM to field lysimeter information and found that IWEM over predicted the leachate concentrations and could be considered conservative. Overall, IWEM performed satisfactorily in predicting groundwater and solute flow at points downstream from a source.

Detailed information on assessing risk and protecting groundwater is available in EPA "Guide for Industrial Waste Management" which can be found at http://www.epa.gov/epaoswer/non-hw/industd/guide/index.asp.

DESIGN CONSIDERATIONS AND GUIDELINES

Highway Subbase

Laboratory and case studies have shown that with proper design and construction, compacted foundry sand provides adequate support as a working platform or subbase material in flexible pavement design (Kleven et al 2000, Edil et al 2000). Moreover, foundry sand-based subbase specimens have been shown to resist winter conditions better than specimens of reference materials (Guney et al 2006).

Highway Subbase Design Considerations: California Bearing Ratio percentages as well as regression coefficients for the power function model to calculate Resilient Modulus, MR, are shown in Table 3. Design charts for selecting the equivalent thickness of compacted foundry sand for working platforms are provided by Tanyu et al (2004). The methodology for including the structural contribution of working platforms made from foundry sand or other alternative material is presented by Tanyu et al (2005).

An increase in strength in highway subbases using foundry sand can be obtained in the field by compacting the foundry sand-based mixtures using higher compactive efforts. The subbase layer mixture should be compacted at dry of optimum for higher strength (Kleven et al 2000, Guney et al 2006).

Embankment

Several states have allowed full use of foundry sand as an embankment material with little or no restrictions, though some states continue to place restrictions on industrial byproduct use and require some type of encapsulation. A proposed AASHTO recommended practice for foundry sand in structural fills and embankments does not reference encapsulation, as recent environmental data suggest that ferrous and aluminum foundry sands have environmental characteristics comparable to native soils.

Geotechnical performance of foundry sand has been found to be comparable to that of the natural sand. In an INDOT embankment project, foundry sand had acceptable strength and compressibility with standard penetration N-values ranging from 33 to 54 (Mast 1997). Leachate collected from a demonstration embankment indicated metal concentrations below regulatory reuse criteria and typically below drinking water standards, indicating that foundry sand would not have a negative impact on environmental quality (Partridge et al 1999). The embankment project saved an estimated $145,000 as a result of using foundry sand (Fox and Mast 1998).

Embankment Design Considerations: Engineering properties important to embankment designs are summarized in Table 4. A draft AASHTO standard for incorporating foundry sand into structural fill and embankment designs is currently being balloted.

For design with geosynthetics, interaction coefficients from pullout tests ranged from 0.2 and 1.7 in the normal stress range of 10 to 50 kPa or 209 to 1044 lb/ft^2 (Goodhue et al 2001). Recommended parameters for embankment design with foundry sand and geosynthetics can be found in Goodhue et al (2001).

Freeze-thaw tests conducted per ASTM D 560 show that the resistance of foundry sand to winter conditions was generally better than reference material (clayey gravel), except for lime amended mixtures which were at the verge of disintegration after eight cycles. The hydraulic conductivity ratio ($K_r = K_n/K_i$) ranges from 2 to 24 with increasing values for higher cycles. The unconfined compressive ratio ($q_{ur} = q_{un}/q_{ui}$) remains nearly constant between the first and eighth cycle after losing 40 to 50 percent of their initial strength after the first cycle (Guney et al 2006).

Hot Mix Asphalt

The Federal Highway Administration (2004) reports that in the United States, asphalt concrete is used to cover over 2 million miles of roadway, accounting for over 94 percent of all pavements. Recycled foundry sand has successfully been used as a partial replacement for aggregate in hot mix asphalt (HMA) in Pennsylvania, Michigan, and Tennessee. Pennsylvania DOT allows the use of 8 to 10 percent foundry sand in asphalt mixtures. One asphalt producer in Michigan consistently supplies HMA with 10 to 20 percent recycled foundry sand to replace conventional aggregate. In Tennessee, HMA with 10 percent foundry sand had been reported to compact better and outperform HMA containing washed river sand. Foundry sand has also been used by a hot mix producer in Ontario, Canada since 1994 in both foundation and surface HMA layers (Federal Highway Administration 2004). Superpave performance tests in Wisconsin found a potential for positive performance in using recycled foundry sand. In particular, the stability of mixes with recycled foundry sand can be higher than HMA with conventional sand; moisture resistance was higher than mixes with conventional sand; and some mixes demonstrated increased resistance to rutting (Delange et al 2001).

Asphalt Design Considerations: Asphalt mixes containing foundry sand can be designed using standard asphalt mix design methods. The amount of foundry sand used in an asphalt mixture depends largely on the amount of fines in the foundry sand. Studies have shown that foundry sand can be used to replace between 8 and 25 percent of the fine aggregate content in asphalt mixes (Federal Highway Administration 2004). The optimum asphalt content for HMA mixtures containing various amounts of foundry sand is comparable (5-6.2%) to the content of mixes not containing foundry sand (Miller et al 2001, Tikalsky et al 2004). HMA made with foundry sands have been shown to display good durability characteristics with resistance to weathering (Emery 1993).

Properties of foundry sand that are of particular interest when used in asphalt paving applications are summarized in Table 5. Generally foundry sand should be free of thick coatings of burnt carbon, binders, and mold additives. These constituents can inhibit adhesion of the asphalt cement binder to the foundry sand. Clay clumps can be removed by screening and/or washing, while iron and rubbish can be removed with magnets and/or hand separation.

Although recycled foundry sand can be successfully incorporated into asphalt designs, large variability can exist between sands. Each sand should be treated as a unique source of aggregate (Tikalsky et al 2004). Foundry sand containing bentonite can be processed to reduce the fine content that affects performance

Conventional AASHTO pavement design methods are appropriate for asphalt paving incorporating foundry sand as fine aggregate. The same methods and equipment used for conventional HMA pavement are applicable to pavements containing foundry sand. If the foundry sand is dry (less than 5 percent moisture), the sand can be metered directly into a pugmill (batch plants only) or through a recycled asphalt feed (drum plants) where the sand can be further dried, by the already heated conventional aggregates (D'Allesandro et al 1990). The presence of bentonite and organic binder materials can increase the time required for drying and can increase the load on the hot mix plant dust collection system. Any coal and organic binders that are present are usually combusted in the process.

The same field testing procedures used for conventional HMA mixes should be used for mixes containing foundry sand. Mixes should be sampled in accordance with AASHTO T 168 (AASHTO 2003c), and tested for specific gravity in accordance with ASTM D2726 and in-place density in accordance with ASTM D2950.

Flowable Fill

Natural sand is a major component of most flowable fill mixes. Foundry sand can be used as a replacement for natural fine aggregate because foundry sand consists of greater than 80 percent fine uniform silica sand. foundry sand has been used in flowable fill in the states of New York, Pennsylvania, Ohio, Wisconsin, Tennessee, and Indiana (Smith 1996, Collins and Ciesielski 1994). Pennsylvania has reported successful use of foundry sand as a sand substitute in flowable fill, as well as Ohio where a field demonstration showed performance on par with conventional sand flowable fills (Smith 1996).

Flowable Fill Design Considerations: Some of the engineering properties of foundry sand that are of particular interest in flowable fill applications are summarized in Table 6.

Structural design procedures for cured flowable fill materials are no different than geotechnical design procedures for conventional earth backfill materials. The same methods and equipment used to mix, transport, and place flowable fill made with conventional aggregates may be used for flowable fill incorporating foundry sand. Additionally, flowable fill made with foundry sand can be produced at a central concrete mixing plant in accordance with ASTM C94 and delivered by concrete truck mixers or using a mobile, volumetric mixer for small jobs.

Portland Cement Concrete

The use of foundry sand in Portland cement concrete mixtures is an emerging application area. Published research and case studies on this subject are limited. As such, the use of foundry sand for this application is not well documented, and any use of foundry sand in Portland cement concrete should be considered somewhat experimental.

Portland cement concrete is a commonly used paving material that consists of approximately 45 percent coarse aggregate, 25 percent fine aggregate, 20 percent cement and 10 percent water (Federal Highway Administration 2004). Foundry sand has been shown to replace some fine aggregate portion of concrete mixtures (Federal Highway Administration 2004).

Portland Cement Concrete Design Considerations: Various characteristics of foundry sand can affect the quality of concrete produced. Because foundry sand properties vary depending on the source from which the foundry sand was produced, it is important that adequate testing of the sand is performed. The material characteristics that are most relevant in Portland cement applications are summarized in Table 7.

Prior to reuse, foundry sand should be screened and crushed to obtain the desired gradation, and magnetic particles should be separated. These processes will remove deleterious materials preventing technical problems when mixing the cement components.

Foundry sand from green sand molding is black or gray and may cause finished concrete to have a slightly darker grayish/black tint. A 15 percent or less fine aggregate replacement with foundry sand typically produces a minimal color change.

Foundry sand can be used in combination with all types of cementitious materials including mixes containing chemical admixtures (Zirschky and Piznar 1988). Retarders and water reducers are compatible with most foundry sands. As with natural sands, any organic material in the foundry sand may affect the dosage and effectiveness of air entraining agents. Trial mixtures should be examined for any potential compatibility problems.

END USER RESOURCES

Several resources are available to end users interested in incorporating foundry sand into construction applications. The RMRC website contains a foundry sand portal that includes information on standards, links, publications, case studies, and webinars related to using foundry sand in construction applications. An elaboration on the user guidelines presented in this paper is also available. The RMRC website can be accessed at www.recycledmaterials.org. The Foundry Sand Portal is available under the "Materials" tab.

The American Foundry Society and Foundry Industry Recycling Starts Today (AFS-FIRST) website contains the most up-to-date information on foundry sand recycling, including technical documents, case studies, recent news, and links to companion organizations. AFS-FIRST can be accessed at **www.afsinc.org/first** or via www.foundryrecycling.org.

Currently, there are around 2000 active foundry operations in the United States that generate over 9 million tons of foundry sand per year (American Foundry Society 2007). Foundry sand is commonly obtained directly from foundries, many of which are located in the Great Lakes region. Other states with a large concentration of foundries include: Alabama, California, Louisiana, Tennessee, and Texas (EPA 2002a). An easy-to-use mapping tool developed by the American Foundry Society is available at http://www.afsinc.org/component/option,com_wrapper/Itemid,254 to assist end users in locating foundries near construction projects.

State regulations of foundry sand reuse are guided by the concept of ensuring the protection of human health and the environment. Rules guiding foundry sand reuse vary from state to state. The U.S. EPA maintains a "Foundry Sand State Reuse Resource Locator" that can be accessed directly at http://www.envcap.org/statetools/fsand/ or via the AFS-FIRST website, under the Environmental page. Regulations guiding the reuse of foundry sand in ten states (Illinois, Indiana, Louisiana, Maine, Michigan, New York, Pennsylvania, Texas, West Virginia, and Wisconsin) can be found in the State Toolkit for Developing Beneficial Reuse Programs for Foundry Sand published by EPA (2006). The toolkit is found at http://www.epa.gov/sectors/sectorinfo/sectorprofiles/metalcasting/foundry.html.

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Table 1. Typical physical properties of spent green foundry sand.

Property	Results	Test Method
Specific Gravity[1,2,3]	2.39 - 270	ASTM D854-06
Bulk Relative Density, lb/ft^3 [4]	160	AASHTO T 084
Absorption, %[1]	0.76 - 6.20	ASTM C128-07a
Moisture Content, %[1,2,3]	0.1 - 15.0	ASTM D2216-05
Clay Lumps and Friable Particles, %[3,5]	1-44	ASTM C142-97
		AASHTO T 112
Hydraulic Conductivity (cm/sec)[1,6,7,8]	10^{-3} - 10^{-9}	ASTM D2434-68
		ASTM D5084-03
		AASHTO T 215
Plastic Index[2,3]	Nonplastic to 12	ASTM D4318-05
		AASHTO T 090

[1] Federal Highway Administration (2004), [2] Goodhue et al (2001), [3] Javed and Lovell (1994ab), [4] Johnson (1981), [5] American Foundrymen's Society (1991), [6] Abichou and Benson (2000), [7] Abichou et al (2002), [8] Dungan et al (2007)

Table 2. Typical mechanical properties of spent foundry sand.

Property	Results	Relevant Test Method
Micro-Deval Abrasion Loss, %[1]	< 2	ASTM D6928-06
Magnesium Sulfate Soundness Loss, % [2,3]	5-15	ASTM C88-05
Internal friction angle (drained)[1,4,5,6]	33° - 43°	ASTM D4767-04
		ASTM D 3080
Cohesion intercept (drained), lb/ft2 [1,4,5,6]	145-585	ASTM D4767-04
		ASTM D 3080
Unconfined compressive strength, lb/ft2 [7]	482-3968	ASTM D 2166
California Bearing Ratio, %[5,7]	4 - 20 average 20	ASTM D1883-05
Resilient Modulus (M_R) Regression Coefficients[7]	K_1 = 122,000 – 248,000 lb/ft^2	AASHTO T-294-94
	K_2 = 0.44 - 0.56	

[1] Goodhue et al (2001), [2] American Foundrymen's Society (1991), [3] Emery (1992), [4] Winkler and Bol'shakov (2000), [5] Javed and Lovell (1994ab), [6] Goodhue et al (1998), [7] Kleven et al (2000)

Table 3. Design parameters for foundry sand in subbase applications.

Design Parameter	Foundry Sand Performance	Relevant Test Method	Considerations
California Bearing Ratio, %[1,2]	4 - 20 average 20	ASTM D1883-05	
Unconfined Compressive Strength, lb/ft2 [2]	482-3968	ASTM D 2166	Guney et al (2006) reported the addition of lime or cement will increase the unconfined compression and CBR of fully hydrated specimens.
Resilient Modulus (M_R) Regression Coefficients	K_1 = 122,000 – 248,000 lb/ft^2	AASHTO T-294-94	
	K_2 = 0.44 - 0.56		

[1] Javed and Lovell (1994ab), [2] Kleven et al (2000)

Table 4. Design parameters for foundry sand in embankment applications.

Design Parameter	Foundry Sand Performance	Relevant Test Method
Specific Gravity[1,2,3]	2.39 – 2.70	ASTM D854-06
Bulk Relative Density, lb/ft^3 [4]	160	AASHTO T 084
Standard Proctor Max Dry Density, lb/ft^3 [3,5]	109	AASHTO T 085
Optimum Moisture Content, %[3,5]	~ 12%	ASTM D2216-05
Hydraulic Conductivity (cm/sec)[1,6,7,10]	10^{-3} - 10^{-9}	ASTM D2434-68
		ASTM D5084-03
		AASHTO T 215
Plastic Index[2,3]	Nonplastic to 12	ASTM D4318-05
		AASHTO T 090
Internal friction angle (drained)[2,3,8,9]	33° - 43°	ASTM D4767-04
		ASTM D 3080
Cohesion intercept (drained), lb/ft2 [2,3,8,9]	145-585	ASTM D4767-04
		ASTM D 3080

[1] Federal Highway Administration (2004), [2] Goodhue et al (2001), [3] Javed and Lovell (1994ab)[4] Johnson (1981), [5] Guney et al (2006), [6] Abichou and Benson (2000), [7] Abichou et al (2002), [8] Winkler and Bol'shakov (2000), [9] Goodhue et al (1998), [10]Dungan et al (2007)

Table 5. Design parameters for foundry sand in Hot Mix Asphalt applications.

Design Parameter	Standard Requirement	Foundry Sand Performance	Relevant Test Method	Considerations
Absorption, %[1]		0.76 - 6.20	ASTM C128-07a	
Plastic Index[2,3,7]	< 4	Nonplastic to 12	ASTM D4318-05 AASHTO T 090	The plasticity index of spent foundry sand should be determined before using in asphalt mix.
Magnesium Sulfate Soundness Loss, % [4,5]	< 20	5-15	ASTM C88-05	The greater amount of clay binder or agglomeration, or the thicker the coatings, the higher the soundness loss.
Particle Size and Gradation	P16 - 85 to 100	P16 - 100[6]		Crushing and screening of spent foundry sand may be necessary to reduce the size of uncollapsed molds prior to use as aggregate. This can be achieved using conventional aggregate processing equipment such as closed loop crushing and screening process equipped with magnetic separating capabilities.
	P30 - 65 to 90	P30 - 85 to 95	AASHTO T 88	
	P50 - 30 to 60	P50 - 85 to 95	AASHTO M29	
	P100 - 5 to 25	P100 - 5 to 15	ASTM D1073	
	P200 - 0 to 5	P200 - 0.9 to 16.5		
	Well Graded	Poorly Graded		
Angularity	Min 40 for low to medium traffic Min 45 for high traffic[6]	39.4 to 48	AASHTO T 33	
Stripping	Varys with Test	See Considerations	AASHTO T 283 AASHTO T 182 AASHTO T 195 MTO LS-283	Stripping can be mitigated by limiting spent foundry sand in the mix to 15% total mass of aggregate or using an antistripping additive such as hydrated lime[6]
Organic Content	Limited		AASHTO T 267	

[1] Federal Highway Administration (2004), [2] Goodhue et al (2001), [3] Javed and Lovell (1994ab), [4] American Foundrymen's Society (1991), [5] Emery (1992), [6] Miller et al (2001), [7] Abichou et al (1998)

Table 6. Design parameters for foundry sand in flowable fill applications.

Design Parameter	Standard Requirement	Foundry Sand Performance	Relevant Test Method	Considerations
Target Flow	230 mm ± 5 mm or 9 in ± 0.2 in [9]	See considerations	ASTM D 6103	Bentonite content >10% can impede flow causing an increase in water requirements. For bentonite contents greater than 6 percent, no fly ash is necessary because the bentonite will be sufficient to prevent segregation.
Particle Size and Gradation	P8 - 80 to 100	P8 - 100[1]	AASHTO T 88	Spent foundry sand may not satisfy the gradation requirements, the uniform, spherical nature of the particles produces a relatively free-flowing mixture.
	P16 - 50 to 85	P16 - 100		
	P30 - 25 to 60	P30 - 85 to 95		
	P50 - 5 to 30	P50 - 85 to 95	ASTM C33	
	P100 - 0 to 10	P100 - 5 to 15		
	Well Graded	Poorly Graded		
Magnesium Sulfate Soundness Loss, %		5-15[2,3]	ASTM C88-05	More clay binder or agglomeration, or the thicker the coatings, the higher the soundness loss.
Corrosivity (pH)	<5.5	4-12[3,4]	AASHTO T 33	Each source of foundry sand should be analyzed separately due to the variability of pH.
28 day Unconfined Compressive Strength	1400 kPa or 200 lb/in^2		ACI Committee 229	S_c is the 28-day unconfined compressive strength in kPa and W/C is the water-cement ratio.
			ASTM D 4842	
Hydraulic Conductivity (cm/sec)		10^{-3} - 10^{-9} [6,7,8,10]	ASTM D2434-68	
			ASTM D5084-03	
			AASHTO T 215	
Organic Content	Limited		AASHTO T 267	Organic content interferes with hydration of the cement and subsequent strength.

[1] Miller et al (2001), [2] American Foundrymen's Society (1991), [3] Emery (1992), [4] Johnson (1981), [5] Bhat and Lovell (1996), [6] Abichou and Benson (2000), [7] Abichou et al (2002), [8] Federal Highway Administration (2004), [9] Dingrando et al (2004), [10] Dungan et al 2007

Table 6. Design parameters for foundry sand in Portland Cement-Concrete applications.

Design Parameter	Standard Requirement	Foundry Sand Performance	Relevant Test Method	Considerations
Particle Size and Gradation	P4 - 85 to 100	P4 - 100[1]	AASHTO T 88	Spent foundry sand may not satisfy the gradation requirement. P200 material reduces the durability of hardened concrete. Fine aggregate should have <5% P200 material.
	P16 - 40 to 80	P16 - 100		
	P50 - 10 to 35	P50 - 85 to 95		
	P100 - 5 to 25	P100 - 5 to 15	ASTM C330/C330M	
	P200 - 0 to 5	P200 - 0.9 to 16.5		
		Poorly Graded		
Magnesium Sulfate Soundness Loss, %		5-15[2,3]	ASTM C88-05	The greater amount of clay binder or agglomeration, or the thicker the coatings, the higher the soundness loss
Clay Lumps and Friable Particles	<2%	1-44%[2,4]	ASTM C142-97	
			AASHTO T 112	
			ASTM C330/C330M	
Organic Content	Limited		AASHTO T 267	Organic content interferes with hydration of the cement and subsequent strength.
Fineness Modulus	2.3 to 3.1	0.9 to 1.6[5]	ASTM C33	Foundry sand has to be blended with a coarser material to meet specification. In some areas, natural sands lack finer material such that Foundry sand can be blended with them as a partial replacement to satisfy specification.

[1] Miller et al (2001,) [2] American Foundrymen's Society (1991), [3] Emery (1992), [4] Federal Highway Administration (2004), [5] Javed and Lovell (1994)

The Use of Tire-Derived Aggregate in Road Construction Applications

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Abstract

The use of shredded scrap tires (also referred to as tire-derived aggregate: TDA) in civil engineering applications has three major advantages: shredded tires (TDA) have engineering properties that are beneficial to civil engineers; TDA is often the lowest cost material that can provide the engineering properties sought and TDA can use large-scale numbers of scrap tires. The use of TDA could provide a much-needed, large-scale market where few other viable end uses for scrap tires exist.

Tire-derived aggregate can be used in a wide range of highway uses and is currently one of the three major markets for scrap tires. In 2007, an estimated 561.6 thousand tons of TDA was used in this market; about 12 percent of the total number of tires that went to an end use market (RMA, 2009). Furthermore, tire shreds have been shown to have a negligible impact on groundwater quality.

This paper will present the special properties of tire shreds that drive engineering applications. Examples will be given of projects where tire shreds were used as lightweight fill for highway embankment construction, bridge abutment backfill and as a thermal insulation to limit frost penetration beneath roads. The guidelines to limit heating and water quality effects of tire shreds will be discussed. From the information presented below, it will be clear that the use of TDA can benefit civil engineering projects and can play a key role in putting this nation's scrap tires to a productive reuse.

SPECIAL PROPERTIES OF TIRE SHREDS

Tire shreds have several special properties that civil engineers can use to solve difficult design situations. The most important property is that tire shreds are lightweight. The in-place unit weight of tire shreds is between 45 and 58 pounds per cubic foot – even after they have been compressed under the weight of overlying fill. For comparison, soil fill typically weighs 125 pounds per cubic foot. This makes tires shreds an excellent lightweight fill material. Civil engineers need lightweight fill to improve the stability of embankments built on weak soils and to help stabilize landslides. Tire shreds also produce a low horizontal stress and they are compressible. Thus, when they are used as fill behind walls, they produce lower horizontal pressure on the back side of the wall. This allows civil engineers to design thinner, less costly walls.

Tire shreds are very free draining. Even when they are compressed under the weight of overlying fill, they still have a permeability greater than 1 cm/sec. With a permeability this high, tire chips can be used as drainage layers in landfills and roads. A useful property of tire shreds is that they have a high insulating value. The thermal conductivity of tire shreds with a 3-in. maximum size is about 0.14 Btu/hr·ft·°F. This is seven times better than soil, which typically has a thermal conductivity of about 1 Btu/hr·ft·°F. When combined with their good drainage properties, this means that tire shreds can be used to limit frost penetration beneath roads and to remove excess water during the spring thaw.

Due to the special properties of tire shreds together with their wide-spread availability, they have been used as lightweight fill for numerous highway embankments and landslide stabilization projects, backfill behind bridge abutments, insulation and drainage layers beneath roads, and drainage layers in landfill liners and caps. Example projects in each category are discussed in the following sections.

HIGHWAY APPLICATIONS

Lightweight Fill

Tire shreds were used as lightweight fill for construction of two 32-ft high highway embankments in Portland, Maine (Humphrey, et al., 1998). These embankments were the approach fills to a new bridge over the Maine Turnpike. The bridge is part of a new interchange that will provide better access to the Portland Jetport and Congress Street. This site was underlain by about 40 ft of weak marine clay. The designers for the project (the Maine offices of HNTB, Inc. and Haley and Aldrich, Inc. and the University of Maine) found that embankments built of conventional soil were too heavy resulting in an unacceptably low factor of safety against slope instability. They looked at several ways to strengthen the foundation soils but these were too costly. What they really needed was to make the embankment lighter. They considered several types of lightweight fill including tire shreds, expanded polystyrene insulation boards, and expanded shale. Tire shreds were chosen because they were $300,000 cheaper than the other alternatives. Moreover, the project would put some 1.2 million tires to a beneficial end use.

Several steps were taken to comply with the guidelines to limit heating of thick tire shred fills (Ad Hoc Civil Engineering Committee, 1997; ASTM, 1998). The guidelines required that a single tire shred layer be no thicker than 10 ft, so the tire shred layer was broken up into two layers, each up to 10 ft thick, separated by 3 ft of soil as shown in Fig. 1. Low-permeability soil with a minimum of 30% fines (passing the no. 200 sieve) was placed on the outside and top of the fill to limit inflow of air and water. The final precaution to limit heating was to use large shreds with a minimum of fines. The shreds had less than 25% passing the 1½-in. sieve and less than 1% passing the No. 4 (approx.

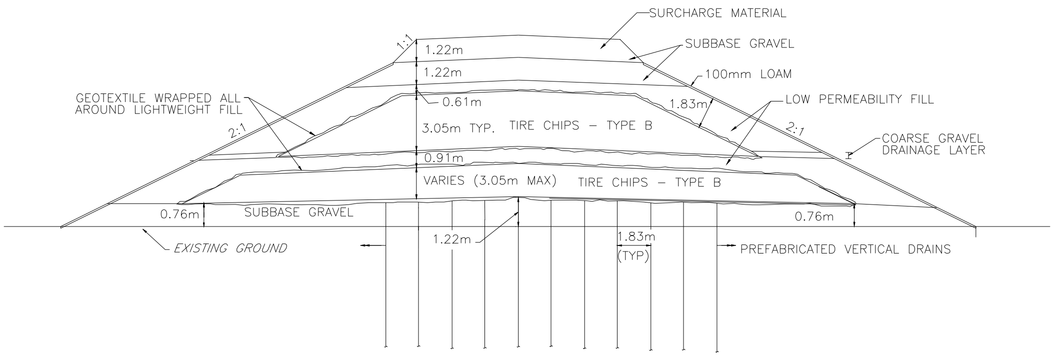


Fig. 1 Cross section through embankment constructed on soft marine clay for the Portland Jetport Interchange (Humphrey, et al., 1998).

¼-in.) sieve. The guidelines are discussed in more detail in a later section. The shreds had a maximum size measured in any direction of 12 in. to ensure that they could be easily placed with conventional construction equipment. The embankment was topped with 4 ft of granular soil plus 4 ft of temporary surcharge. The purpose of the surcharge was to increase the rate of consolidation of the soft clay foundation soils and was unrelated to the tire shred fill.

The tires for this project came from an abandoned stockpile in Durham, Maine. The Maine Turnpike Authority and the Maine Department of Environmental Protection shared the cost to produce the shreds and deliver them to the construction site. The tire shreds were produced by J.P. Routhier & Sons of Ayer, Mass. and Arthur Schofield, Inc. of Lancaster, Mass. At peak production, they had four shredding machines at the stockpile site. The machines had knife spacings ranging from 2 to 6 in. A rotating screen (called a trommel) with 6-in. square holes was used to capture pieces that exceeded the 12-in. maximum length criterion for recirculation back through the shredders. The source tires contained a significant amount of extraneous soil, so as the last step, tire shredding contractors had to use a trommel with a ½-in. screen to produce shreds with less than 1% passing the No. 4 sieve.

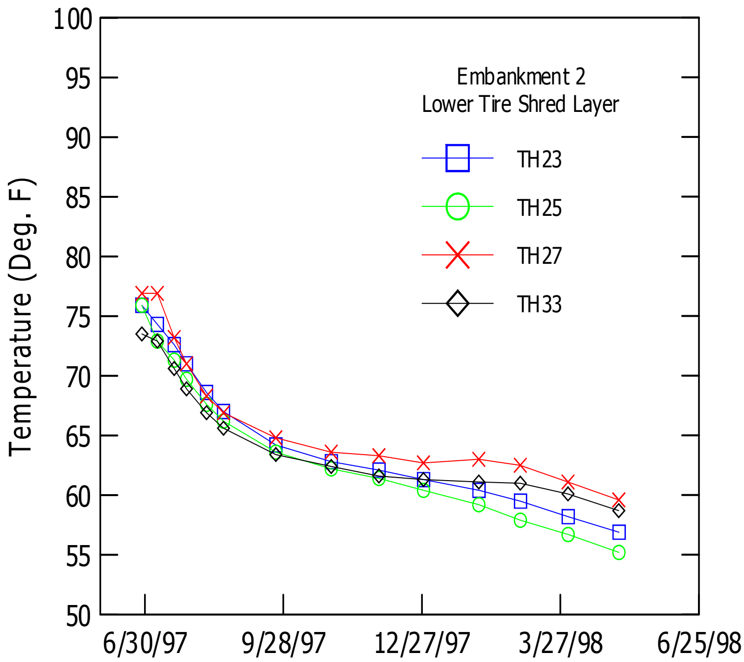
The tire shreds were placed with conventional construction techniques. First geotextile was placed on the prepared base to act as a separator between the tire shreds and surrounding soil. Then the tire shreds were spread in 12-in. thick lifts using a Caterpillar D-4 dozer as shown in Fig. 2. Each lift was compacted with six passes of a vibratory roller with a minimum 10-ton operating weight. After placing the shreds, the contractor placed a geotextile separator on the sides and top of the tire shred zone. Finally, the surrounding soil cover was placed.

Monitoring the temperatures of the tire shred fill was of great interest because of past problems with heating of thick tire shred fills (Humphrey, 1996). The warmest temperatures were measured at the time of placement when the black tire shreds were heated by exposure to direct sunlight. Initial temperatures ranged from 75 to 100 °F. After being covered with the first few lifts of fill, the temperatures began dropping with time. Temperatures were still dropping when monitoring was discontinued in April, 1998. Typical temperature measurements are shown on Fig. 3. From these results it can be seen that there was no evidence of self-heating.

Fig. 2 Catipillar D-4 spreading tire shreds for lightweight embankment fill at Portland Jetport Interchange

Fig. 3 Temperatures in lower tire shed layer of lightweight embankment fill at Portland Jetport Interchange.

Retaining Wall Backfill



There are many reasons a civil engineer would choose tire shreds as backfill for retaining walls. They are lightweight so they produce low horizontal pressure on the back side of the wall. Moreover, they are free draining so there is no problem with water pressure building up behind the wall and they are a good insulator so they prevent difficulties with frost action. Tire shreds have been used in this application in a test wall constructed at the University of Maine (Tweedie, et al., 1998a,b) and behind the north abutment of the Merrymeeting Bridge in Topsham, Maine (Whetten, et al., 1997; Humphrey, et al., 1998; Cosgrove and Humphrey, 1999). However, a unique application is using the compressibility of tire shreds to reduce the pressure on a rigid frame bridge. This was done for a project constructed in Topsham, Maine and will be described in the following paragraphs.

Most retaining walls and bridge abutments are designed to move outward an inch or so as the backfill it placed. This small movement allows the soil backfill to develop its strength thereby reducing the horizontal pressure on the wall. However, for rigid frame bridges, the tops of the abutment walls are connected together with a concrete slab so they are prevented from moving away from the backfill. In addition, movement of the base of the abutment is restricted by batter piles (piles driven at an angle) or a concrete base slab. These were the challenges faced by the Maine offices of T.Y. Lin International, and Haley and Aldrich with the assistance of the University of Maine as they designed a rigid frame bridge that would carry Route 196 over an existing rail line in Topsham, Maine.

The rigid frame bridge spans a single track railroad providing a 25 ft wide by 23 ft high opening for rail traffic. Approach fills were up to 36 ft high. The road alignment intersects the railroad at an acute 24-degree angle. This necessitated a bridge with a 305-ft width. Overall, the bridge resembles a long tunnel.

The designers were faced with a choice. Since the abutment walls could not move away from the backfill, a conventional design would call for the walls to resist relatively high “at-rest” horizontal pressures. A cheaper alternative would be to find a way to allow the soil backfill to move an inch or so toward the abutments. The solution was a 3-ft wide zone of tire shreds placed against each abutment wall as shown in Fig. 4. The tire shred zones would provide enough compressibility to allow the adjacent soil backfill to move toward the bridge, lowering the stress on the wall to “active” pressures. This allowed the designers to use abutment walls with less steel reinforcement and concrete (Whetten, et al., 1997; Humphrey, et al., 1998; Cosgrove and Humphrey, 1999).

The tire shreds for this project had a maximum size of 3 in. This size was preferable since each lift of shreds would need to be hand leveled prior to compaction. Moreover, self-heating of a 3-ft wide zone was not a concern, so there was no reason to use larger size shreds. Even though the tire shred zone was only 3 ft wide, the project used some 100,000 tires. The sources for the tire shreds were abandoned stockpiles and recently generated scrap tires.

Construction started by placing a geotextile to act as a separator between the tire shreds and adjacent soil. Tire shreds and adjacent granular borrow were raised in 8-in. lifts. The shreds were placed with a front end loader as shown in Fig. 5. Each lift was

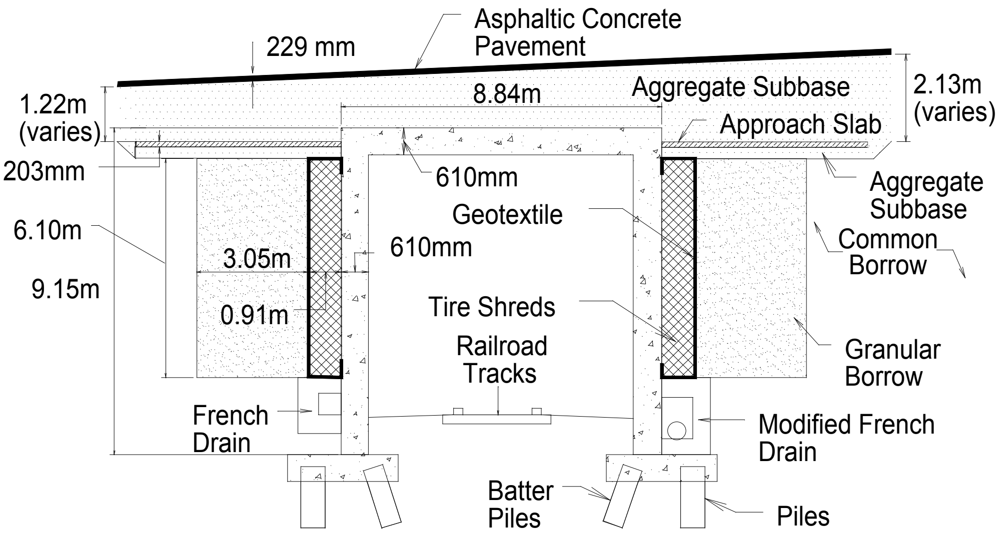


Fig. 4 Tire shreds used as compressible backfill for rigid frame bridge on Topsham-Brunswick By-Pass project constructed in 1996 by the Maine DOT

Fig. 5 Placing tire shreds using front end loader for rigid frame bridge.

compacted by four passes of a walk-behind roller with an operating weight of 2750 lb. In retrospect, it would have been acceptable to use 12-in. thick lifts.

The tire shred zone significantly reduced the horizontal pressure on the backs of the abutment walls. Pressures were measured with pressure cells mounted in the concrete walls. At each of two vertical sections there were three pressure cells with tire shreds as backfill and one with soil backfill. The pressures recorded by cells at one section are shown in Fig. 6. The pressures are dramatically lower for the cells with tire shred backfill showing the benefit of using tire shreds as bridge abutment backfill.

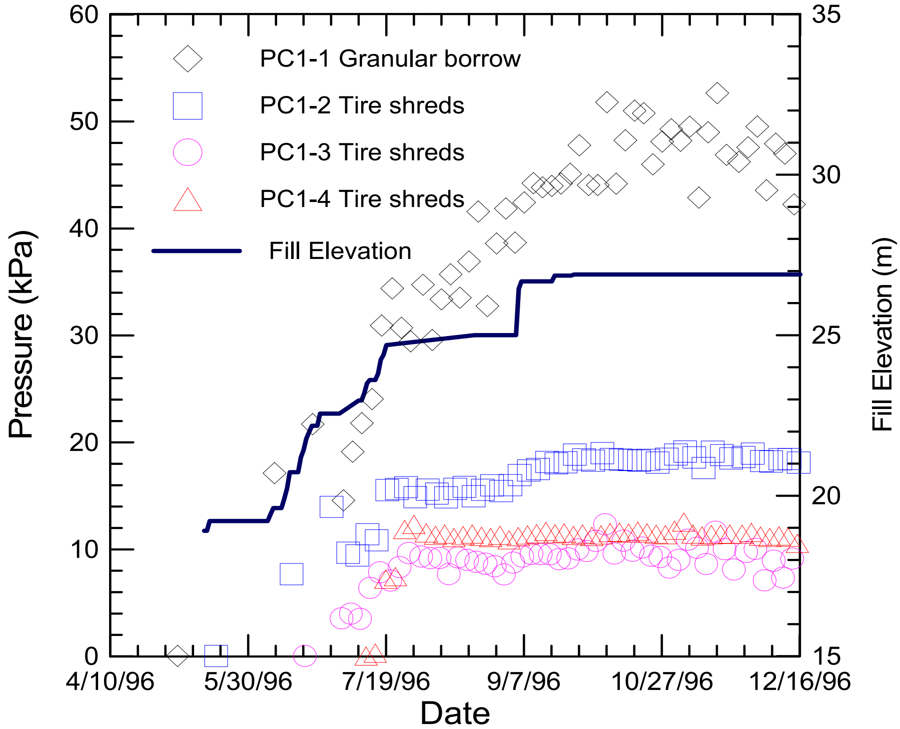


Fig. 6 Horizontal stress as measured by the pressure cells and approximate fill elevation versus date (Humphrey, et al., 1998).

Insulation to Limit Frost Penetration

Frost penetration beneath roads in northern climates can be very destructive. When silty soils are frozen, water is drawn up from the water table creating lenses of ice that can be more than an inch thick. This causes heave of the road that can produce an uneven driving surface and crack the pavement. In some cases, the total amount of heave can be greater than 5 inches (Humphrey, et al., 1995). In the spring, the ice lenses melt, releasing their water to the road surface. This excess water weakens the road subbase leading to rutting of gravel surfaced roads and pavement cracking in paved roads. Over the long term, the damage caused by frost action greatly increases roadway maintenance costs. What is needed is a material that has good insulating properties and is free draining. That material is tire shreds. Tire shreds are a seven-times better insulator and are more permeable than gravel. Tire shreds have been used as subgrade insulation for projects in Maine, Vermont, and Quebec (Humphrey, et al., 1995; Frascoia and Cauley, 1995; Dore, et al., 1995; Lawrence, et al., 1998). A project constructed in Orono, Maine will be given as an example.

A test section using tire shreds as insulation and drainage was constructed on the Witter Farm Road on the University of Maine campus in Orono, Maine. This dead-end road provides access to one of the University's research farms and carries truck traffic with some cars. Two thicknesses of tire shreds (6 and 12 in.) and two thicknesses of overlying subbase gravel cover (13 and 19 in.) were used. There are also sections with 12 in. of 33%/67% and 67%/33% mixtures of tire shreds and gravel. Mixtures were based on the approximate volume of tire shreds and gravel. The mixture sections are topped with 19 in. of subbase gravel. The tire shreds for this project had a 3-in. maximum size. This size is preferable for insulation applications since it appears that larger size shreds have a lower insulating value. All the sections are topped with 5 in. of asphalt pavement. A tire shred filled edge drain was constructed beneath one shoulder of the road. A typical cross section is shown in Fig. 7.

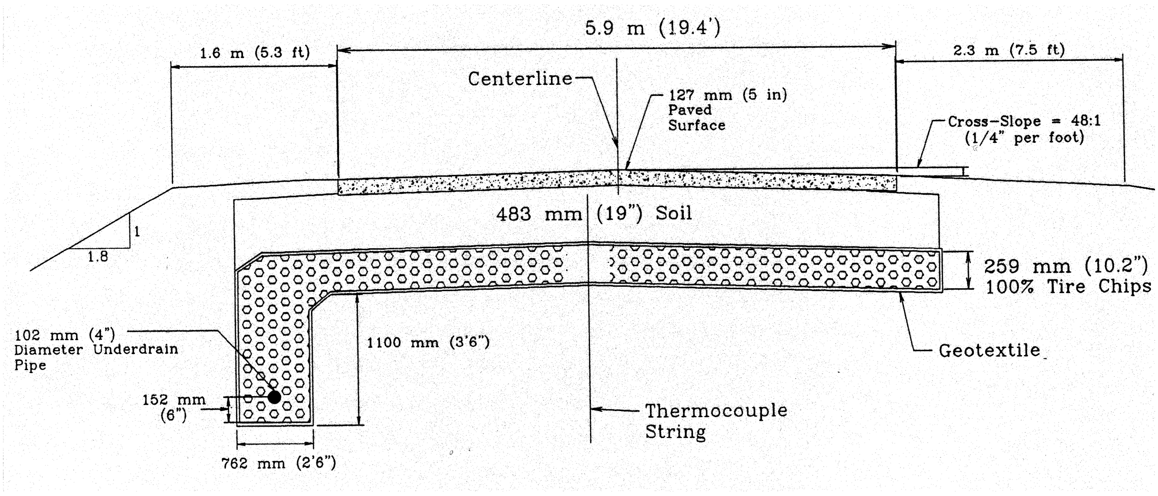


Fig. 7 Typical cross section using tire shreds for insulation and drainage on Witter Farm Road.

This was a "low-budget" project so the author and his students did all the construction except for the first and the last steps. The first step was excavation and removal of the existing road surface in preparation for tire shred placement. This was done by an outside contractor. The next step was to unroll geotextile on the exposed subgrade and in the edge drain trench. The geotextile acts as a separator, preventing the surrounding soil from washing into the tire shreds over time. Next came placement of the tire sheds and tire shred/gravel mixtures. The shreds were hauled to the site in a 3-ton capacity dump trailer and spread either by hand or with a small farm tractor. Compaction in the trench was accomplished by dropping a 700-lb block on each 12-in. lift or by a walk-behind roller as shown in Fig. 8. Compaction across the width of the roadway was accomplished with six passes of a vibratory roller with a 12-ton operating weight. Next came the overlying geotextile and subbase gravel. The final step was paving which consisted of a 3½-in. thick hot-mix bituminous base course followed by a 1½-in. thick wearing course. The fact that a college professor and his students constructed this project illustrates how straightforward it can be to use tire shreds as subgrade insulation and drainage.

The effectiveness of using tire shreds as subgrade insulation is shown in Fig. 9. This figure shows that the 12 in. thickness of 100% tire shreds in Sections 3 and 5 prevented the frost from penetrating beneath the tire shred layers. Some frost penetrated into the subgrade soils in Section 4, which had only 6-in. of 100% tire shreds. Thus, a 12-in. thickness of shreds is needed to provide complete protection of subgrade soils for climates similar to those in eastern Maine. Section 2, which had 12 in. of a mixture of 67% tire shreds/33% soil, and Section 1, which had 12 in. of a 33%/67% mixture, allowed frost to penetrate into subgrade soils showing that the mixtures provide less

Fig. 8 Placing and compacting tire shreds in edge drain for Witter Farm Road.

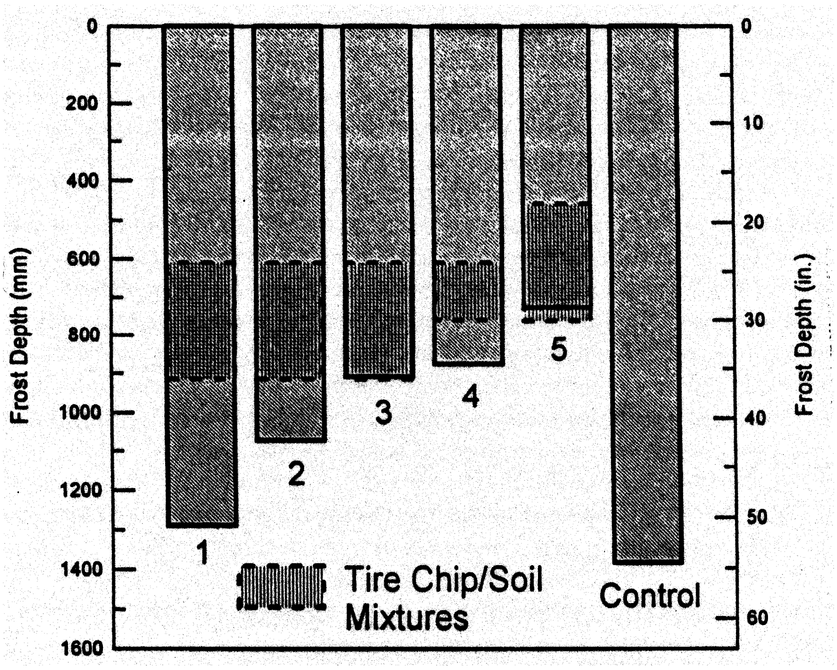


Fig. 9 Maximum depth of frost penetration for winter of 1996/7 in the Witter Farm Road test project (Lawrence, et al., 1998).

insulation than 100% tire shreds. A control section with a conventional gravel subbase had 54 in. of frost penetration, which is nearly twice as much as Section 5 with 12-in. of 100% shreds. Moreover, heave of the road surface was three times greater in the control section than in Section 5. These results show that tire shreds are effective both at reducing frost penetration and frost heave.

Guidelines to Limit Heating

Three thick tire shred fills (greater than 26 ft thick) have undergone a self-heating reaction. Two of these projects were located in Washington State and one was in Colorado. These projects were constructed in 1995 and each experienced a serious self heating reaction within 6 months after completion (Humphrey, 1996). The lessons learned from these projects were condensed into design guidelines developed by the Ad Hoc Civil Engineering Committee (1997), a partnership of government and industry dealing with reuse of scrap tires for civil engineering purposes. The guidelines were subsequently published by ASTM (1998). For tire shred layers ranging in thickness from 3.3 to 10 ft, the guidelines give the following recommendations:

- Tire shreds shall be free of contaminants such as oil, grease, gasoline, diesel fuel, etc., that could create a fire hazard
- In no case shall the tire shreds contain the remains of tires that have been subjected to a fire
- Tire shreds shall have a maximum of 25% (by weight) passing 1½-in. sieve
- Tire shreds shall have a maximum of 1% (by weight) passing no. 4 (4.75-mm) sieve
- Tire shreds shall be free from fragments of wood, wood chips, and other fibrous organic matter
- Tire shreds shall have less than 1% (by weight) of metal fragments that are not at least partially encased in rubber
- Metal fragments that are partially encased in rubber shall protrude no more than 1 in. from the cut edge of the tire shred on 75% of the pieces and no more than 2 in. on 100% of the pieces
- Infiltration of water into the tire shred fill shall be minimized
- Infiltration of air into the tire shred fill shall be minimized
- No direct contact between tire shreds and soil containing organic matter, such as topsoil
- Tire shreds should be separated from the surround soil with a geotextile
- Use of drainage features located at the bottom of the fill that could provide free access to air should be avoided

The guidelines further recommend that a tire shred layer be no greater than 10 ft thick. The guidelines also give less stringent requirements for tire shred layers less than 3.3 ft thick (Ad Hoc Civil Engineering Committee, 1997; ASTM, 1998).

WATER QUALITY EFFECTS

Several studies have shown that tire shreds can be used in most applications with negligible effects on ground water quality. Humphrey, et al. (1997), studied the effect of tire shreds placed above the water table in a test project in North Yarmouth, Maine. In this study, two 10 ft x 10 ft geomembrane-lined collection basins are used to collect water after it has passed through a 2-ft thick layer of tire shreds. A third basin is overlain only by soil and serves as a control. Water samples have been taken quarterly since January, 1994. Samples were analyzed for metals with primary and secondary drinking water standards[1]. For metals with a primary drinking water standard, the levels are about the same for basins overlain by tire shreds compared to the control basin overlain by soil. As and example, the results for chromium (Cr) are shown in Fig. 10. Similar results were found for metals with secondary (aesthetic) standards except for manganese (Mn) and, to a lesser extent, iron (Fe). Manganese consistently had higher levels in the basins overlain by tire shreds compared to the control basin (Fig. 11). The source of the manganese is thought to be the exposed steel belts, which contain 2 to 3% manganese by weight. On some sampling dates, iron was higher in the basins overlain by tire sheds as shown in Fig. 12. Volatile and semi-volatile organics were tested on two dates. On both dates all substances were below the test method detection limits. Similar results for metals and organics were found for the Witter Farm test project (Humphrey, 1999a).

[1] Metals with a primary standard are a known or suspected health risk. Metals with a secondary standard are of aesthetic concern, which means that they may impart some taste, odor, and/or color to water but they do not pose a health risk.

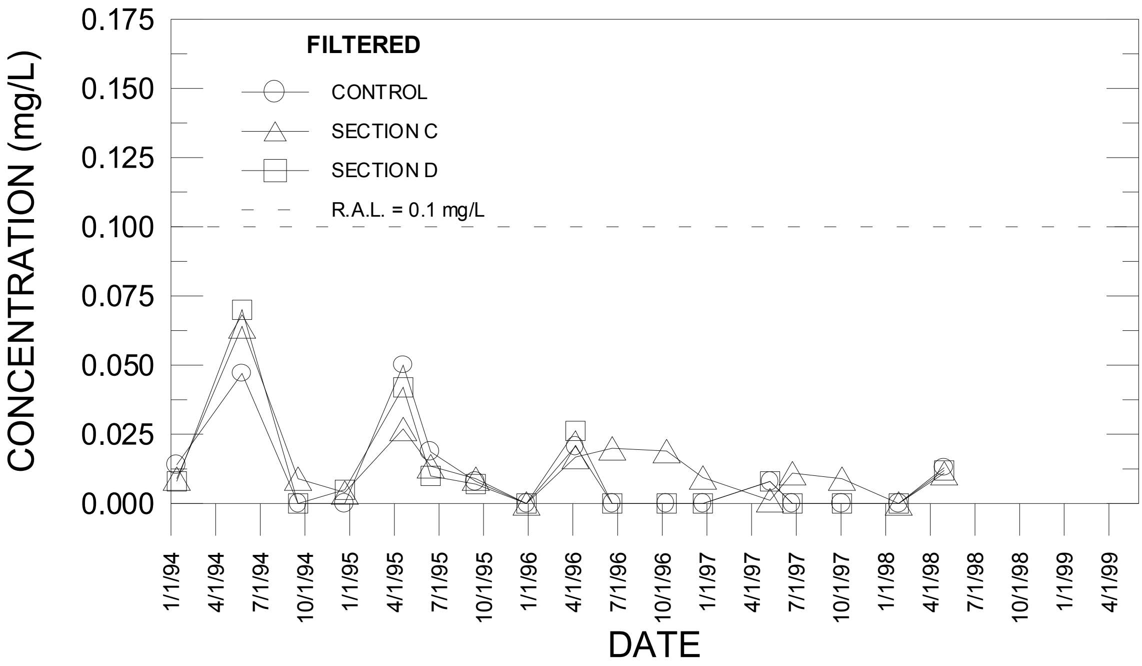


Fig. 10 Chromium levels for filtered samples at North Yarmouth field trial.

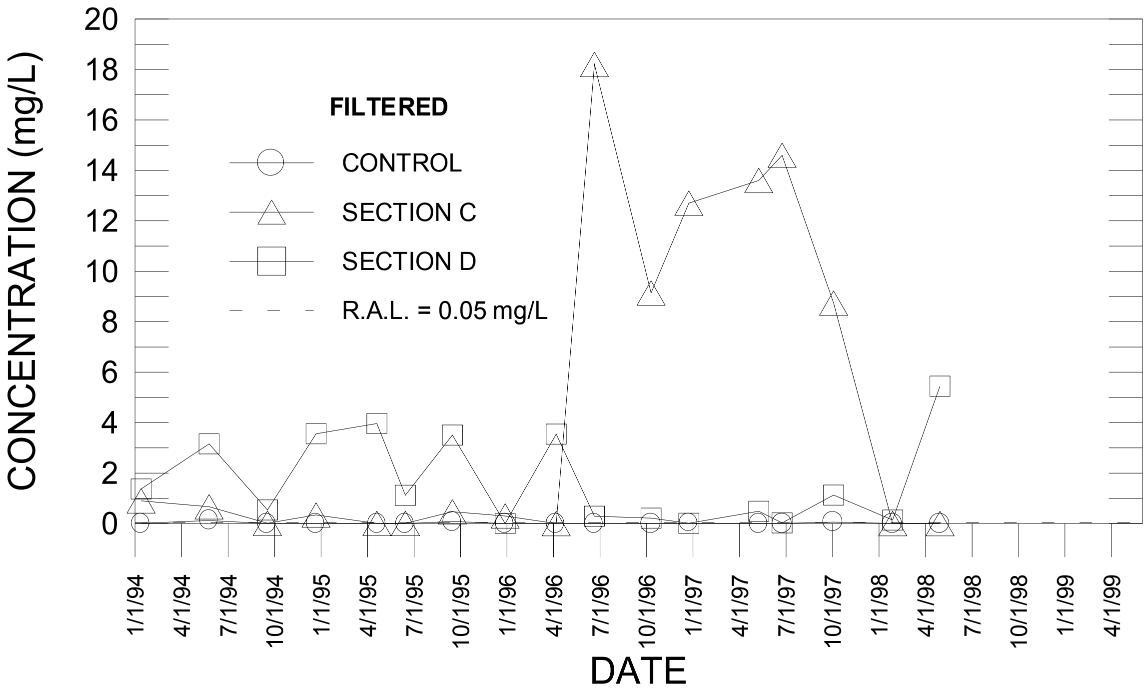


Fig. 11 Manganese levels for filtered samples at North Yarmouth field trial.

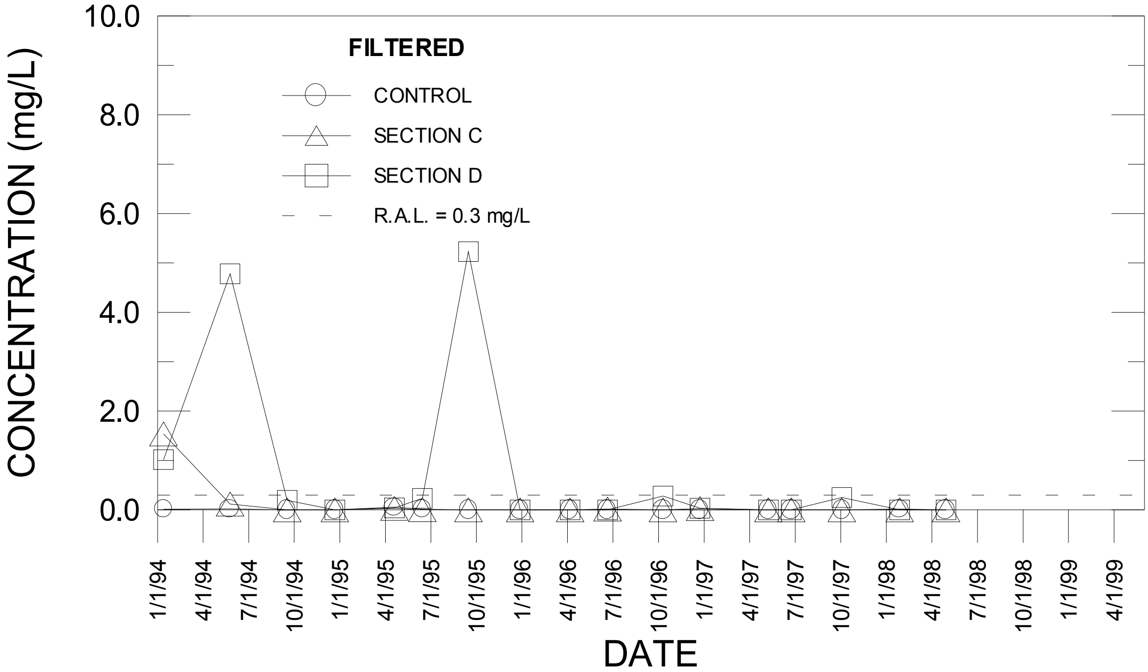


Fig. 12 Iron levels for filtered samples at North Yarmouth field trial.

Tire shreds placed below the water table were the subject of another study at the University of Maine (Downs, et al., 1996; Humphrey, 1999b). In this study, 1.5 tons of tire shreds were buried below the water table in three different soil types (a silty marine clay, glacial till, and peat). Samples were taken over a three year period from the tire shred filled trench and from wells located 10 ft up-gradient (control wells), 2 ft down-gradient, and 10 ft down-gradient. For samples taken from the tire shred filled trench, the levels of metals with a primary standard were below their respective regulatory limits. However, the levels of manganese and iron were above their secondary (aesthetic) standards. A few organic compounds were present at detectable levels in the tire shred filled trench. However, after flowing through only 2 ft of soil to the first down gradient wells, the levels in the groundwater had decreased to below the detection limit except for three compounds (benzene, cis-1,2-dichloroethene, and toluene) which were present at levels below their respective drinking water standards. 1,1-dichloroethane was present in some down-gradient wells at the marine clay and till sites but the highest concentration was 6.9 parts per billion. Concentrations of 1,1-dichloroethane were below detection limit in all down-gradient wells on the most recent sampling date. A drinking water standard has not been established for this compound.

Volatile and semivolatile organic compounds were monitored for two sites where TDA was placed above the water table and for three sites where TDA was placed below the water table. For water in direct contact with TDA, a few compounds are found above the detection limit. The concentrations tended to be slightly higher for below groundwater table sites. For those compounds with drinking water standards, the concentrations were below the corresponding standard with the exception of one compound on one sample date at a below groundwater table site. Measurements taken at the three sites where TDA was placed below the groundwater table show that flow through as little as 2 ft (0.6 m) of soil generally reduces concentrations of monitored compounds to below the test method detection limits (Humphrey and Swett, 2006).

CONCLUSIONS

Tire shreds have a low unit weight, high permeability, and high insulating value making them an excellent fill for embankments constructed on weak ground, landslide stabilization, retaining wall and bridge abutment backfill, insulation to limit frost penetration beneath roads, and drainage layers for landfills. Field testing on the environmental impacts of TDA have demonstrated that TDA can be used safely. When the special properties of tire shreds are needed for a project they are often the lowest cost alternative. Thus, civil engineers are choosing tire shreds because they offer both the properties needed to solve special problems and lower costs to satisfy the demands of their clients for the most economical project possible. In the next few years, major increases in the number of scrap tires used for civil engineering applications is possible because of their growing record of successful performance combined with guidelines to limit self-heating of thick fills, recently published ASTM guideline specifications, and groundwater data showing that they have a negligible environmental impact.

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DEVELOPMENT OF DESIGN SYSTEM FOR PERMEABLE INTERLOCKING CONCRETE PAVEMENT

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ABSTRACT

National, state/provincial and municipal legislation regulating stormwater runoff in the United States and Canada has provided increased incentives for using permeable pavements. In addition, regulatory frameworks for implementation of sustainable design have embraced permeable pavement solutions. These regulations are often called low impact development (LID) or sustainable urban drainage systems (SUDS). A logical and technically sound design process using design software can support design professionals and help permeable pavement achieve full potential in North America. In 2008, the Interlocking Concrete Pavement Institute (ICPI) introduced a non-proprietary software program called Permeable Design Pro that integrates hydrological and structural design solutions for permeable interlocking concrete pavement (PICP). The hydrological analysis determines if the volume of water from user-selected rainfall events can be stored and released by the pavement structure. User defined parameters determine how much water infiltrates the subgrade, infiltrates into the soil subgrade, enters pipe subdrains or flows from the pavement surface. The structural capacity of PICP is determined using the American Association of State Highway and Transportation Officials (AASHTO) 1993 structural design equations for base/subbase thickness to support vehicular traffic. This paper describes the development of the structural and hydrological design methodology with an example of its use.

Keywords: Permeable pavement, permeable interlocking concrete pavement, permeable pavement structural/hydrologic design software

INTRODUCTION

Environmental responsibility through green or sustainable design is being embraced throughout North America from grass roots community groups to federal governments. One technology in the sustainable infrastructure design tool box is PICP which can help replicate natural hydrology, encourage groundwater recharge or provide water harvesting while offering other environmental and visual benefits.

PICP consists of solid concrete units molded with joints and/or openings that create an open area across the pavement surface. The openings allow water from storm events to flow freely through the surface into an open-graded base where it is collected and stored before it infiltrates into the underlying soils. For low-infiltration rate soils, drain pipes are often placed in the subbase to drain excess water, thereby functioning as a detention facility with some infiltration. The entire pavement system can support vehicular or pedestrian traffic while minimizing stormwater runoff and recharging groundwater supplies. Research has demonstrated that PICP is an effective method for reducing stormwater runoff and pollutants from urbanized areas. Initial surface infiltration rates exceed 500 in./hour. Like all permeable pavements the surface will accept sediment thereby decreasing its infiltration rate. The rate of decrease depends on sources of deposited sediment typically from ordinary use and unexpected soil erosion from adjacent surface. Such reductions still render a surface that can infiltrate most rainstorms.

DESIGN PROCESS

As designers use PICP, they should understand the need for traditional structural design to ensure traffic load support and the need to satisfy hydrological design requirements for accommodating expected rainfall events. Permeable Design Pro software [ICPI, 2008] was created to satisfy both needs. Like any pavement, PICP design should provide a safe driving surface for cars, commercial vehicles and pedestrians. PICP can accommodate rainfall onto the pavement or draining from adjacent areas. The overall design process is outlined in Figure 1.

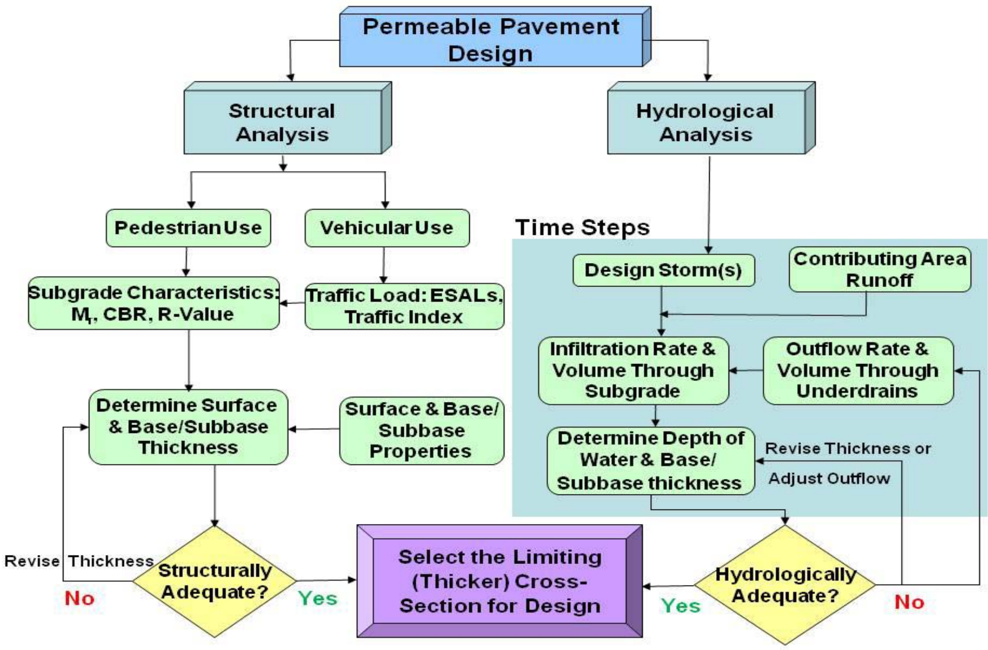

Figure 1. Flow chart of the permeable pavement design process

<u>Flexible Pavement Structural Design</u>
With Permeable Design Pro, PICP design is approached as a flexible pavement. Like asphalt pavement, PICP materials are typically placed in layers of increasing strength such that traffic loads are in contact with the strongest layers that distributing loads and reducing stresses to deeper layers. The intent is to prevent deformation of subgrade soil under the anticipated vehicle or axle loads over the pavement life. Figure 2 illustrates this familiar notion of how pavements distribute loads.

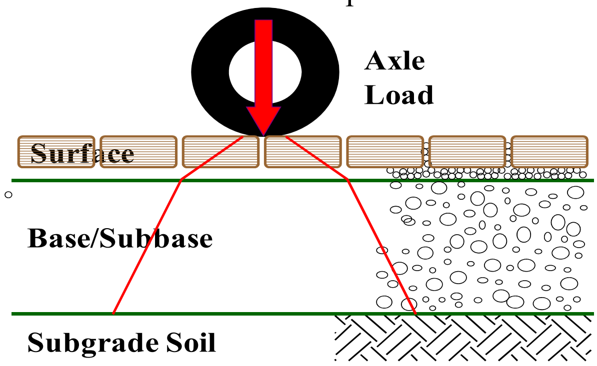

Figure 2. Distribution of traffic loads into underlying layers

Pavement ride quality relies on structural capacity. Within Permeable Deign Pro, PICP structural capacity derived from the subbase, base and surface thicknesses is determined from the flexible pavement design methodology in the American Association of State and Highway Transportation Officials (AASHTO) 1993 *Guide for Design of Pavement Structures* (AASHTO, 1993). The AASHTO procedure defines pavement layer strengths and calculates the thickness of each layer required to protect the underlying subgrade material from permanent deformation from traffic loads over a design life. The AASHTO methodology was selected because its underlying concepts are transferrable to PICP (using open-graded bases) and the procedure is familiar to North American pavement designers.

<u>Traffic Requirements</u>
In AASHTO, the anticipated traffic and load information is characterized by 80 kN equivalent single axle loads (ESALs) over the pavement's design life. To estimate the total number of ESALs expected over the pavement design life, the number and types of vehicles driving on the road need to be determined. Vehicles have different characteristics including the number and spacing of axles and vehicle weight. Examples of truck weight factors are provided in the AASHTO *Guide* and can be used to estimate the total number of ESALs. Since PICP typically is used for low traffic volume applications, it is common to make general assumptions for the design traffic loads rather than conduct detailed traffic surveys. Experience has shown that while traffic volumes are typically low, PICP can withstand high axle loads as shown in Figure 3. Permeable Design Pro software enables the user to characterize traffic for roadways and parking lots up to 1 million 18,000 lb (80 kN) ESALs. However, the recommended limit is a maximum of 600,000 lifetime ESALs using unstabilized aggregate bases. This suggests uses such as parking lots and residential collector streets that experience some truck traffic over their lifetime.

Figure 3. High axle load traffic on PICP

Hydrological Analysis

The stormwater quantity entering the pavement surface is described as a water balance among sources and destinations. These are shown in Figure 4. Permeable Design Pro software manages the volume of water in the pavement system as:

$$Water\ Volume(Time) = Initial\ Water\ Level + \int_{o}^{Time} (Inflow(Time) - Outflow(Time))$$

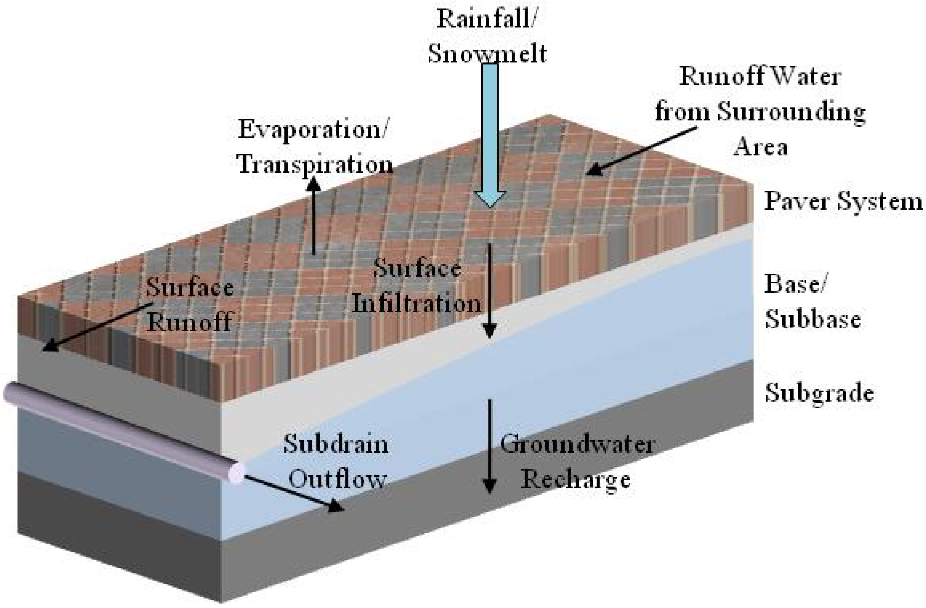

Figure 4. Inflow and outflow of water on permeable pavement

The analysis procedure uses small time steps to estimate the expected water inflow from precipitation and any surrounding areas that drain onto the PICP. The outflow from surface runoff to groundwater recharge and subsurface drainage during each time step is also estimated. The inflow/outflow analysis enables the water level in the pavement base/subbase to be estimated during the storm and while draining afterwards. Antecedent water levels in the base/subbase can also be modeled to simulate the outflow effects from sequential storms. Water harvesting can be modeled by limiting the subgrade infiltration rate.

Water Inflow

Water entering the PICP surface including surrounding areas is estimated using rainfall, soil type, land use and runoff characterizations based on Natural Resource Conservation Service Technical Release 55, *Urban Hydrology for Small Watersheds* (NRCS 1986). All inflow from adjacent areas is assumed to be sheet flow. PICP surface infiltration rates can be input by the user based on test results data and/or experience. Rainfall events can be selected from 2 year to 100 year storm events. Figure 5 illustrates the rainfall events screen with rainfall events selected for Buffalo, New York, USA. The software contains a library of storm events for Canada and the United States, and allows for additional rainfall events sites to be manually entered.

Rainfall timing can be important when evaluating PICP potential to infiltrate water from surrounding areas. The time delay between the rainfall on these areas (with some infiltration) and the time the water enters the PICP surface during the peak rainfall intensity can also reduce the peak outflow, thereby conserving the need for larger storm sewer pipes and reducing potential downstream erosion.

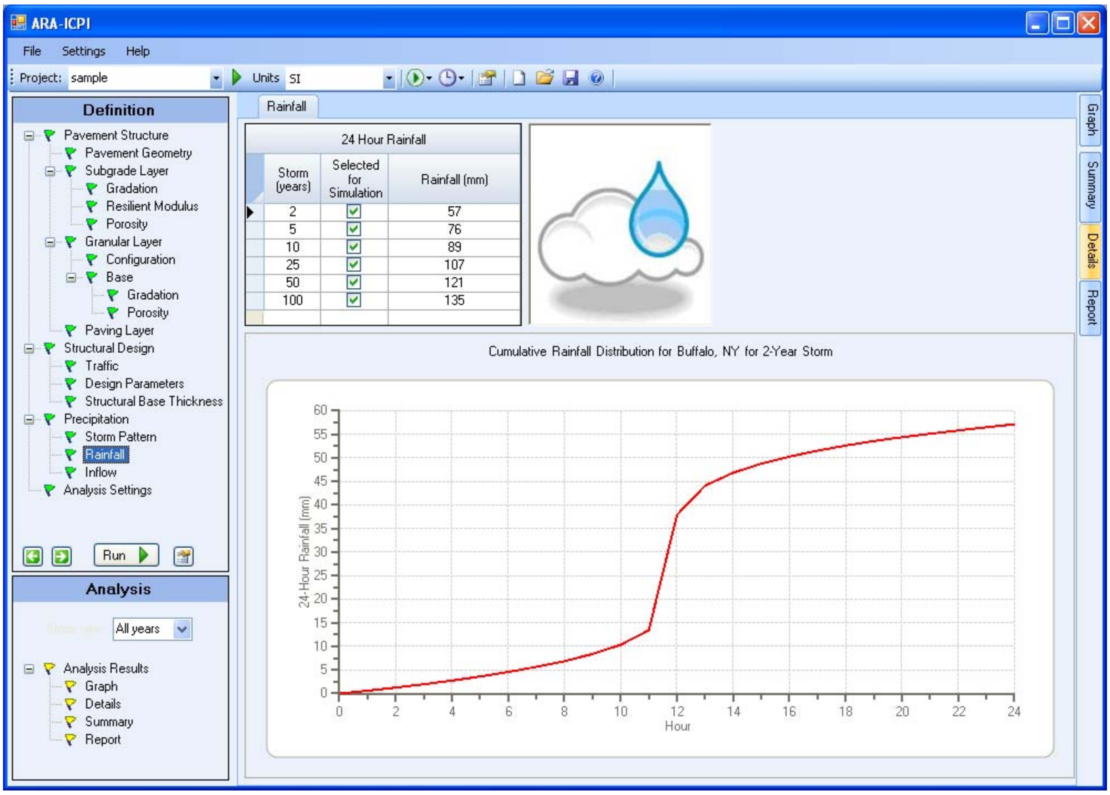

Figure 5. Permeable Design Pro can simulate 2, 5, 10, 25, 50 and 100 year, 24-hour rainfall events in cities throughout the United States and Canada.

Water Outflow

Stormwater exits PICP via groundwater recharge (soil subgrade infiltration), subdrains (generally perforated pipes) and through evaporation/transpiration. Permeable Design Pro estimates the water infiltrating into the soil subgrade and into pipe subdrains. The drains are typically used with low infiltration soils and the user can specify the pipe size, slope, horizontal spacing and height above the soil subgrade. The latter can be important to creating some water detention in the base for infiltration and nutrient reduction. Besides modeling complexities, evaporation and transpiration are considered insignificant and are not part of the program.

Groundwater Recharge
Based on the user selected soil subgrade permeability, the program assumes saturated conductivity and calculates infiltration over time using Darcy's Law [Cedegren, 1989]. Since the water table is typically some distance below the base/subbase layer, the hydraulic gradient can be assumed to be 1.0 as the drop in elevation causes downward flow. The program assumes that drainage occurs uniformly across the bottom of the pavement as the base/subbase becomes saturated.

$$Q_{Groundwater} = k_{Subgrade} \cdot \frac{Depth\ of\ Water\ in\ Pavement}{Thickness\ of\ Pavement} \cdot Subgrade\ Infiltration\ Factor$$

Where
$Q_{Groundwater}$: Flow rate of water into groundwater recharge (m/day, ft/day)
$k_{Subgrade}$: Hydraulic conductivity of the subgrade material (m/day, ft/day)
Subgrade Infiltration Factor: Expected reduction in subgrade permeability due to clogging

Since predicting sediment loading within the base/subbase is practically impossible, a subgrade infiltration reduction factor can be applied to conservatively account for potential clogging and reduction of the soil subgrade infiltration rate. The base/subbase water depth changes and as this factor increases, and the static pressure increases affecting the drainage rate.

Material Selection
PICP typically uses highly permeable, open-graded crushed stone (granular) materials between the paving units and for bedding under them. The open-graded base/subbase materials maximize water storage. (Dense-graded bases are not recommended in PICP.) The paving units are typically 80 mm thick for vehicular applications and the bedding layer is no greater than 50 mm thick. Aggregates should be crushed, angular materials to ensure high interlock. PICP typically uses ASTM No. 8, 89 or 9 stone (10 to 1 mm) for the joints and bedding, an ASTM No. 57 (25 to 2 mm) for the base and ASTM No. 2 for the subbase (65 to 20 mm).

Subdrain Use
In most traditional pavements, perforated drain pipes are placed at the bottom of the subbase layer so that water entering the system can be drained quickly. However, in permeable pavement subdrains prevent over-saturation of the pavement during high depth rain events. To accomplish this, subdrain pipes are typically placed above the soil subgrade, filling when a substantial portion of the base material under them has

become saturated. This allows the water from the majority of storm events to infiltrate into the subgrade. Subdrain pipes can exit to drainage ditches, storm sewers and natural drainage features such as ponds or streams. By adjusting subdrains height above the soil subgrade, discharge rates can be controlled to prevent flooding. Furthermore, the pavement base/subbase can drain within 48 to 72 hours to aid in maintaining a stable structure under vehicle loads.

Other Design Considerations

Other design factors include:

- adjacent land uses
- available stormwater systems
- aggregate filter requirements
- geotextiles
- winter maintenance
- edge restraint design
- constructability
- paver type and configuration

Many of these factors depend on the site specific conditions and layout. These factors are not directly considered in the Permeable Design Pro software, but must be carefully considered in the overall PICP design. The Interlocking Concrete Pavement Institute provides guidance on these factors in *Permeable Interlocking Concrete Pavements – Selection Design Construction Maintenance* (Smith, 2006). In addition, another paper submitted at this conference entitled “Structural/Hydrologic Design and Maintenance of Permeable Interlocking Concrete Pavement” (Smith, 2010) provides maintenance guidelines.

EXAMPLE DESIGN

The following example illustrates how PICP reduces runoff and peak flows. The project is parking lot near Omaha, Nebraska USA. The parking is 580 m^2 of PICP set within a 2,600 m^2 traditional impermeable pavement parking lot. This site is bordered by an upslope grassed area that allows stormwater runoff onto the pavement. Drainage ditches are adjacent to the PICP to handle water volumes that exceed the PICP storage and the soil subgrade infiltration capacities.

For structural capacity, the design traffic was estimated at 91,000 ESALs over the life of the pavement (typically 20 years). The local subgrade material is low plasticity clay with low permeability and California Bearing Ratio (CBR) of 3. This requires a pavement structure consisting of the paving units and bedding material over 100 mm of ASTM No. 57 stone and 450 mm of ASTM No. 2 stone.

For this area of Nebraska, rainfall intensities typically start low, have short periods of high intensity and then slow near the end of the storm. This rapid water inflow from intense rainfall onto impervious surfaces tends to deliver water quickly into the PICP. Although this site has a low permeability soil subgrade, stormwater management can be greatly improved by storing the water in the PICP base, allowing for a modest amount of infiltration, and slowly draining the remainder over two days. This is a substantial improvement over two hours required to drain the water from a completely impervious pavement.

For this project, water released from PICP base/subbase when full will enter drainage ditches using subdrain pipes to control the flow. Using the software program, three 100 mm diameter perforated pipe subdrains placed at the bottom of the pavement subbase at equal spacing enables water to slowly drain out within two days. The difference in inflow and outflow illustrated in Figure 6 indicates that there is some infiltration and a delay in peak flow.

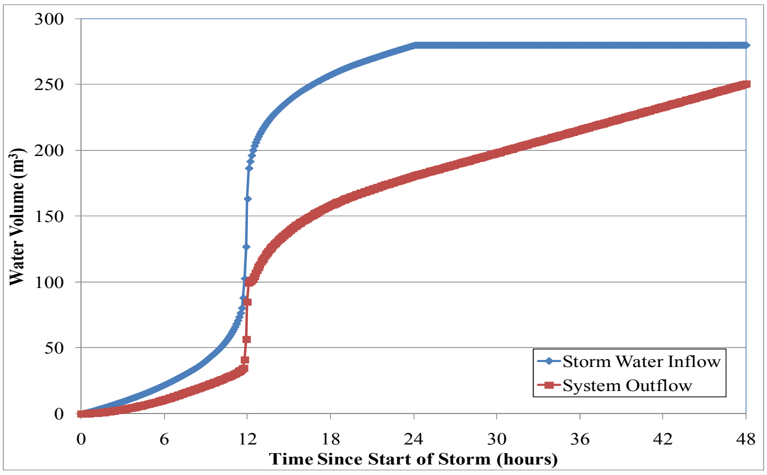

Figure 6. Comparison of PICP inflow vs. outflow

As shown in Figure 6, the rate of water inflow is very rapid with a most occurring at the 12 hour mark. With the planned design layout, the entire pavement structure is sloped towards the drainage ditches. The design forces the runoff to flow into the PICP surface and slowly release the water over time. This causes the peak inflow to be reduced by about 50 percent and for the remaining water to be drained over an additional 24 to 48 hours, depending on the storm intensity.

CONCLUSIONS

The Permeable Design Pro software tool can develop appropriate PICP designs having sufficient structural capacity to accommodate vehicular traffic and hydrological properties to accommodate and slowly release stormwater. The software uses an iterative procedure to estimate the water balance during rainfall and for up to six days afterwards to determine if the system will drain in a reasonable length of time. This allows designers to quickly determine if a site can be used for PICP and if appropriate, help assess the base/subbase thickness required for structural and hydrologic capacity for a wide range of site conditions and features.

Other detailed program outputs that support hydrological design includes hydrographs for the rainfall, inflow from contributing areas, infiltration and outflow through subdrain pipes if required. The program also calculates the NRCS curve number and runoff coefficient. On the structural side, the program calculates the required AASHTO structural number given input properties for each pavement layer. The program selects the thicker of the base/subbase required from either the structural or hydrological calculations for use as the PICP design cross section. The user can select conservative design values and program default values for input variables, especially when little or no design information is available. This enables the user to conduct sensitivity analyses and select the optimal base thickness design.

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THE EFFECT OF RECYCLED ASPHALT MATERIALS ON HOT MIXED ASPHALT PAVEMENT PERFORMANCE

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Abstract

Rises in construction and asphalt binder costs, as well as the growing pressures on landfills, have contributed to the increased use of Recycled Asphalt Shingles (RAS) in Hot Mixed Asphalt (HMA) Pavement Mixtures. Initial incorporation of Manufacturers Waste Scrap Shingles (MWSS) into HMA pavements yielded encouraging results and prompted waste management organizations, industry and government to investigate incorporation of Tear-Off Scrap Shingles (TOSS).

As of 2009, the Minnesota Department of Transportation (Mn/DOT) standard specifications only allowed a 5% MWSS replacement for the allowable Recycled Asphalt Pavement (RAP) and TOSS was permitted, only with, "*prior approval from the engineer*". This need to get approval greatly reduced the willingness of local entities to use TOSS. Furthermore, a high-profile, pre-mature, and expensive, pavement failure prompted many to re-evaluate the benefits of using RAS in HMA pavement mixtures.

A multi-agency research effort between Mn/DOT and the Minnesota Pollution Control Agency (MPCA) was initiated with the goal of making a recommendation on a comprehensive RAS specification, including the option of using TOSS that would allow agencies to realize the economic and environmental benefits without compromising pavement performance or durability. The research study (1) incorporated both controlled laboratory experiments and evaluations of in service pavements.

Several producers submitted their ground RAS samples to the Mn/Dot laboratory for inclusion in the study. These RAS samples were tested for gradation, and deleterious materials (DM) content; these results were later used to assist in the development of an initial specification. In addition, the RAS samples were tested for the performance grade (PG) of the asphalt binder. Laboratory-produced HMA mixtures incorporating: Tear-Off Scrap Shingles

(TOSS), or Manufacturer Waste Scrap Shingles (MWSS), and/or Recycled Asphalt Pavement (RAP) were tested for both asphalt binder PG grades and mixture dynamic modulus. It was concluded that the shingle properties, especially the fineness of the grind, and shingle type and the amount of recycled materials used in the HMA mixture had an impact on pavement performance.

The knowledge gained from the collaborative research effort helped decision makers make an informed decision on a 2010 comprehensive RAP/RAS specification, which now allows the use of TOSS as a substitute for the total RAP content of the mix.

Introduction

Recycled Asphalt Pavement (RAP) has been actively incorporated into Mn/DOT pavement mixtures for the past few decades. The first documented pavement project in Minnesota occurred in 1976, next there were several projects in the early 1980's after which RAP usage was incorporated into Mn/DOT specifications. In addition highway departments have been cooperating with the paving industry and local solid waste environmental groups to incorporate Manufacturer Waste Scrap Shingles (MWSS) and, more recently Tear-Off Scrap Shingles (TOSS) into asphalt pavement mixtures. The incorporation of recycled materials into HMA pavement mixtures has been driven by the economic incentive to reduce the amount of virgin asphalt binder and aggregate in the mixture. Although in Minnesota, the emphasis has been more on the asphalt binder, as many parts of the state have relatively good access to quality aggregates.

Since the completion of a number of RAS projects in Minnesota, several issues have arisen, which prompted the Minnesota Department of Transportation (Mn/DOT) Office of Materials and Road Research (MRR) to enter into an interagency agreement with the Minnesota Pollution Control Agency (MPCA) in order to conduct research (1) that was motivated by the increasing disposal of MWSS and TOSS in landfills, and the rising costs of construction and asphalt binder. This study focused on addressing the performance associated with allowing RAS into the specifications – this paper will focus primarily on the effects of both RAS and RAP in HMA pavement mixtures.

Literature Review

Using recycled asphalt shingles (RAS) in hot mix asphalt (HMA) has been a developing technology for more than two decades with growing acceptance by both construction contractors and government agencies. The recent spike in asphalt and cement prices, has prompted the search for acceptable, in terms of performance, supplements to virgin materials. The state of Minnesota has sponsored several research studies on the use of RAS in HMA mixtures over the past 15 years.

The economic incentive to use of recycled materials is to both reduce the demand for virgin asphalt binder and to reduce the amount of materials entering landfills. The results of laboratory and field evaluations done by others (2 - 5) have consistently indicated that HMA mixture properties are influenced by both the amount and type of recycled materials (MWSS and TOSS have different effects). RAP only mixes have different effects on the high and low temperature properties of HMA than RAP plus RAS and RAS only mixes. Generally, the addition of recycled materials stiffens the mixture, the amount of stiffening depends primarily upon the amount of mixing between the recycled and virgin binder, which is influenced by the mixing dwell time, the fineness of the grind of the processed shingle material (Bonaquist), which can also affect the uniformity of the mixture. The stiffness of the recycled binder also plays a role, with RAS typically much stiffer than RAP and TOSS stiffer than MWSS.

In general it has been found that greater than 5% shingle content (by weight of aggregate) adversely decreased the modulus (2), thus this study (1) did not test or evaluate any mixtures containing RAS contents greater than 5%.

Field Performance

Four projects were identified for field evaluations during 2008, although only two will be discussed here. The projects utilized either TOSS, separate sections of TOSS and MWSS, or had an important MWSS performance history. Both projects were constructed after 2005. Evaluations consisted of establishing 500-foot long monitoring stations. The stations were visually rated for transverse, longitudinal and joint cracking. Rutting performance and surface characteristics were also noted. Results were reported in terms of cracked linear feet per section.

<u>Project No. 1: Urban Arterial Reconstruction</u>

In 2005 an urban arterial (CSAH 26) was reconstructed using both MWSS and TOSS. The wear course used a performance graded (PG) 58-34 binder and 25% RAP and 5% MWSS. Three separate non-wear Marshall Mixture designs were used in the project:

1. 5% MWSS and 15% RAP with a PG 58-28 binder
2. 5% TOSS and 15% RAP with a PG 58-28 binder
3. 20% RAP with a PG 58-28 binder

Three 500-ft monitoring stations, one for each non-wear mix design, were established in the westbound lane during the 2008 performance review. A number of transverse cracks were observed in each section, usually coinciding with locations of storm drains, manholes, or concrete median termini. Rutting was not apparent and not measured. A survey performed in 2006 by Mn/DOT Pavement Management collected data showing that the portion of this project on CR 26 contained 60.8% low severity, 37.4% medium severity, and 0.1% high severity rutting. Transverse cracking was found infrequently in the 2006 record.

Table **1** shows the number of cracks and the total linear feet of cracking after three years of service for each non-wear mix design. Note that the 15% RAP and 5% TOSS section appears to be performing the best, followed closely by the 20% RAP section. The 15% RAP and 5% MWSS has the greatest amount of transverse cracking and the lowest amount of longitudinal joint cracking. Any conclusions on performance related to new binder/total binder ratio must be tempered by the presence of utilities (curb and gutter, manholes, etc.) which appeared to significantly influence pavement performance. Thus, the recycled materials did not appear to be a dominant factor in the pavement's performance as it was overshadowed by the presence of utilities.

Table 1. CSAH 26, 3rd-Year Performance Review (1)

Section	Length	Longitudinal Joint		Transverse Cracking		Notes
		No.	Lin. Ft.	No.	Lin. Ft.	
20% RAP 0% RAS	500	5	89	3	15	7 LF shoulder cracking.
15% RAP 5% MWSS	500	2	56	8	48	31 LF shoulder cracking.
15% RAP 5% TOSS	500	5	59	2	15	20 LF shoulder cracking.

Project No. 2: High Speed, Rural highway

A total of four inches of asphalt was placed in two lifts over a variable thickness bituminous pavement on high speed rural highway (TH 10). The asphalt mix designs for the upper two inch lift used a PG 64-34 asphalt binder and included 25% RAP plus either 3% or 5% MWSS. Note that the lower two inch lift did not incorporate RAS.

District engineers reported that the RAS sections experienced substantial reflective cracking during the first winter of service. The traditional "rule of thumb" had been that an inch of pavement delayed reflective cracking for one year, thus this pavement cracked much sooner than most. The pavement was very brittle in appearance, and cracks continued to deteriorate during the following year. The poor condition necessitated a micro-surface treatment in order to repair the pavement.

Results from a field review of two 500-ft monitoring sections of the RAS mixture (before the repair) yielded mean values of 17 transverse cracks per lane and 146 linear feet of transverse cracking. A performance review of the control section conducted between 2006 and 2008 revealed 16 transverse cracks per lane and 137 linear feet of transverse cracking. The review also showed the cracks to be less severe, which agrees with field observations made by district personnel (Figure 1). Rutting was not apparent on any section, and Mn/DOT pavement management data showed that the shingles rutting stations had developed medium severity rutting over 19.4 and 6.6% of the stations, with low severity rutting on the remainder. The control section had developed medium severity rutting over 16.4% of the section with low severity on the remainder.

Figure 1. T.H. 10 - 5% RAS: May 2008 (Left) and March 2007 (Right) (1)

The performance of this project, contrary to the previous project, did in fact appear to be negatively impacted by the presence of RAS in the HMA pavement mixture. However, there were other construction factors which may have negatively impacted pavement performance including, long haul times and late season paving. There are parameters that contribute to a successful RAS project and it is critical to identify these parameters in order to avoid rejection of recycling technology.

Recycled Asphalt Shingle Properties

MWSS and TOSS samples tested in the study (1) are shown below in Figure 2. The MWSS material was much coarser, less uniform than the TOSS material, which undoubtedly has an impact on the amount of recycled binder that gets incorporated into HMA mixture. In addition, the coarser MWSS material could contribute to moisture and durability problems in the HMA mixture. The MWSS and TOSS gradations are shown in Figure 3, which confirms the visual analysis. The two TOSS samples had consistent gradation results, and both satisfied Mn/DOT's gradation requirement for roofing shingles in hot mix asphalt (100% passing the 1/2-in. (12.5 mm) sieve and 90% passing the #4 (4.75 mm) sieve). The MWSS sample did not meet the Mn/DOT gradation requirements.

Figure 2. MWSS (Left) and TOSS (Right) (1)

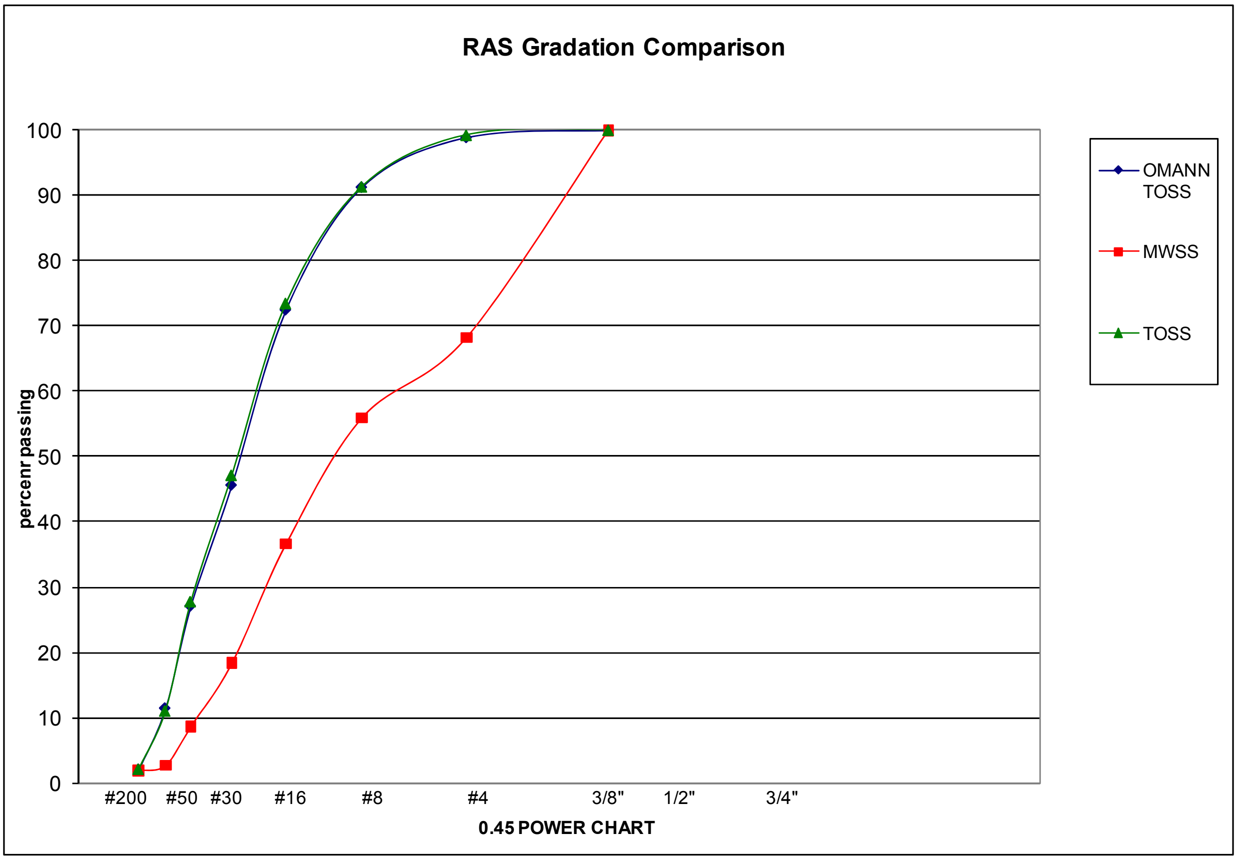

Figure 3. MWSS and TOSS Gradations (1)

The deleterious material (DM) specification for processed shingles states that scrap asphalt shingles shall not contain extraneous waste materials. Extraneous materials include, but are not limited to: asbestos, metals, glass, rubber, nails, soil, brick, tars, paper, wood, and plastics and shall not exceed 0.5% by weight as determined on material retained on the 4.75-mm (No. 4) sieve. DM testing consists of sieving a 500-700 gram sample on the #4 sieve, then manually picking and weighing the deleterious material. Figure 4 shows the DM testing results of the MWSS and TOSS, the TOSS met the 0.5% DM specification, and the MWSS did not.

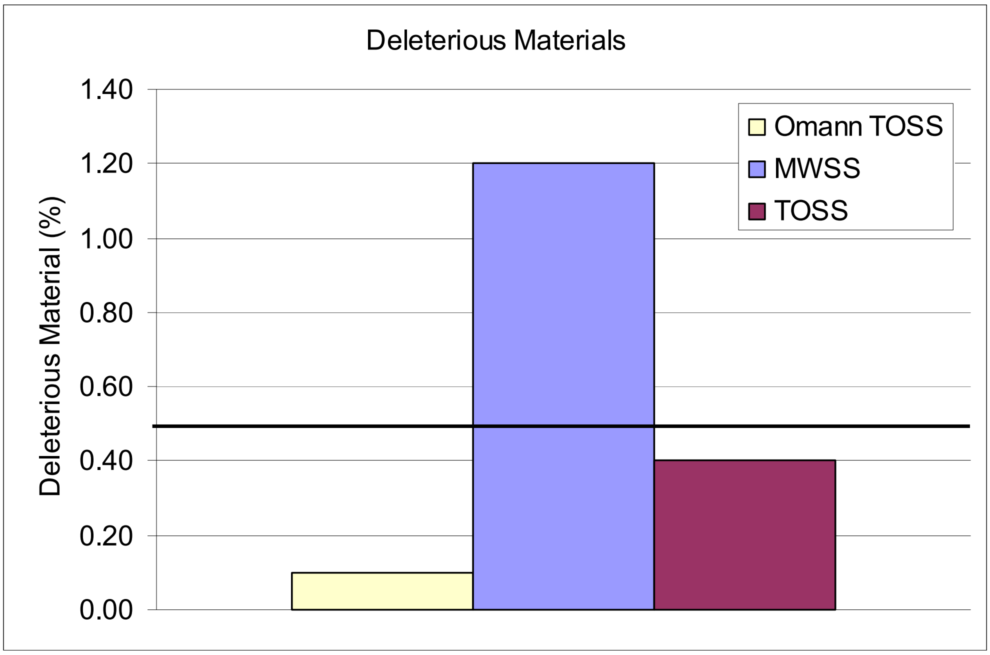

Figure 4. Deleterious Material Content of TOSS and MWSS (1)

Asphalt Binder Extraction/Recovery and PG Grading

The two different types of RAS, MWSS and TOSS were incorporated into a matrix of laboratory produced HMA mixture specimens. A PG 58-28, non-polymer modified, asphalt binder (specific gravity of 1.036), was used in all but two of the RAS/RAP mixtures. A comparably priced, PG 51-34, non-polymer modified, asphalt binder was used in the remaining two mixtures. Each mixture was adjusted to meet the following mixture design requirements: 4.0% air voids, minimum 14.0% voids in the mineral aggregate (VMA), 65-78% voids filled with asphalt (VFA), and a Dust to Binder ratio of 0.6-1.2 (F/E). The gradation of these mixtures is shown in figure 5.

It was observed that mixture temperatures cooled quicker with the addition of RAS, as the designers noticed a loss in workability. RAS also made the mixtures appear dryer (less asphalt binder) than those produced with just RAP. Mixtures incorporating the coarser ground MWSS had a tendency to clump up during the mixing process, and those incorporating the finer ground TOSS appeared to be more homogenous.

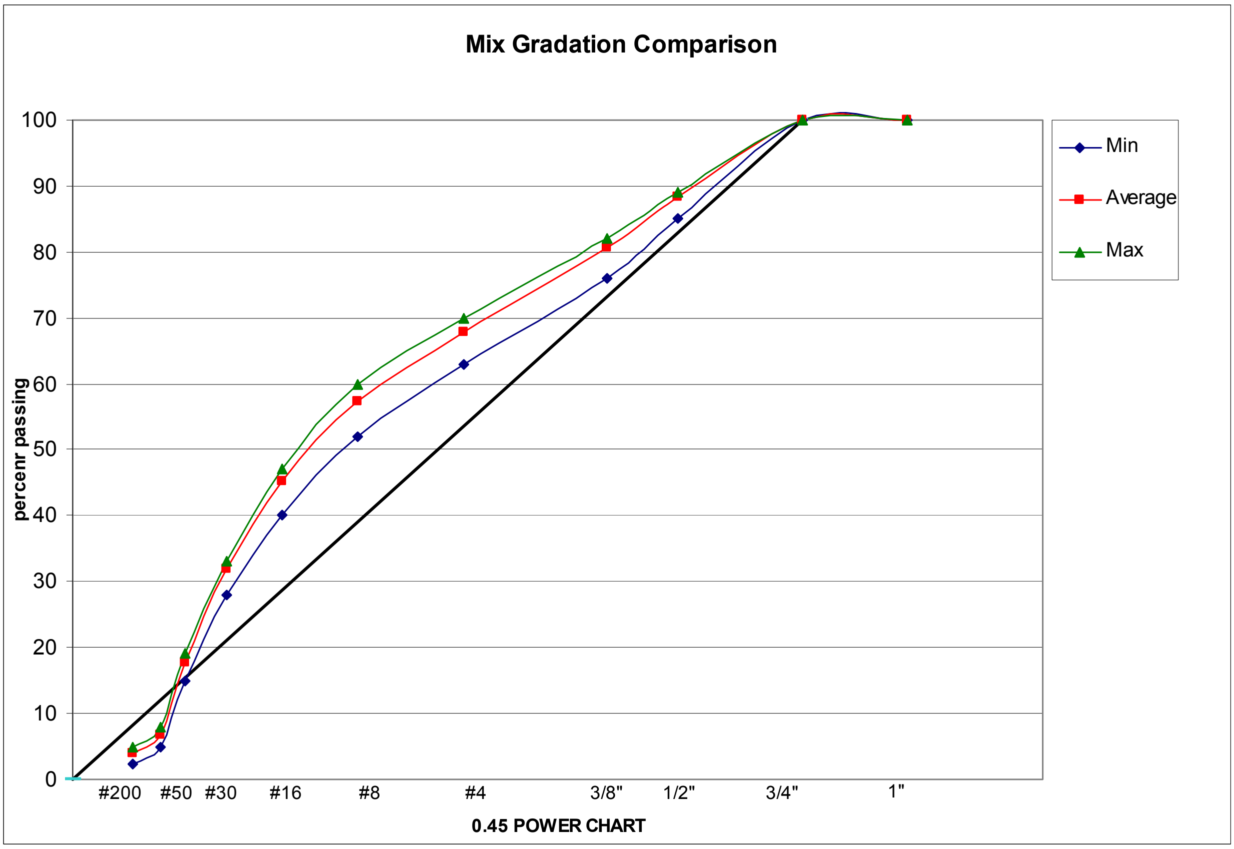

Figure 5. Mixture Design Gradations (1)

The asphalt binders were extracted from the prepared mixtures using a process involving a solvent centrifuge extraction. The extract is centrifuged at high speeds to remove the mixture fines from the binder. The solvent is removed using the ASTM D5404- Rotovap recovery process.

The behavior of asphalt binders is highly dependent upon temperature. An asphalt binder need to be sufficiently stiff at higher temperatures to resist rutting and yet flexible at lower temperatures to resist thermal cracking. Asphalt binders are commonly specified according to the PG grading system, which is based upon the maximum and minimum pavement design temperatures in Celsius. For example, a PG 58-28 asphalt binder is designed for a pavement that experiences high temperatures cooler than 58°C and low temperatures warmer than -28°C. Table 2 shows the high and low temperature PG values of the extracted asphalt binder from the recycled materials.

Table 2. Recycled Material Binder Performance Grade (PG) Binder Grading (1)

Material Identification	High PG Temp	Low PG Temp	Continuous PG Grade	PG Grade
RAP	79.9	-17.4	79.9 -17.4	76-16
RAP2	74.3	-28.8	74.3 -28.8	70-28
Omann TOSS	112.7	-11.4	112.7-11.4	
Knife River MWSS	107.5	+6.0	107.5+6.0	

The TOSS does have higher PG values for both the high and low temperatures than the MWSS, which could be explained by the additional aging induced by exposure to oxidation, solar radiation and high temperatures. There are also observable differences between the two RAP sources. It is evident from table 2 that it is not practical to construct an HMA pavement using only recycled asphalt binder derived from RAS as few pavements experience temperatures up to 108°C (226°F) and many states experience temperatures cooler than 6°C (42.8°F). Due to the fact that TOSS and MWSS are 'stiffer' than what is commonly used in HMA pavements, they are incorporated into the HMA pavement along with the less stiff RAP and the virgin asphalt binder.

Table.3 shows the continuous PG grading of the binder extracted from laboratory prepared mixture specimens. It can be seen that the addition of RAP and/or RAS consistently increases the high and low temperature PG grades. This is not surprising as the composite binder experiences complete mixing in the extraction/recovery process.

Table.3. RAS Mixture Binder Performance Grade (PG) Binder Grading (1)

Mix #	Mix Identification	High PG Temp	Low PG Temp	Continuous PG Grade	PG Grade
1	PG 58-28 Control	63.7	-31.0	63.7 -31.0	58-28
2	15% RAP	72.4	-20.9	72.4 -20.9	70-16
3	25% RAP	77.2	-19.7	77.2 -19.7	76-16
4	30% RAP	75.4	-25.6	75.4 -25.6	70-22
5	15% RAP 5% MWSS	78.7	-16.7	78.7 -16.7	76-16
6	15% RAP 5% TOSS	80.1	-16.3	80.1-16.3	76-16
7	25% RAP 5% TOSS	84.6	-14.1	84.6 -14.1	82-10
8	25% RAP 5% MWSS	79.3	-18.7	79.3 -18.7	76-16
9	25% RAP 5% TOSS 51-34	75.9	-21.9	75.9 -21.9	70-16
10	25% RAP 5% MWSS 51-34	75.1	-23.2	75.1 -23.2	70-22
11	25% RAP 3% TOSS	81.0	-17.5	81.0 -17.5	76-16
12	25% RAP 3% MWSS	79.5	-18.2	77.2 -18.2	76-16
13	15% RAP 3% TOSS	78.1	-18.6	78.1 -18.6	76-16
14	15% RAP 3% MWSS	78.5	-19.2	78.5 -19.2	76-16
15	10% RAP 5% TOSS	77.7	-17.1	77.7-17.1	76-16
16	15% RAP2 5% TOSS	79.4	-20.3	79.4-20.3	76-16
17	5% TOSS	75.6	-24.2	75.6-24.2	70-22

As an example consider mix number 7, the high PG temperature of the composite binder of 84ºC is higher than the 58ºC of the virgin binder and even slightly higher than 80ºC of the RAP, but is much less than the 108ºC of the TOSS. A similar observation can be made of the low PG temperature as well; the overall composite binder low temperature of -14ºC is greater than the -28ºC of virgin binder, slightly greater than the -17ºC of the RAP, but less than the -11ºC of the TOSS. The resultant low temperature properties of the composite binder may not be flexible enough to resist thermal cracking, a major concern for Minnesota. The dramatic increase of the low temperature PG grade of the composite asphalt binder could possibly be mitigated by using a 'softer' virgin asphalt binder as demonstrated by mix numbers 9 and 10. Consider mix 9, which has the same amount and type of RAS and RAP as mix 7, but a virgin binder low temperature of -34ºC as opposed to -28 ºC, this difference has significant effect on the low temperature properties of the composite binder, lowering it from -14ºC to nearly - 22ºC.

The type of RAS doesn't appear to have a significant effect on the low temperature PG grade at the 15% RAP and 3% RAS concentration. Note that HMA producers did not think adding 3% RAS to a mixture was practical, 5% was the minimum practical concentration that could be added to a mix (outside of a laboratory). When the RAP content is 25% and the RAS content is 5% there is a visible difference between mixtures containing TOSS vs. MWSS as shown in the difference in both high and low composite binder PG temperatures of mixes 7 and 8.

Asphalt Mixture Testing

The dynamic modulus test was performed on a minimum of two samples representing each of the 17 mixtures containing various amounts of RAS and RAP as described earlier. The testing was performed in accordance with AASHTO TP62 which included six loading frequencies (0.1, 0.5, 1, 5, 10, and 25 Hz) and five temperatures (10, 40, 70,100 and 130 ºF). Mixtures containing the PG 51-34 binder could not be tested at the highest temperature (130 ºF), due to the softness of the mixture preventing a secure fit of the LVDTs.

This testing is invaluable in comparing the mixture's performance as the mixture master curves capture how well the RAS/RAP binder mixes with the new, or virgin, asphalt binder. In general, the modulus increases as RAP content increases and these differences appear to be more pronounced at the lower frequencies (higher temperatures) than the higher frequencies (lower test temperatures). The master curves were plotted on a set of logarithmic axes. This convention tends to graphically compress high numeric values and emphasize differences at low numeric values. Figure 6 shows mix 7 and 8, as well as the control mix, not surprisingly the addition of recycled materials stiffens the mixture. Mix 7 appears to be stiffer than Mix 8, suggesting that TOSS has a stiffer binder than the MWSS, which is expected due to the increased aging of TOSS through long term exposure to oxidation, solar radiation and high temperatures, which was confirmed earlier through binder extraction and gradation (Table 2). In addition, due to the coarse gradation, the MWSS binder is contributing less to the mixture than the finely ground TOSS binder. Not only is the TOSS asphalt binder stiffer, a greater portion of it is mixing with the virgin asphalt binder than the MWSS asphalt binder. It is interesting to note the difference between the control (Mix 1) and Mix 8 appears to be similar as the difference between Mix 7 and Mix 8 at certain frequencies, which is a very significant difference. This large difference in performance between the MWSS and TOSS RAS sources was not expected to be as large as the difference between a virgin mix and a MWSS mix.

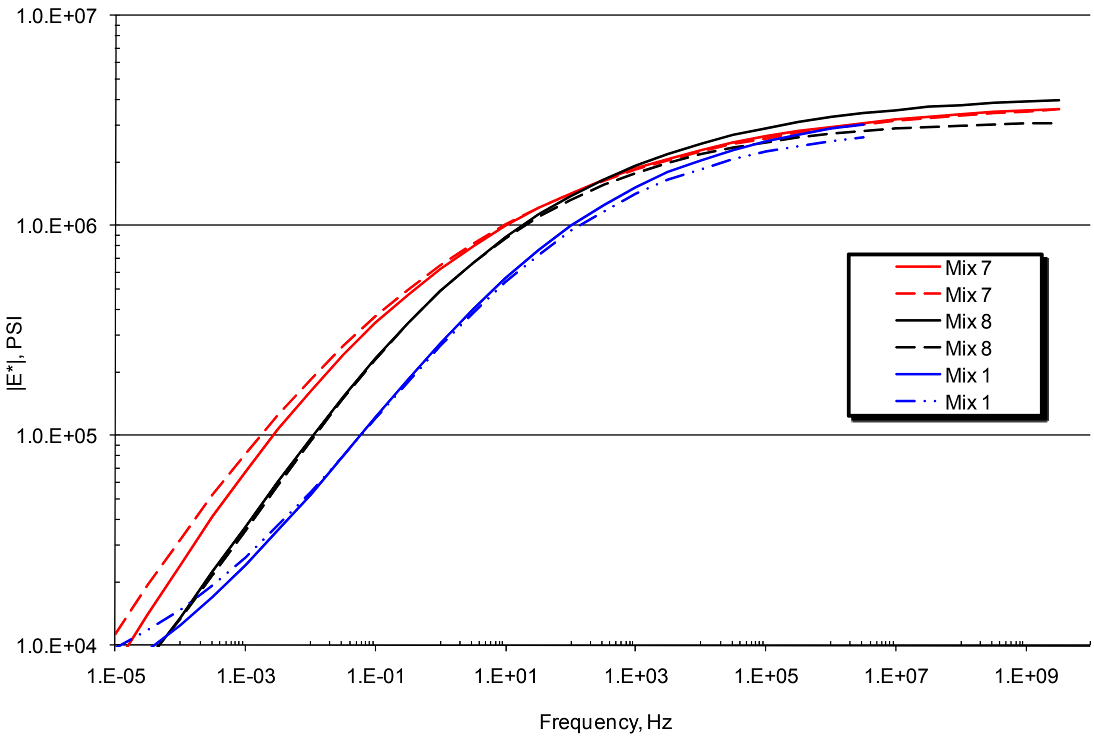

Figure 6. |E*| of Mix 1, Mix 7 (25% RAP/5% TOSS) and Mix 8 (25% RAP/5% MWSS)

Figure 7 shows the master curves of mix 7 and 9 both of which contain 25% RAP and 5% TOSS and are identical except that mix 7 has a virgin asphalt binder of PG 58-28 and mix 9 has a PG 51-34. The impact of the softer virgin asphalt binder is evident as mix 9 has lower modulus values than mix 7, indicating that it's less stiff.

Dynamic modulus tests demonstrated that TOSS is stiffer than MWSS. The difference between the two RAS sources was most pronounced at the 5% level, and was apparent regardless of RAP concentrations. The largest ratios among modulus values were observed at the lower frequencies, which corresponded to the higher temperatures. The dynamic modulus testing did not test at temperatures low enough to effectively characterize low temperature cracking. Dynamic modulus testing also demonstrated that the stiffening effects TOSS alone appears to be much greater than RAP alone.

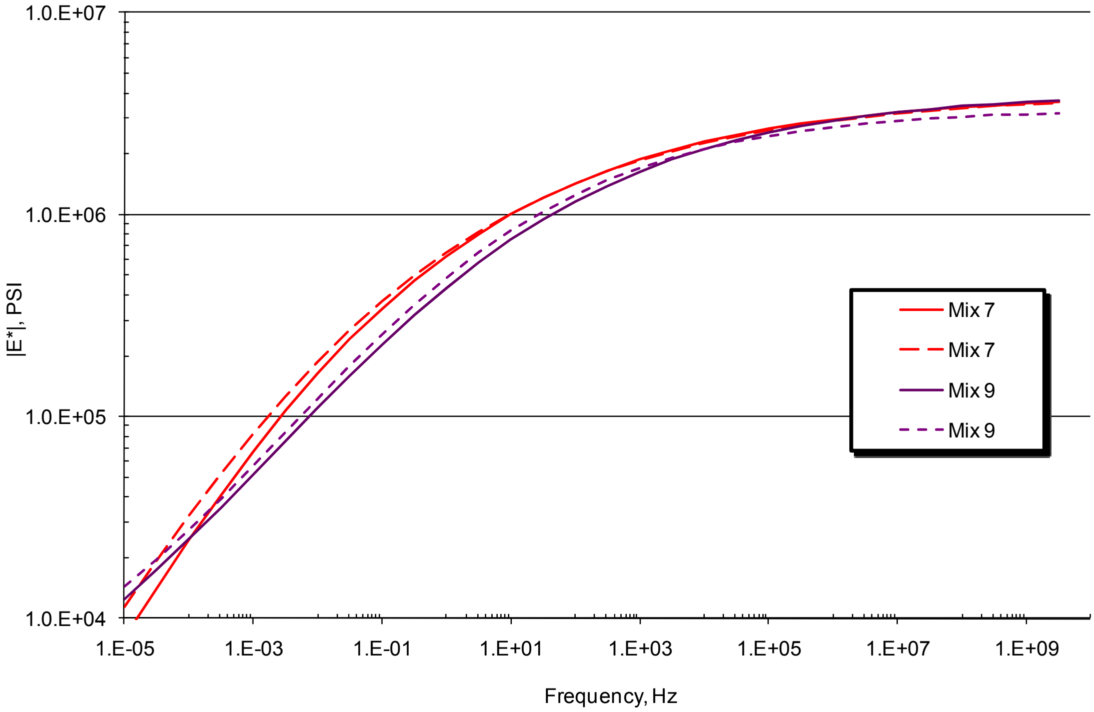

Figure 7. |E*| of Mix 7 (25% RAP/5% TOSS) and Mix 9 (25% RAP/5% TOSS)

Conclusions

Incorporating recycled materials into pavements has been motivated by both environmental concerns of rising landfill deposits of RAS and the financial concerns of rising construction and materials costs, especially asphalt binder. The incorporation of RAS into HMA pavement mixtures must be done so in a prudent manner to avoid unnecessary and costly premature pavement failures which could potentially jeopardize the widespread implementation of the technology.

There have been successful RAS/RAP projects that are performing adequately; however it only takes one failure to serve as a reminder of the potential negative effects of recycled materials on HMA durability. Dynamic modulus tests on laboratory produced mixtures for this study demonstrated that there is in fact, a significant difference in stiffness, especially at the lower frequencies (higher temperatures), between mixtures containing RAS/RAP and virgin mixtures. Thermal (low temperature) cracking heavily influences the durability of Minnesota HMA pavements. The low temperature binder PG grade was increased with the addition of RAP and RAS suggesting an increase in thermal cracking potential of the mixture. Thus RAS/RAP can and should be used in HMA pavement mixtures, but too much will compromise pavement durability.

Minnesota currently has a comprehensive RAS/RAP specification that does not require contractors to seek approval before using the recycled materials, which has expanded the use of MWSS. Mn/DOT's specification seeks to balance the economic and environmental benefits of using RAS/RAP against the impacts on pavement performance by limiting the total amount of material that can be incorporated and by requiring the material to meet gradation and deleterious material requirements.

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City of Saskatoon's Green Streets Program - A Case Study for the Implementation of Sustainable Roadway Rehabilitation with the Reuse of Concrete and Asphalt Rubble Materials

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Abstract

In 2006 the City of Saskatoon recognized that the large amounts of asphalt and concrete rubble materials stockpiled in its yards must be addressed. After experimenting with the material as a replacement backfill material with City forces, the City determined that improved engineering specifications and structural design processes needed to be implemented to facilitate the standard use of the recycled aggregates. In 2009, the City of Saskatoon developed the Green Streets Program to pilot the use of advanced mechanistic engineering and state of the art impact crushing of rubble materials for roadway construction. For the program to be considered successful value added processing, mechanistic-climatic characterization and sustainable holistic life cycle analysis had to be considered.

Based on the findings of the City of Saskatoon Green Streets Program, the City is now producing five types of high value specified crushed concrete materials, and three types of specified asphalt aggregate materials. These materials are being used as subbase, base course, drainage rock, stress dissipation layers and structural black base. From a mechanistic engineering characterization perspective, this research shows the crushed concrete and crushed asphalt aggregates are technically superior to conventional locally available aggregates.

The City of Saskatoon Green Streets Program identified many benefits achieved through the use of recycled materials in road construction on a technical, social, environmental and economic basis. Residents are provided a roadway with superior structural performance and waste rubble generated from aging city infrastructure is diverted from landfills. In addition, the cost savings generated by the Green Streets Project was determined to be approximately 55 percent through the structurally equivalent substitution of recycled aggregates for virgin sourced aggregates.

To further address the key aspects of road infrastructure sustainability the quantification of the energy used to rehabilitate roads and carbon generation during roadway rehabilitation will assist in quantifying the benefits of sustainable construction solutions. The future implementation of mechanistic based End Product Specifications will also ensure that the City will have a reliable engineering framework from which to employ innovative and sustainable road infrastructure solutions utilizing recycled road materials.

1 Introduction and Background

Like many municipalities, the City of Saskatoon is facing decreasing road level of service and decreasing road preservation budgets resulting in an infrastructure crisis. Much of the existing infrastructure has been in service beyond its original design life and has experienced severe climatic conditions as well as increased vehicle loadings which result in many roads requiring rehabilitation. In addition, recently constructed roads have also shown rapid deterioration to the point where rehabilitation is also required (Prang and Berthelot 2009).

Through utility and infrastructure repairs, the City of Saskatoon generates approximately 100,000 MT of hot mix asphalt concrete (HMAC) and Portland cement concrete (PCC) rubble each year (Berthelot et al. 2009). At the same time, landfill space is becoming more expensive and limited. Also, the lack of quality aggregate sources near Saskatoon is resulting in natural aggregate materials being hauled from distances up to 100 kilometres away. As infrastructure funding is not increasing rapidly enough to respond to the growing infrastructure deficit and cost of construction and materials, innovative methods of rehabilitation must be developed to allow more rehabilitation to occur to close the infrastructure gap.

For a number of years prior to 2006, the City of Saskatoon stockpiled HMAC and PCC rubble until it had a sufficient amount of rubble to warrant issuing a contract to crush the material. In the past, difficulties crushing HMAC rubble was experienced due to contamination in the stockpile. The crushed material was used as a marginal quality fill material.

In 2008, due to increasing construction prices and the large amounts of rubble available in City stockpiles, the City decided to investigate processing rubble materials into recycled aggregates for use as a replacement for base course aggregate in roadways. In 2009, the City realized there was a potential to crush the rubble material into a high quality aggregate that could be used within roadway construction as a structural system. However to accomplish this, the City of Saskatoon would have to implement improved engineering specifications to facilitate the proper use of the recycled aggregate. The result of this realization was the creation of the City of Saskatoon's Green Streets Program.

2 Key Technical Aspects of Green Streets

For the Green Streets Program to be successful, key technical aspects of roadway materials and construction were considered in three areas of research:

1. Value added processing of rubble materials through crushing into high quality road construction materials in order to meet the traditional City of Saskatoon gradation specifications,

2. Mechanistic-climatic characterization of the recycled materials to develop a sound scientific design and materials specification process that is based on engineering mechanics, and;
3. Quantification of the holistic life cycle and long term sustainability of Green Street Technology.

The purpose of this paper is to summarize these key technical aspects of the City of Saskatoon's Green Streets Program in the context of sustainability.

2.1 Value Added Processing

Past efforts by the City of Saskatoon to crush concrete resulted in only one type of 50 mm minus subbase material used as a low quality backfill material. This type of low quality end product material is currently the most common recycled concrete product. By refining the crushing process and conducting pre-processing for deleterious materials, a number of high quality products can be processed that meet the current City of Saskatoon gradation specifications for natural aggregates.

Berthelot et al. (2010) found that an impact crusher produced superior end product aggregate from diverse sources of rubble material compared to the traditional jaw and cone type crushing equipment. Due to of the amount of contamination and subgrade fines, the use of the traditional jaw-cone crushing resulted in materials that were high in fines relative to City of Saskatoon base course specifications. Economically sufficient production rates were not achieved using conventional jaw and cone crushing due to difficulties processing rubble materials containing residual asphalt cement content and/or reinforcing steel.

To produce high quality aggregates that meet the City of Saskatoon gradation standards with economically sufficient production rates, an impact crusher with a magnetic metallic extruder and screener was implemented. Upstream processing which involved the removal of reinforcing steel and other waste materials and breaking down of the materials to a proper size for feeding into the crusher resulted in reduced fines in all of the end products. The production rate with this crushing equipment configuration was found to be on average between 100 MT and 200 MT per hour (Berthelot et al. 2009). Figure 1 illustrates the state-of-the-art impact crusher and screening system used and the ability to produce several high quality materials simultaneously.

Figure 1: State-of-the-art Impact Crusher, Producing Five Specified Materials with no Waste

Based on the findings of the Green Streets Program, the City of Saskatoon is now producing five high quality crushed PCC materials and three HMAC materials. The end-use of each product is summarized in Table 1, and Table 2. The unit cost of production for the PCC and HMAC products is $12/MT and $9/MT, respectively (PSI Technologies 2010). The subbase material that is produced is comprised of material removed by a grizzly screen in the pre-processing phase. The removal of these materials assists with keeping the fines content low in the other produced materials.

Table 1: Crushed Portland Cement Concrete (PCC) Materials

Material	Use
50mm Well Graded (GW) High Fines PCC	Subbase
19mm Well Graded PCC	Base Course
25mm Open Graded Base Course (OGBC) PCC Rock	Structural Base Course / Drainage
65mm Crushed Open Graded PCC Rock	Drainage / Stress Dissipation
150mm Crushed Rock	Rip Rap and Drainage

Table 2: Crushed Hot Mix Asphalt Concrete (HMAC) Materials

Material	Use
19mm Well Graded HMAC	Structural Black Base
25mm Crushed Open Graded HMAC Rock	Structural Black Base
65mm Crushed Open Graded HMAC Rock	Drainage /Stress Dissipation Layer

The recycled materials produced with the impact crusher met the City of Saskatoon well graded and crushed rock material gradation specifications for traditional aggregates. The gradations of the recycled PCC and HMAC produced aggregates are presented in Figure 2 and Figure 3.

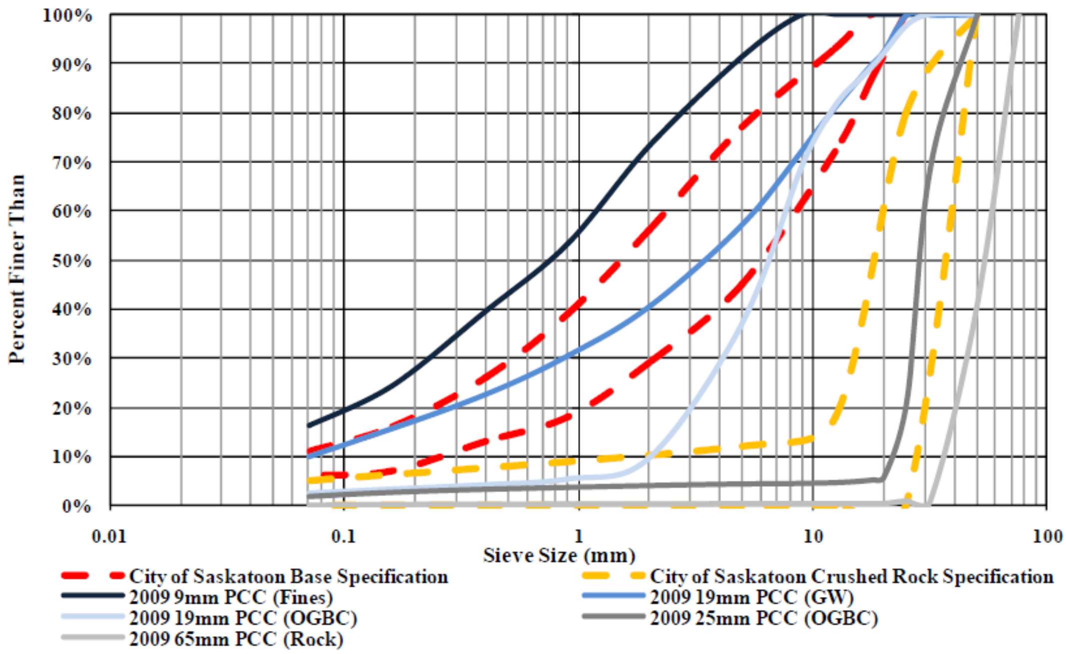

Figure 2: Crushed Portland Cement Concrete (PCC) Grain Size Distribution

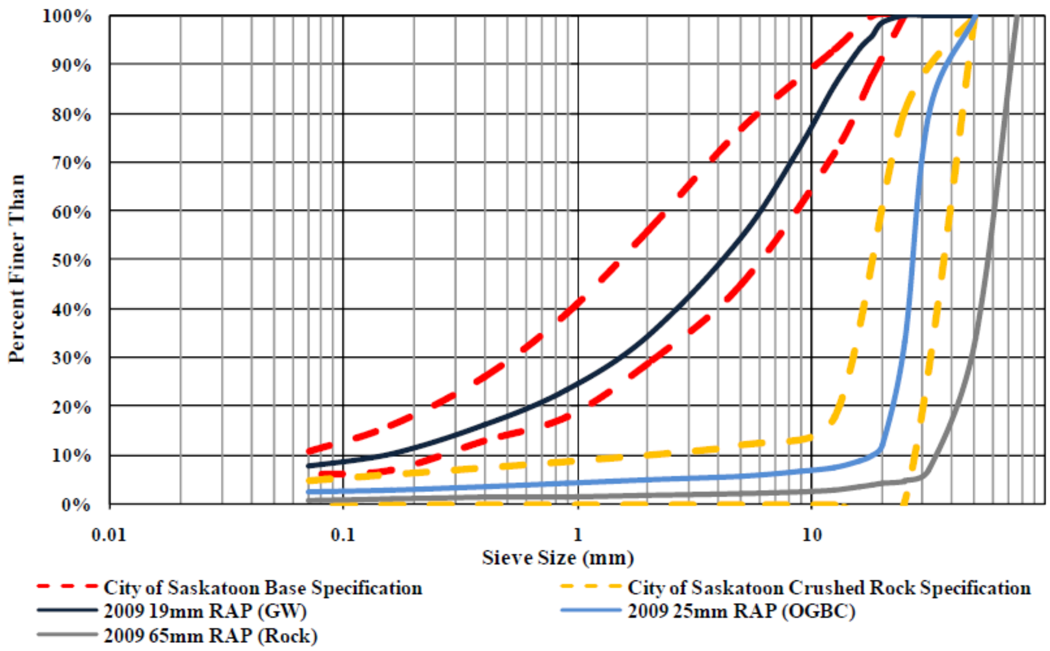

Figure 3: Crushed Hot Mix Asphalt Cement (HMAC) Grain Size Distribution

2.2 Mechanistic-Climatic Characterization

California Bearing Ratio (CBR) characterization was performed on the recycled materials as it is specified for conventional City of Saskatoon granular material structural design and quality control. Traditional tests, like the CBR, rely on empirical relationships between the test properties and expected field performance. As seen in Figure 4, evaluation of the recycled materials by CBR resulted in test results that were unreasonably low and not indicative of the observed field performance.

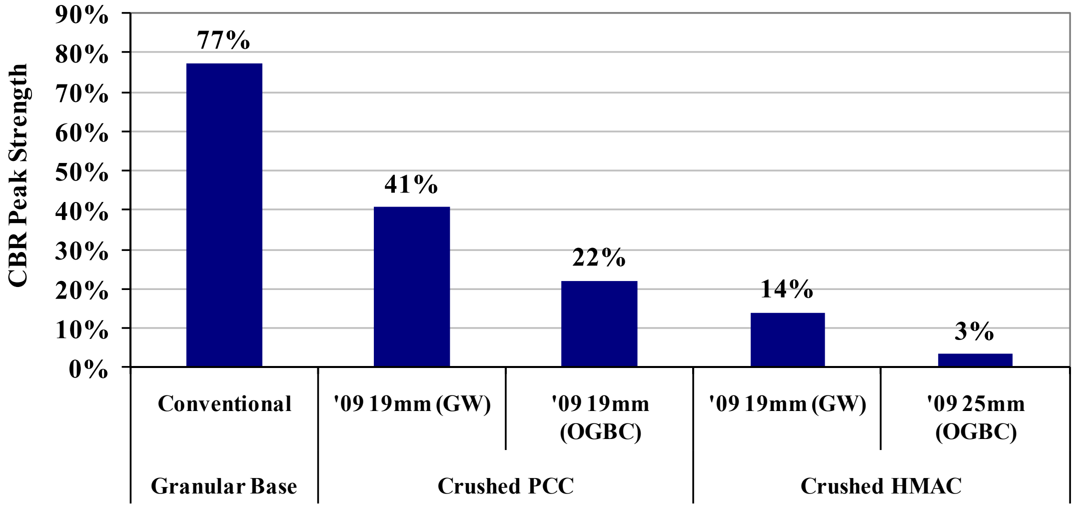

Figure 4: California Bearing Ratio Characterization of Materials

Due to the limitations of conventional test methods, the recycled materials were subjected to triaxial frequency sweep testing. The triaxial frequency sweep testing was completed to determine the mechanistic constitutive relations of the recycled materials across various stress states and load frequencies representative of Saskatoon field state conditions. The dynamic modulus determined through this testing quantifies the stiffness of a material under various states of dynamic loading and triaxial stress states.

As seen in Figure 5, the recycled materials showed improved stiffness behaviour in comparison to the conventional granular base. At high deviatoric and fully reversed stress states, conventional granular base failed under the loadings. However, the recycled HMAC and PPC aggregates did not fail under high deviatoric or fully reversed stress states. The recycled HMAC materials exhibited a greater sensitivity to load rate in comparison to the granular base and PCC materials, this is the result of the residual bitumen in the recycled HMAC materials.

When compared to conventional City of Saskatoon aggregate base materials the mechanistic properties of the recycled materials showed improvements between 30 and 50 percent and the high quality recycled materials showed improvements in excess of 200 percent (PSI Technologies 2010).

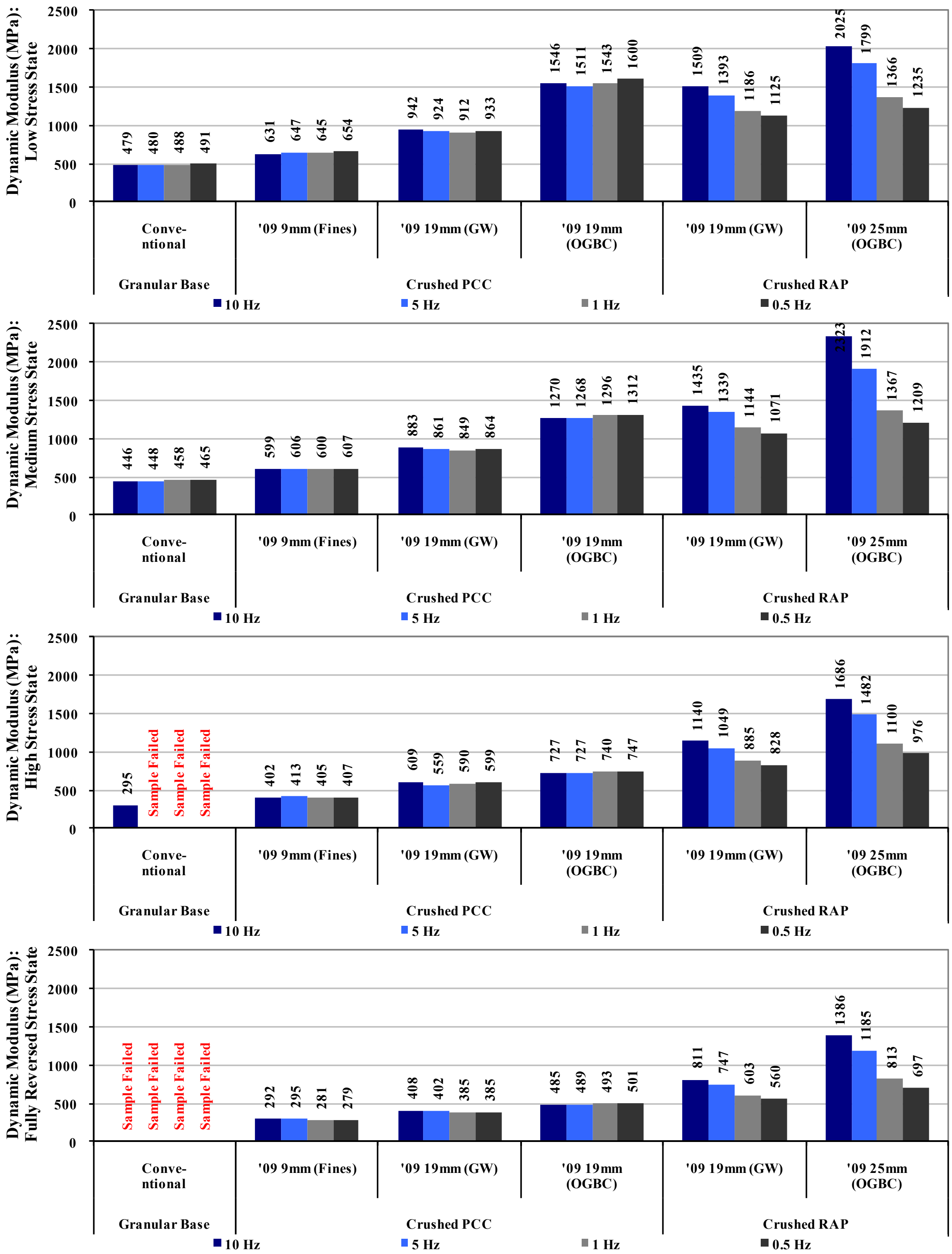

Figure 5: Dynamic Modulus Characterization of Materials

Understanding how recycled materials perform under severe climatic conditions is also critical given the severe Saskatoon field state conditions. As a result, climatic sensitivity testing including moisture conductivity and permeability characterization were conducted.

For climatic durability characterization, a 14-day ambient soak test was conducted for which the surface conductivity and percent moisture uptake were evaluated. As shown in Figure 6 it was observed that the recycled asphaltic rubble was the least susceptible to moisture uptake compared to the conventional base and PCC. The recycled PCC open graded base course showed improved climatic moisture durability over PCC materials with higher fines content. This is evidence that the removal of fines and deleterious materials is critical to have in the crushing process. All materials characterized were found to have permeability greater than 10^{-4}cm/s (PSI Technologies 2010).

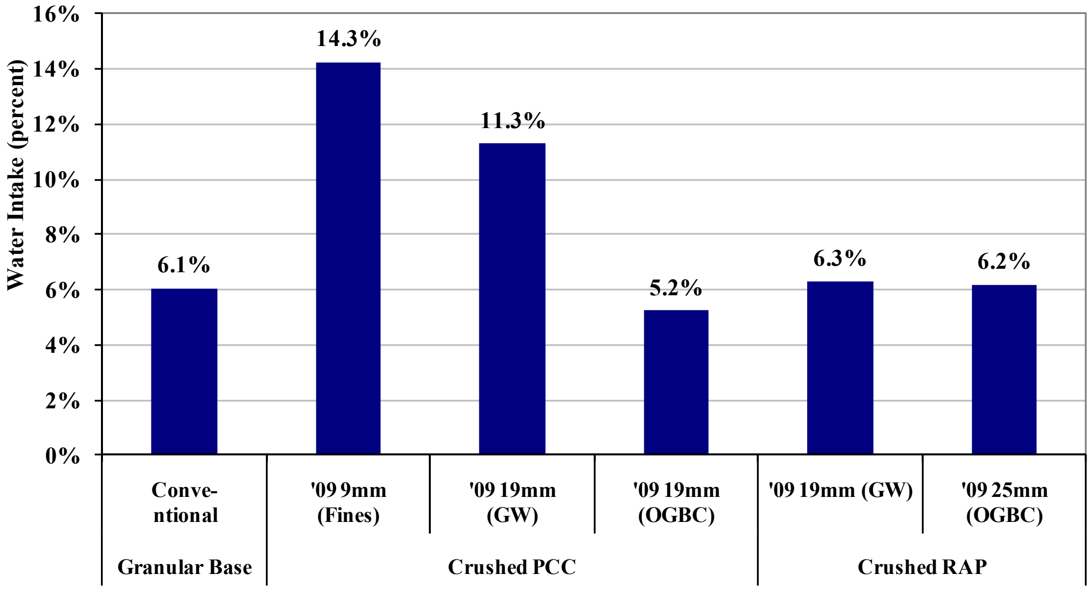

Figure 6: Climatic Moisture Intake

2.3 Holistic Sustainability Analysis

The triple bottom line definition of sustainability indicates that for sustainability to be realized there must br net benefits in economic, social and environmental areas (Wallace 2005). The technical merits of a well performing roadway must also be considered when looking at holistic sustainability. A holistic sustainability analysis framework was completed for the use of recycled materials in roadways.

Technical - Through mechanistic-climatic durability characterization, the recycled materials were compared to traditional materials under realistic field state conditions. The improved strain behaviour of the recycled materials relative to conventional granular base indicates that the recycled materials will likely have equal or superior field performance in comparison to conventional road construction materials.

Economic - Evaluation of the economics of using recycled materials was reviewed through the quality/performance of the materials and the lifecycle costs. The technical merit of recycled materials was discussed above. Through the implementation of the Green Streets Program the City of Saskatoon has seen significant savings, based on initial capital for aggregate materials in 2008 and 2009 of $1.37M and $1.65M respectively which is an approximately 55 percent savings. Through the technical advances in crushing operations in 2009, the 2010 projected savings are $1.81M, or 60 percent (PSI Technologies 2010).

Social - The social benefits that are realized through the reuse of recycled rubble materials in roadway construction include the diversion of waste from landfills, increased capacity for more rehabilitation work to occur, and better long term performance of the roadways. With the use of recycled materials, hauling distances are also reduced resulting in savings in fuel and less damage on highways caused by heavy truck traffic hauling aggregates over increasing distances. Traditionally rubble asphalt and concrete have been either landfilled or used as fill material. However, as the amount of available landfill air space is decreasing and the difficulties to site new landfills are increased, landfill air space is becoming more expensive. Currently the approximate value of the landfill space for Saskatoon is $\$50/m^3$. This cost is presumed to increase overtime. Through diversion of rubble PCC and HMAC, the life of the existing landfill may be of prolonged. Road users benefit from the use of recycled materials through the ability of the City to rehabilitate more roadways with the same budgets due to the lower cost of recycled materials in comparison to virgin aggregates. With the use of superior performing materials within the road structure, it is also expected that the roadway should also have an extended life.

Environmental – The quantification of the amount of energy used for three types of rehabilitation construction methods were reviewed. The three types of rehabilitation include conventional remove and replace, remove and replace with recycled materials and in-place recycling and strengthening. Haichert et el. (2009) found that, when compared to traditional construction methods, the amount of energy consumed with the use of recycled materials was significantly less mainly due to the reduction of the associated haul length distances. When using recycled materials the energy consumed for hauling was reduced by 51 percent and for in-place recycling and strengthening 79 percent compared to the conventional remove and replace (Haichert et el. 2009). In-place recycling used the least amount of energy mainly due to all of the materials were used in place and reduced hauling of materials was required. Based on these early calculations, further investigation of the environmental benefits of using recycled materials and alternative construction methods is planned.

3 Future Work

Through the success of the Green Streets Program, there have been two specific areas identified for further study. The first area is to further quantify the amount of energy consumed and carbon equivalents generated with the use of alternative rehabilitation methods. The second is the development of End Product Specifications for the use of recycled aggregates.

3.1 Construction Energy Consumption and Carbon Generation Quantification

As alternative methods of roadway rehabilitation are being used more readily and are proving to be performing as well or better than traditional road structural systems, construction methods, other aspects of the road construction process must be evaluated to distinguish the alternatives. At the same time, the need for and pursuit of sustainability within infrastructure has become important to many agencies. The work by Haichert et al. (2009) reviewed the amount of energy consumed in alternative methods of rehabilitation but was limited to the equipment used for construction. Further investigation into how material production, hauling and placement methods affect the amount of energy consumed as well as the amount of carbon equivalent emissions generated will be pursued. The information gathered through this research will allow the City of Saskatoon to move forward with constructing roadways that are technically sound and also consider the environmental implications of sustainable roadway construction.

3.2 Mechanistic Based End Product Specifications

A critical component to implementing recycled road materials systems is the implementation of end product performance based materials specifications that are based on sound engineering measures. The City of Saskatoon has identified that high quality road aggregate end products can be developed through crushing PCC and HMAC rubble which can be used within roadways as structural as well as drainage layers. To ensure that high quality end products are continually produced in the City of Saskatoon, the City has implemented mechanistic based End Product Specifications for climatic durability and material constitutive relations. As the City of Saskatoon is working towards becoming aggregate neutral for public works projects, the need for the production of materials to a consistent and technically proven product will ensure that the City will receive well constructed roadways to a minimum standard.

4 Summary and Conclusions

Through the Green Streets Road Recycling Program commissioned by the City of Saskatoon in 2009, the City is becoming a leader in the production, characterization and use of recycled PCC and HMAC rubble materials in roadways. Through this program the City has shown that rubble materials may be processed into high quality materials that perform mechanistically superior to traditional materials while still being in compliance with traditional road material physical characterization such as gradations.

The use of an impact crusher over a jaw-cone crushing system and the pre-processing or inclusion of a mechanism in the crushing process to reduce deleterious materials are keys to producing high quality materials. The City has found that five specified concrete products and three specified asphalt materials can be produced simultaneously with minimal waste at an average production rate of between 100 – 200 MT/hr on average.

Through the implementation of the Green Streets Program the City has been able to construct roadways that technically perform better compared to roadways constructed with conventional materials. The predicted cost savings on aggregate supply for 2010 through the use of recycled aggregates will allow the City to rehabilitate more roadways and therefore improve the overall condition of the City's network. Through the reuse of rubble materials that are generated in the City, haul distances and the associated road infrastructure damage as well as the energy consumed during construction are reduced.

The City of Saskatoon plans to continue the Green Streets Program and work towards being "aggregate neutral" for the projects completed by the Public Works Department. Work to further quantify the environmental impacts in terms of energy consumption and carbon equivalent generation and the development of End Product Specifications are underway.

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Utilization of Post Consumer Recycled Asphalt Shingles and Fractionated Recycled Asphalt Pavement in Hot Mix Asphalt

Andrew Cascione, R. Christopher Williams, Steve Gillen, Ross Bentson, and Debra Haugen

Abstract

The use of recycled materials for roadway construction has received increased interest from transportation agencies in the past several years. One commonly overlooked recycled material is the use of post consumer recycled asphalt shingles (RAS) in hot mix asphalt (HMA). With the availability of post consumer recycled asphalt shingles (RAS) increasing in the United States, there is a growing interest in the application of post consumer RAS in HMA. More than 10 million tons of post consumer shingles are being placed in landfills annually. These shingles contain and estimated 20 to 30 percent asphalt. The research presented in this paper studies the effects of post consumer shingles on the performance of HMA and its compatibility with fractionated recycled asphalt pavement (FRAP), the sizing and subsequent proportioning of RAP for use in HMA. In the summer of 2009 a field demonstration project was conducted by the Illinois State Toll Authority on Interstate Highway I-90. Eight mix designs containing five percent RAS and varying percentages of FRAP were developed and placed in three different areas of the pavement structure: the base course, the shoulder binder course, and the shoulder surface course. The field demonstration included five experimental sections and three control sections. Production and laboratory samples of the mixes were obtained for dynamic modulus testing. Master curves for each of the mixes were constructed and analyzed for material response at different temperatures and loading conditions. These material characteristic results indicate the experimental mixes contain an increased resistance to permanent deformation without a significant decrease in low temperature cracking susceptibility.

Introduction

The prevalence of asphalt shingles as a building material in the United States has created a steady supply of post consumer shingle waste that is being continually added to landfills. More than 10 million tons of post consumer asphalt shingles are being placed in landfills on an annual basis. Since post consumer shingles contain an estimated 20 to 30 percent asphalt binder by weight of the shingles, utilization of this waste product in Hot Mix Asphalt (HMA) not only presents an opportunity for cost savings when virgin asphalt prices are high but also an opportunity for environmental stewardship. Recycling asphalt shingles can be incorporated into HMA in lieu of virgin asphalt binder. This reduces the need for landfill space and greenhouse gases generated at refineries that produce virgin asphalt binder. Thus, a material that was previously known as a solid waste product can be used to create sustainable technologies in asphalt pavements.

The use of recycling asphalt shingles is not a new concept as RAS has been used in HMA for several decades, but only by local governments and private developers in smaller scale paving projects. Recently, more state transportation agencies have become interested in the use and applications of post consumer RAS in HMA for highway pavements. An application that is of particular interest to agencies is adding RAS with higher percentages of fractionated recycled asphalt pavement (FRAP).

Background

A typical recycled asphalt pavement (RAP) stockpile contains variable amounts of aggregate particles sizes and binder content. This variability lowers a producer's control of the HMA end product. By fractionating RAP into multiple sizes and stockpiles, a producer has more control during production than was previously possible with single size RAP. More control of RAP material allows for higher percentages of RAP to be used in HMA.

With higher percentages of RAP, the pavement stiffness modulus will increase (Valdés et al 2010). Stiffening of the asphalt pavement is caused by the change in rheological behavior of the RAP bitumen due to the effects of the construction process and long-term oxidative aging.

As with the asphalt in RAP materials, the asphalt in roofing shingles undergoes a similar aging phenomenon. However, the vast majority of asphalt aging is not from long-term exposure to the elements, but from the manufacturing process of the shingles. Asphalt used to coat shingles during production is first "air-blown", or bubbled, a process that incorporates oxygen into the asphalt and further increases the viscosity. Research completed by McGraw et al. (2007) concludes that both post manufacturer and post consumer recycled shingles stiffened HMA mixtures and that post consumer shingles provided the greatest stiffening effect.

Objective

An asphalt pavement with a higher stiffness exhibits a greater resistance to permanent deformation. While it has been demonstrated that higher amounts of FRAP or the use of RAS can enhance this performance characteristic of asphalt pavements, little research has been done using RAS and FRAP on major (high traffic level) state highways. The objective of this research is to study the effects of post consumer shingles on the performance of HMA on highway pavements containing FRAP, the effects of post consumer shingle compatibility with different amounts of FRAP on low traffic pavements, and the effects of sizing and subsequent proportioning of RAP in HMA.

The objectives of the research will be achieved by sampling and testing experimental mixes on an Illinois Tollway field demonstration project. The project is located on I-90 west of Chicago. Both field and laboratory mixes will be sampled and tested for dynamic modulus (E*) in the simple performance testing device. Master curves for each of the mixes will be constructed and analyzed for material response at different temperatures and loading conditions.

Dynamic Modulus

The dynamic modulus was chosen as the material parameter to characterize the pavement mixtures because it can be highly correlated to the occurrence of pavement distress (e.g., cracking and rutting). To obtain the dynamic modulus, an axial compressive stress is applied to a specimen in a haversine wave. The dynamic modulus is defined mathematically as the peak stress divided by the peak recoverable axial strain.

The testing procedure was derived from AASHTO TP 62 and adapted with in-house procedures for compatibility with the laboratory equipment. The in-house procedures deviated from the AASHTO procedures due to the omission of saw cutting the specimens. These in-house procedures were verified by Robinette et al. (2007) to produce statistically similar results as the AASHTO procedures. Furthermore, five replicate specimens of each sampled mix were fabricated and tested in a random order to reduce the standard error.

A gyrator compactor with a 100mm diameter mold was used to fabricate samples 150mm in height by 100mm in diameter at the design air void level. Each sample was tested at three temperatures (4^o, 21^o, and 37^oC) and nine frequencies (0.1, 0.3, 0.5, 1, 3, 5, 10, 15, and 25 Hz) to capture the viscoelastic properties of the HMA. By measuring the dynamic modulus at each temperature frequency combination, three dynamic modulus curves were plotted over frequency. Based on the time-temperature superposition of asphalt materials, the curves were shifted over frequency using a Levenburg-Marquardt least squares method to form one smooth. This curve can be used to characterize the performance of an asphalt pavement at various temperature and loading conditions. The response of a mixture at low frequencies can be correlated to its response at high temperatures (rutting potential) and its response at high frequencies can be correlated to its response a low temperatures (thermal cracking potential).

Project Scope

On July 29, 2009, the Illinois Tollway began a field demonstration project on I-90 west of Chicago. For the project, eight mix designs containing five percent RAS with varying percentages of FRAP were developed and placed in three different areas of the pavement structure: the base course, the shoulder binder course, and the shoulder surface course. The field demonstration included five experimental sections and three control sections as outlined in Table 1. The location of each section within the pavement layer is presented in Figure 1.

Table 1: Mix Design Plan

Mix Type	Section #	FRAP	Experimental Sections	Control Sections
Bituminous Base Mix w/ 2% air voids	1	30%	5% FRAP replaced with 5% RAS	Standard Mix w/ 50% FRAP
	2	40%	5% FRAP replaced with 5% RAS	
	3	50%	5% FRAP replaced with 5% RAS	
Shoulder Binder Mix w/ 3% voids	4	40%	5% FRAP replaced with 5% RAS	Standard Mix w/ 40% FRAP
Shoulder Surface Mix w/ 4% voids	5	25%	5% FRAP replaced with 5% RAS	Standard Mix w/ 25% FRAP

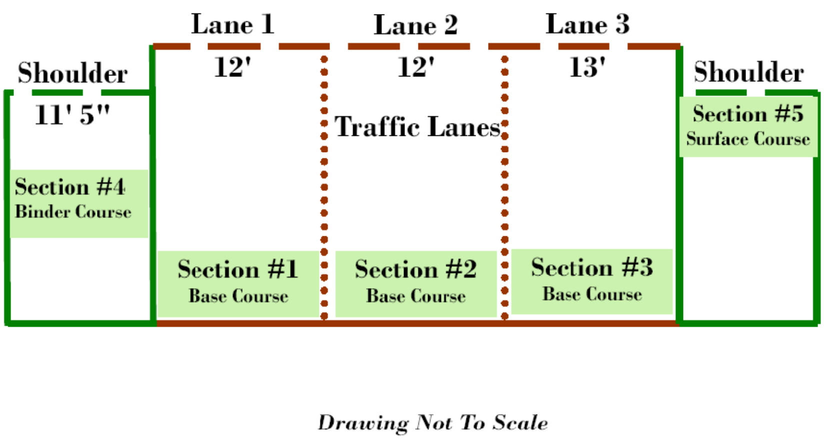

Figure 1: Cross-section of Experimental Section, Interstate I-90

Each mix design had a nominal maximum aggregate size of 12.5mm with a PG 58-22. The HMA was produced by Rock Road Companies at the Janesville/Beloit Plant in Wisconsin. The FRAP for each mix was comprised of two different RAP stockpiles. One stockpile contained RAP retained on the No. 4 sieve size, and the other stockpile contained RAP passing the No. 4 sieve size.

For each experimental section, field and laboratory samples were obtained to determine if the performance characteristics of the field produced mix significantly deviated from performance characteristics of the laboratory produced mix. For each control section, either a field or laboratory sample was obtained. A field sample was obtained for the Bituminous Base Mix control section, a laboratory produced sample was obtained for the Should Binder Mix control section, and a field sample was obtained for the Shoulder Surface Mix control section.

Results and Discussion

FRAP and RAS for High Volume Roads

The master curves from laboratory samples of experimental sections one through three are presented in Figure 2. These samples represent the Bituminous Base Mix sections in the high volume traffic lanes. Each mix has the same amount of RAS (5%) with different percentages of FRAP (25%, 35%, and 45%).

As the percentage of FRAP increases from 25% to 35%, the dynamic modulus increases at the low temperature and high temperature portions of the curve. This trend gives the indication that when 5% RAP is utilized in this Bituminous Base Mix in this FRAP range, the HMA increases in rutting resistance but decreases in low temperature cracking susceptibility. When the amount of FRAP is increased from 35% to 45%, there is no notable change in the shape of the curve.

Master curves from field samples of experimental sections one through three indicate a different trend than the corresponding laboratory samples. The master curves from field samples are presented in Figure 3. In the field produced samples there is no notable change in thermal cracking susceptibility with an increasing amount of FRAP. Rather, the 35% FRAP appears to have an unusually lower E* than the 45% FRAP sample. Since a review of the data proved no identifiable equipment error could be used to indicate if these results were inaccurate, the data was kept in the analysis. However, because the rest of the data suggests that rutting resistance increases with an increasing amount of recycled material, these results are suspect to be outliers.

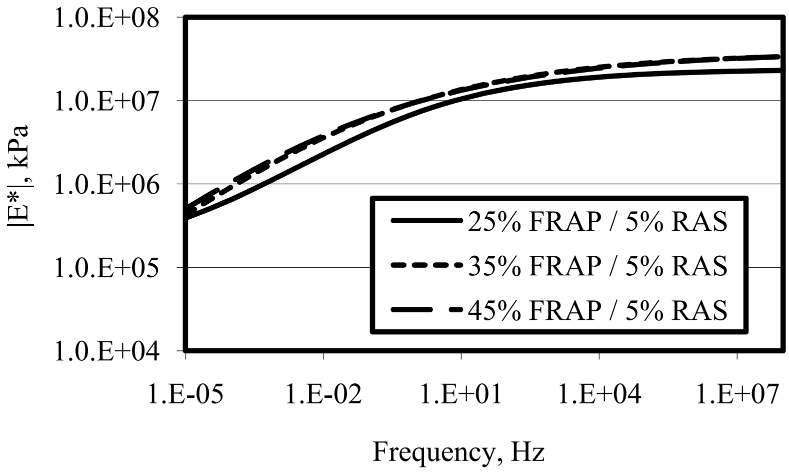

Figure 2: Bituminous Base Mix Laboratory Samples (Sections 1 – 3)

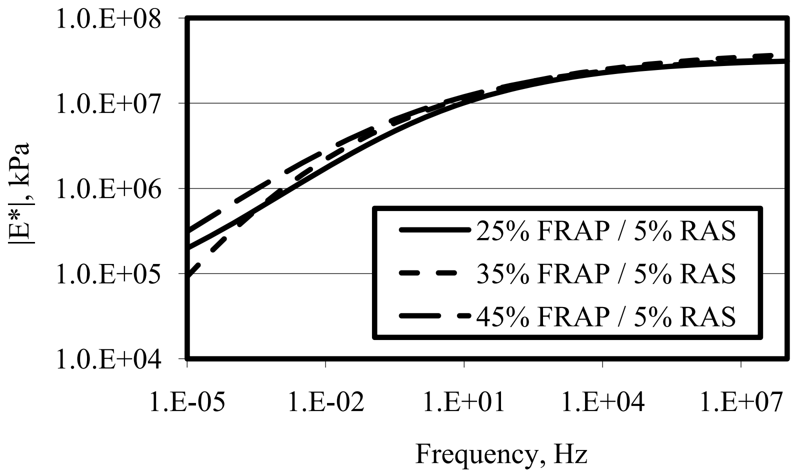

Figure 3: Bituminous Base Mix Field Samples (Sections 1 – 3)

Replacing FRAP with RAS in HMA

The master curves that compare experimental sections to control sections are presented in Figures 4 through 6. With respect to the Bituminous Base Mix in Figure 4, there is a slight difference in the shape of the curves for the experimental and control mix. The control mix has an increase in stiffness at the intermediate temperature range which indicates a possible increase in fatigue cracking susceptibility for this mix when RAS is not used. There is also an increase in stiffness in the experimental mix at high temperatures indicating improved rutting performance with 5% RAS replacement.

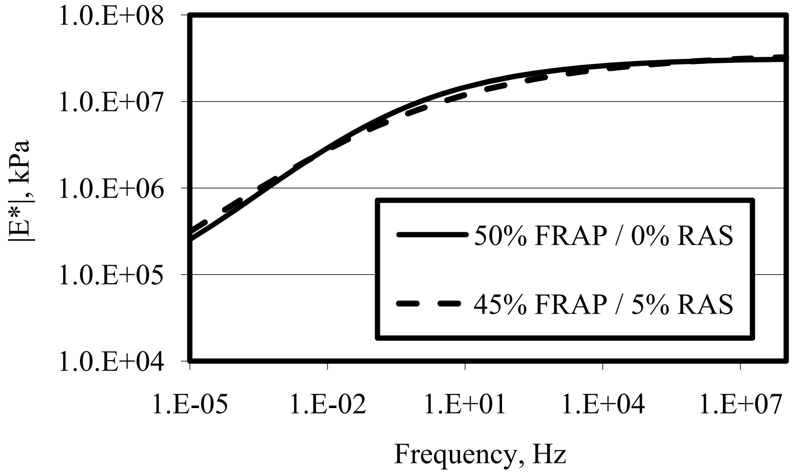

Figure 4: Bituminous Base Mix Laboratory Samples (Section 3)

With respect to the Shoulder Binder Mix in Figure 5, the effect of a high temperature / low frequency condition on the experimental mix slightly improves the rutting resistance of the material. There is also an increase in stiffness of the control section at the low temperature condition. This indicates that replacing 5% FRAP with 5% RAS for this mix design results in a decrease in low temperature cracking susceptibility. However, this is not indicated in the Figures 4 and 6.

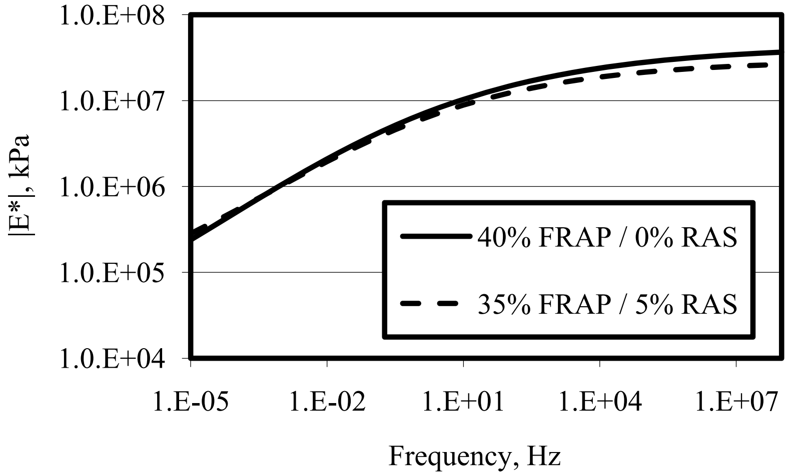

Figure 5: Shoulder Binder Mix Laboratory Samples (Section 4)

With respect to the shoulder surface mix in Figure 6, the stiffness clearly increases when replacing 5% FRAP with 5% RAS for this mix design giving a strong indication of increased rutting resistance in the experimental material. At the low temperature range of the curve there is no notable difference in the level of stiffness.

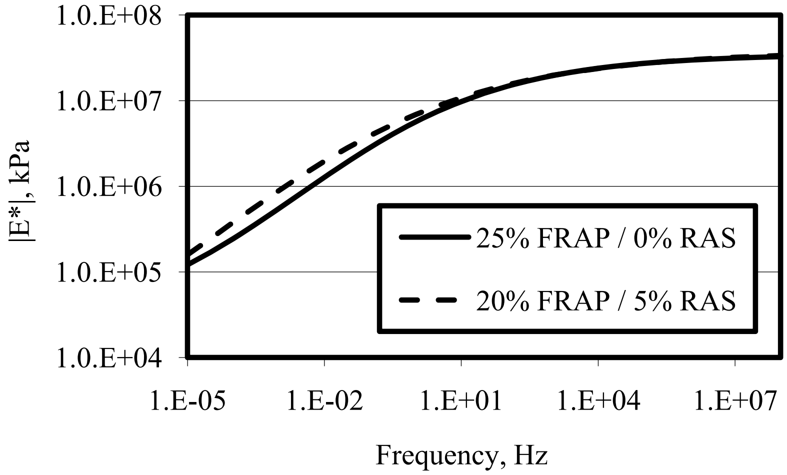

Figure 6: Shoulder Surface Mix Field Samples (Section 5)

Comparing Laboratory and Field RAS Mixes

The comparison between laboratory and field samples in Figures seven through 11 indicates an increase in stiffness at the high temperature range for all five sections. In this case stiffness not only gives an indication of rutting resistance but also the amount of aging that occurred in the field compared to the lab. A higher laboratory sample stiffness in all five sections indicates the lab samples did not represent the true aging the material incurred during production. The most likely scenario is the laboratory sample curing time was too long which aged the HMA more than what the hot mix asphalt production facility did.

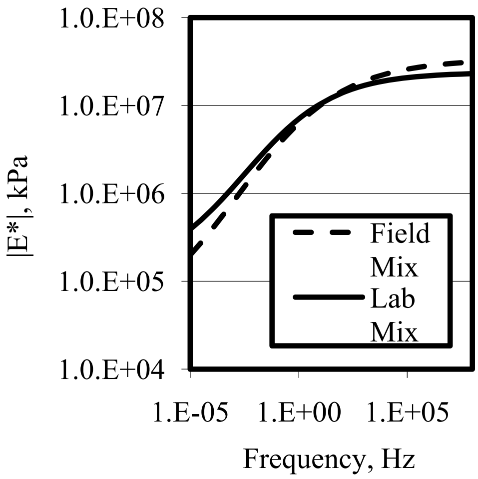

Figure 7: 25% FRAP Base Mix

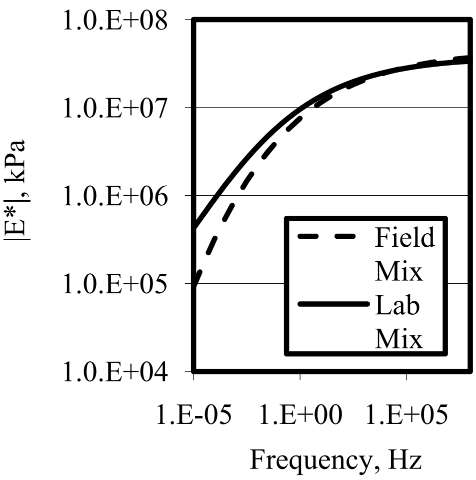

Figure 8: 35% FRAP Base Mix

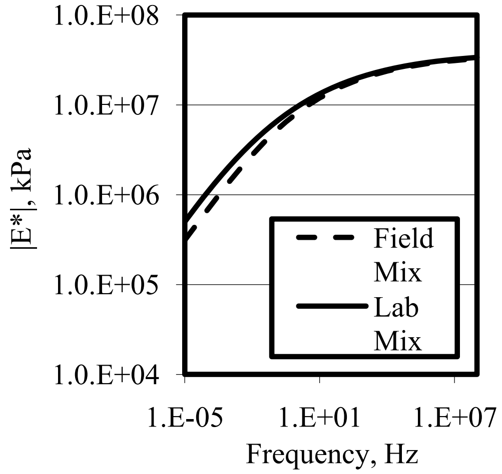

Figure 9: 45% FRAP Base Mix

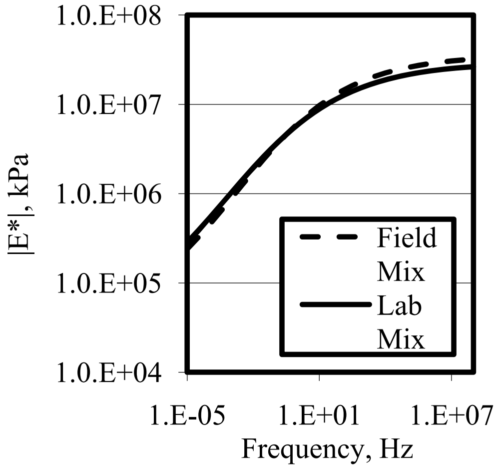

Figure 10: 35% FRAP Binder Mix

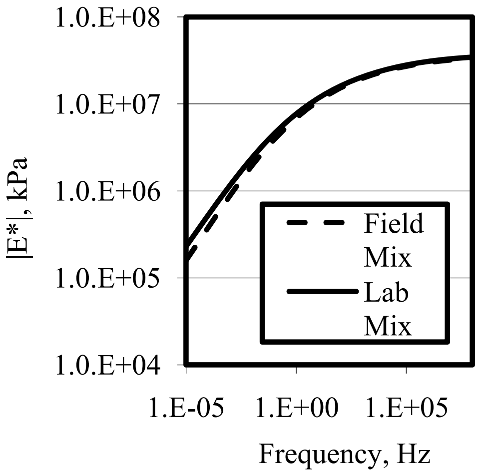

Figure 11: 20% FRAP Surface Mix

Conclusions

This paper describes the I-90 field demonstration project by the Illinois Tollway that used post consumer recycled asphalt roofing shingles with high amounts of fractionated RAP in experimental mix designs. The project included five experimental sections and three control sections. The experimental sections contained mix designs with 5% RAS and varying amounts of FRAP while the control sections contained mix designs with 0% RAS and FRAP. The mixes were placed in three different areas of the pavement structure: the traffic lane base course, the shoulder lane binder course, and the shoulder lane surface course.

Field and laboratory samples of the mix designs were obtained for measuring the dynamic modulus at three temperatures and nine frequencies. Master Curves were constructed to determine the how the behavior of the asphalt materials containing

RAS differed from the behavior of the asphalt materials not containing RAS when varying percentages of FRAP where a part of the mix designs.

The high traffic volume bituminous base course mix designs in sections one through three indicated the 45% FRAP mix design has an increased amount of rutting resistance compared to the 25% FRAP mix design. Although base course mixes typically do not fail in rutting, the data still indicates that higher amounts of FRAP with the utilization of RAS potentially improves the rutting performance characteristics of asphalt mixtures. The field mix data in sections one through three also indicate there is no notable increase in low temperature cracking susceptibility when increasing the amounts of FRAP.

When 5% RAS was used to replace 5% FRAP in a high traffic volume bituminous base course, a low volume binder course, and a low volume surface course and when high amounts of FRAP to intermediate amounts of FRAP were utilized in the mix design, the results of the master curves indicated an a increase in rutting resistance for the mix designs with 5% RAS. The increase in rutting resistance was more pronounced in the mix design incorporating lower amounts of FRAP than the mix designs incorporating higher amounts of FRAP. Based on the results of the dynamic modulus testing, replacing 5% FRAP with 5% RAS in asphalt pavements utilizing intermediate to high amounts of FRAP improves rutting resistance without decreasing the low temperature cracking resistance.

The laboratory produced samples for all five mix designs that utilized RAS exhibited a higher stiffness than the field mix designs. The materials used to fabricate the laboratory samples for these mix designs may need to be aged less in the oven to compare with the amount of aging that occurred during production.

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STRUCTURAL/HYDROLOGIC DESIGN AND MAINTENANCE OF PERMEABLE INTERLOCKING CONCRETE PAVEMENT

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ABSTRACT

Permeable interlocking concrete pavements (PICP) combine stormwater infiltration, detention and a riding surface for vehicles into one location. These pavements rely on an open-graded crushed stone base for storage, infiltration and vehicular support. Much research has been conducted on the hydrologic and water quality aspects. State and municipal best management practices (BMP) and low impact development (LID) manuals have incorporated design guidelines developed from university research, industry guidelines and experience by various agencies, project owners, civil engineers and contractors. This paper integrates hydrological and structural design for PICP for potential use in the emerging American Society of Civil Engineers (ASCE) guidelines for permeable pavement. Hydrological analysis determines if the volume of water from user-selected rainfall events can be stored and released by the pavement base. Designer-selected parameters determine how much water infiltrates the soil subgrade and/or is carried away by subdrains. Structural capacity for vehicular loads is determined using PICP industry design charts or the American Association of State Highway and Transportation Officials (AASHTO) 1993 structural design method. This paper includes design examples using these methodologies with an example using design software. The paper includes input design considerations as well as outputs for stormwater drainage and pavement design. In addition, recent experience is summarized on surface cleaning and surface repair.

Keywords: sustainable paving, permeable pavements, permeable pavement structural design, permeable interlocking concrete pavement

INTRODUCTION – SYSTEM DEFINITION AND TERMS

Permeable interlocking concrete pavement (PICP) surfaced with manufactured concrete units reduce stormwater runoff volumes, outflow rates and pollutants. Base layers support the pavers while providing storage and runoff treatment.

PICPs are visually attractive, durable, easily repaired, require low maintenance and can withstand heavy vehicle loads.

Figure 1 illustrates a PICP cross section and a definition of the pavement components follows.

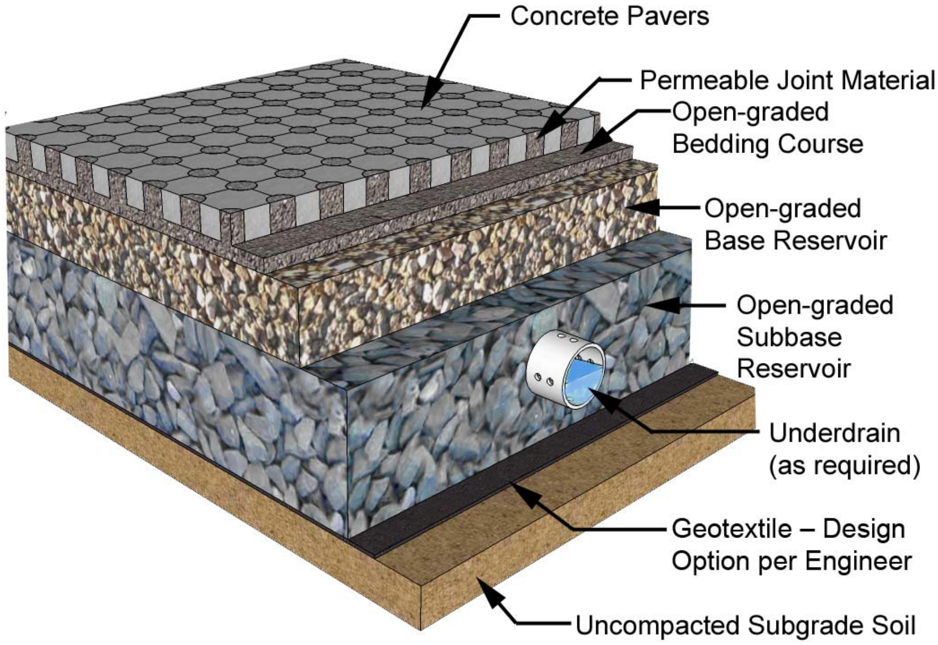

Figure 1. Typical PICP components

- Concrete pavers with permeable joint material comprise the PICP surface layer of PICP. Concrete pavers should conform to American Society for Testing and Materials, ASTM C 936 in the U.S. or Canadian Standards Association, CSA A231.2 in Canada. Pavers are typically 80 mm (3 1/8 in.) thick for vehicular areas and pedestrian areas may use 60 mm (2 3/8 in.) thick units. They are manufactured in a range of shapes and colors and can be produced with light colored surfaces to satisfy a minimum solar reflectance index or SRI of 29 per ASTM E 1980 (ASTM 2009). The top surface of units may also be coated with photocatalytic cement materials containing titanium oxide to reduce nitrous oxide air pollutants (Beeldens 2008). The impervious units have joints and/or openings that typically comprise 5% to 15% of the paver surface. These are filled with highly permeable, small-sized aggregates such as ASTM No. 8, 89 or 9 stone. The permeable joints allow stormwater to enter a crushed stone, open-graded aggregate bedding course.
- Open-graded bedding course – This permeable layer is typically 50 mm (2 in.) thick and provides a level bed for the pavers. It consists of small-sized, open-graded aggregate.
- Open-graded base reservoir – This is an aggregate layer 75 to 100 mm (3 to 4 in.) thick and made of crushed stones typically 20 mm down to 5 mm

(3/4 in. to 3/16 in.). Besides storing water, this high infiltration rate layer provides a transition between the bedding and subbase layers.

- Open-graded subbase reservoir – The stone sizes are larger than the base, typically 65 mm down to 20 mm (2½ in. to ¾ in.). Like the base layer, water is stored in the spaces among the stones. The subbase layer thickness depends on water storage requirements and traffic loads. A subbase layer may not be required in pedestrian or residential driveway applications. In such instances, the base layer thickness is increased to provide water storage and support. The base and subbase layers should have a minimum void ratio of 32% for water storage.
- Underdrain (optional) – In sites where PICP is installed over low-infiltration soils underdrains facilitate water removal from the base and subbase. The underdrains are perforated pipes that connect to an outlet structure. Supplemental storage can be achieved by using a system of pipes in the aggregate layers. The pipes are typically perforated and provide some additional storage volume beyond the stone base. Significant amounts of runoff can be stored under or adjacent to PICP using plastic or concrete vaults or plastic crates.
- Geotextile (optional) – This can be used to separate the subbase from the subgrade and prevent the migration of soil into the aggregate subbase or base.
- Subgrade – The layer of soil immediately beneath the aggregate base or subbase. The infiltration capacity of the subgrade determines how much water can exfiltrate from the aggregate into the underlying soils. The subgrade soil is generally not compacted. However, poorly draining clays are often compacted to help insure structural stability especially when saturated. Compaction of course reduces water infiltration substantially and managing the excess water must be considered in the hydrologic design via the base/subbase thickness and use of perforated pipe underdrains.

RESEARCH – PAST, PRESENT AND FUTURE

Much research has been conducted on the hydrologic and water quality aspects provided by these bases. While this paper is not intended to provide a detailed literature list and review, institutions and researchers noted below provide a broad range of information on infiltration performance, water volume and pollutant reductions as well as maintenance and air pollutant (nitrous oxides/smog) mitigation with photocatalytic cements.

- Central Florida University by Professors Manoj Chopra and Martin Wanielista's study examined surface clogging and restorative vacuuming of PICP, porous asphalt and pervious concrete. Their paper appeared in the Conference Proceedings of the ASCE 2010 International Low Impact Development Conference, San Francisco, CA.
- City of Chicago Department of Transportation: Janet Attarian, AIA introduced and implemented the "Green Alleys" of various permeable pavements types including PICP to reduce combined sewer overflows. Other cities such as Los Angeles, CA and Richmond, VA have developed green alley projects. Visit

http://brandavenue.typepad.com/brand_avenue/files/greenalleyhandbook.pdf. Ms. Attarian is currently conducting studies examining the reduction of nitrous oxides air pollutants using photocatalytic cements in PICP on a Chicago street.

- Coventry University, UK: Professors Christopher Pratt, Stephen Coupe, and Alan Newman have done numerous laboratory and in-situ studies of PICP, especially studying the ability of PICP and geotextiles to process (digest) oils. Coupe has done additional research integrating horizontal ground source heat pumps with PICP as a means to reduce building heating and cooling energy use. Some of the their papers appear in the 2006 and 2009 Conference Proceedings of the 8th and 0th International Conferences on Concrete Block Paving in San Francisco, CA and Buenos Aires, respectively. Now retired, Professor Pratt composed one of the most comprehensive pre-2004 literature reviews on all permeable pavement research in the Europe, the U.S. and Canada. Professors Coupe and Newman are no longer in academia but are working in allied fields.
- Hannover University, Germany: Professor Sönke Borgwardt has written many papers (some in English) examining surface clogging of PICP and concluded that while surface infiltration decreases from normal use, PICP can infiltrate most storms. His salient papers appear in *BFT Magazine* (Precast Concrete Technology) published in Germany as well as in the Conference Proceedings of the 8th International Conference on Concrete Block Paving, 2006 San Francisco, CA. Professor Borgwardt is currently an independent consultant.
- Morton Arboretum, Lisle, Illinois: Andrew Sikich. PE and Patrick Kelsey. PE introduced PICP and published papers in the 2002 Stormcon Conference Proceedings. Both authors are consulting engineers.
- North Carolina State University: Professor William Hunt with Eban Bean and Kelly Collins provided extensive infiltration studies of PICP and concrete grid pavements as well as examined PICP and pervious concrete at several sites in North Carolina. Visit http://www.ncsu.edu/picp/ for more information.
- Toronto and Region Conservation Authority: Tim van Seters, Glenn MacMillan conducted a three year study of PICP and a bioswale at a heavily used parking lot at a community college. The annual and final reports provide a wealth of data showing how soils under PICP process stormwater pollutants. A new three year study of another parking lot with various permeable surfaces was initiated late in 2009.
- University of Connecticut: Professor John Clausen conducted a year-long evaluation of PICP in residential driveways comparing water quantity and quality to that from asphalt driveways. Visit http://www.jordancove.uconn.edu/jordan_cove/publications/final_report.pdf.
- University of Guelph: Professor William James examined pollutants and clogging and restoration of surface infiltration of PICP. Many of his papers are found in *Modeling the Management of Stormwater Impacts*, Vol. 5, Ann Arbor Press, 1997.
- University of Washington: Professor Derek Booth examined reduction of metals under PICP. A summary of his work is found in

http://www.lowimpactdevelopment.org/pubs/Permeable_Pavement_factsheet.pdf.

- In October 2009, the US EPA commissioned a multi-year research project on PICP, pervious concrete and porous asphalt parking lots at their National Risk Management Research Laboratory in Edison, New Jersey. A paper introducing this project was presented at the ASCE 2010 LID Conference in San Francisco, CA.

Reports on research and monitoring projects are expected in coming years from the following academic institutions and agencies. The list below is by no means comprehensive as there are other federal, state and local agencies initiating PICP monitoring projects.

- Denver Urban Drainage & Flood Control District: Kenneth McKenzie, PE and other staff are evaluating the water pollution reduction performance of PICP and porous asphalt in central Denver, CO.
- Elmhurst College, Illinois: Professor Eugene Losey is evaluating PICP pollution processing on PICP parking lots at this college in Elmhurst, IL.
- University of New Hampshire Stormwater Center: Professor Robert Roseen has initiated a PICP study where monitoring will begin in late summer 2010 on a PICP road and parking lot in the central university campus.

With respect to LID and BMP design manuals, many states and cities have incorporated PICP into them. Some of these guidelines are outdated since much of the research noted above has occurred within the past five years. This growing body of knowledge provides additional design guidance for these state and local regulatory agencies to issue updated information.

Among many BMP design guidelines for PICP, one recently drafted by the Virginia Department of Conservation and Recreation communicates exemplary guidance. Authored for this agency by Kelly Collins with the Center for Watershed Protection and Tom Schueler with the Chesapeake Stormwater Network, the design approach provides pollutant credit with volume reductions using PICP and other permeable pavements. See http://www.vwrrc.vt.edu/swc/OctoberUpdates/PermeablePavementSpec7.html.

Finally, ASCE Permeable Pavements committee through the ASCE Environmental & Water Resources Institute is expected to release a practice guide for PICP, porous asphalt, pervious concrete and other permeable pavements in fall 2010.

PICP CONSIDERATIONS AND LIMITATIONS

PICP new and retrofit applications include patios, walks, residential driveways, commercial plazas, parking lots and low-speed roads. Basic site considerations include the following:

Soils - PICP can be used in a range of soil infiltration rates. Soil infiltration capacity should be measured through on-site testing with a double-ring infiltrometer per ASTM D 3385 or ASTM D 5093. High infiltration rate soils will generally not require under drains in the subbase while some silts and most clay soils will require underdrains to remove excess water. PICP with underdrains can be used over clay soils with infiltration rates as low as 3×10^{-7} m/sec (0.05 in/hr.). Such designs may require additional subbase depth and/or area for water storage. Sites with seasonally high water tables, high depth to bedrock, low-strength or expansive soils can use PICP with impervious liners under the stone base reservoir. While there is no infiltration and volume reduction, there are peak flow delay and water quality benefits from the stone base detaining and filtering the runoff before release.

Topography - The bottom of the reservoir should be flat or slightly sloped to allow uniform infiltration. For soil subgrade slopes greater than 2%, terracing of the subgrade may likely be needed to slow runoff from flowing through the pavement structure. The PICP surface is sloped at 0.5% to a maximum of 5% to encourage surface drainage should the surface become inadvertently and completely clogged.

Water Table – PICP should be located at least 30 m (100 ft) from drinking water wells and with a minimum of 0.6 m (2 ft) of soil above the seasonally high ground water table. PICP (infiltrating into the soil subgrade) has been successfully performed in coastal areas on sandy soils with higher water tables with and without underdrains. PICP with an impermeable liner should have at least 0.3 m between the bottom of the liner and the seasonal high ground water table.

Hotspots – PICP is not appropriate for stormwater hotspots where hazardous materials are loaded, unloaded or stored where there is a potential for spills and fuel leakage.

Pretreatment – Stone-filled openings in PICP surfaces pretreat runoff that enters the stone reservoir by trapping sediment and fines (i.e., material passing the 0.075 mm sieve). Periodic surface cleaning is necessary to prevent clogging from sediment and fines. While not always convenient to incorporate into most PICP, effective off-site pretreatment methods are upslope/up flow bioswales, rain gardens or sand filters that trap sediment before it enters the PICP surface.

Drainage area – PICP can receive stormwater from adjacent drainage areas, but such areas should have soils fully stabilized with vegetation. Measures should be taken to protect PICP from high sediment loads, particularly fine sediment during and after construction. Runoff from disturbed areas should be diverted away from the PICP until they are stabilized. Preventing sediment from entering the base or permeable pavement is critical during and after construction while adjacent vegetation is growing.

Managing Overflows – When the storage capacity of the base/subbase is exceeded in extreme rain events, overflow can be managed by raised storm drain inlets, perforated pipes, an overflow swale/trench or bioswales next to the permeable pavement. Figure 2 illustrates this approach.

Figure 2. PICP overflow to a bioswale at Elmhurst College parking lot, Elmhurst, Illinois

ADA - There are many PICP paver designs on the market. PICP openings and joints filled with aggregate comply with the 2004 Americans with Disabilities Act Design Guidelines. If smoother surfaces are needed, such areas can be paved with solid interlocking concrete pavements.

Construction – PICP installation requires specialized, experienced contractors who understand material and construction requirements for these systems. The industry association for PICP, the Interlocking Concrete Pavement Institute (ICPI), has initiated a training course for contractors entitled the "PICP Installer Technician Certificate Course" (ICPI, 2009). Such credentials have been placed in project specifications in an effort to increase quality control and quality assurance. While no construction training course guarantees adequate field construction, this course can help civil engineers and project owners differentiate contractors experienced with PICP from those who only construct conventional pavements.

Water Pollutant Reduction - PICP reduces pollutant concentrations and mass loads through several processes. The aggregate filters the stormwater and slows it sufficiently to allow sedimentation to occur. Sandy soils will infiltrate more stormwater, but have less treatment capability. Clay soils have a high cation exchange capacity and will capture more pollutants such as metals, but will infiltrate less. Also, studies have found that in PICP encourages treatment via bacteria in the soils and beneficial bacteria growth has been found on established aggregate bases (Newman 2002). In addition, PICP can process oil drippings from vehicles (Pratt 1999). While there is an extensive body of literature on PICP pollutant removals, Table 1 provides measured pollutant removals from a sample of studies.

Table 1. Monitored Pollutant Removals of PICP

Application	Location	TSS	Metals	Nutrients
Driveways (1)	Jordan Cove, CT	67%	Cu: 67% Pb: 67% Zn: 71%	TP: 34% NO_3-N: 67% NH_3-N: 72%
Parking lot (2)	Goldsboro, NC	71%	Zn: 88%	TP: 65% TN: 35%
Parking lot (3)	Renton, WA	--	Cu: 79% Zn: 83%	--
Parking lot (4)	King College, ON	81%	Cu: 13% Zn: 72%	TP: 53% TKN:53%

(1 - Clausen 2006) (2 - Bean 2005) (3 - Brattebo 2003) (4 - Van Seters 2007)

Van Seters (TRCA 2007) compared pollutants in soils under and next to six PICP sites 3 to 16 years old in Ontario. There were no increases in oils (PAHs), iron, lead, zinc, copper in soils under the PICPs compared to soils adjacent to them. Chlorides saw some increase under the PICP sites and would be expected under all permeable pavements subject to snow and deicers. Like other permeable pavements, PICP drains snowmelt, offering an opportunity to reduce deicing materials. Van Seters also documented the condition of the six PICP sites and found that they were providing adequate structural support after years of use.

PICP water quantity and pollutant reduction characteristics such as 80% total suspended solids (TSS) reductions can qualify it to earn credits under sustainable building evaluations systems such as Leadership in Energy and Environmental Design (LEED®) and Green Globes. Credits also can be earned for water conservation, urban heat island reduction, conservation of resources by utilizing some recycled materials and regional manufacturing and resource use. In addition, PICP is now being used as an energy storage medium for horizontal ground source heat pumps (Coupe 2009). This represents an innovative integration of stormwater management with building energy conservation.

Industry Resources - ICPI provides a significant amount of information through a manual entitled, *Permeable Interlocking Concrete Pavements – Selection Design Construction Maintenance* (Smith 2006). In addition guide specifications for PICP construction are available on icpi.org. These include a density testing method for the base layer plus methods for quality control and quality assurance for construction planning and execution. In addition, ICPI offers a sophisticated software program for hydrologic and structural PICP design called *Permeable Design Pro* (Swan 2009). This software incorporates infiltration plus inflow/outflow hydrographs and structural design using the American Association of State Highway and Transportation Officials (AASHTO) flexible pavement design methodology. The following sections provide an overview of the PICP design and illustrate an example using this software program.

INTEGRATING HYDROLOGICAL AND STRUCTURAL DESIGN

Hydrological Design - PICP hydrological design generally relies on the following variables:

- Design storm or storms, typically issued by the local stormwater agency

- Long-term soil infiltration rate, estimated from soil samples or field measured with an appropriate safety factor added by the designer
- Base/subbase reservoir thickness and storage capacity

The stormwater quantity entering the pavement surface is described as a water balance among sources and destinations. These are shown in Figure 3. *Permeable Design Pro* software uses algorithms developed for the U.S. Federal Highway Administration's Drainage Requirements in Pavement or DRIP model (Mallela 2002). The analysis procedure uses small time steps to estimate the expected water inflow from precipitation and any surrounding areas that drain onto the PICP. The outflow from surface runoff to groundwater recharge and subsurface drainage during each time step is also estimated. The inflow/outflow analysis enables the water level in the pavement base/subbase to be estimated during the storm and while draining afterwards. Antecedent water levels in the base/subbase can also be modeled to simulate the outflow effects from sequential storms. Water harvesting can be modeled by limiting the subgrade infiltration rate. Each input design variable is summarized below.

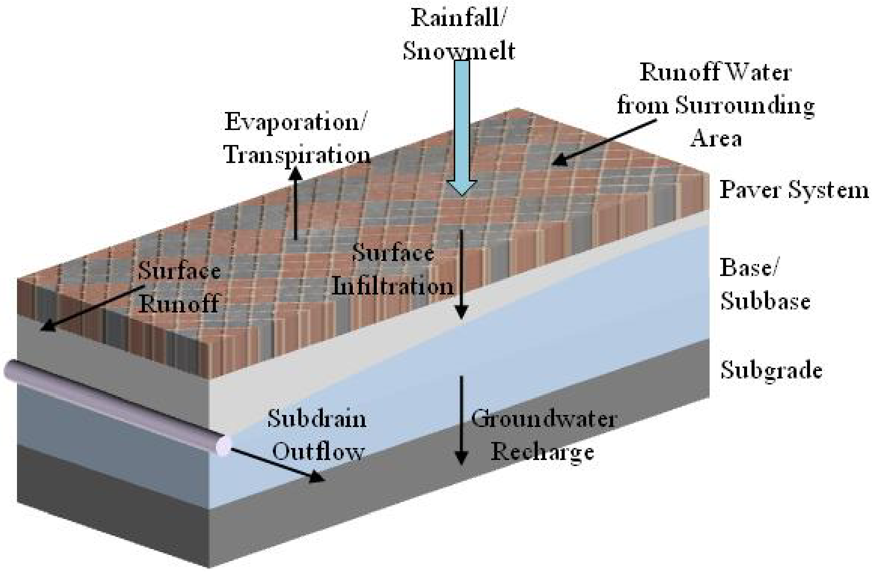

Figure 3. Inflow and outflow of water on permeable pavement

Runoff from Surrounding Area - Water entering the PICP surface including surrounding areas is estimated using rainfall, soil type, land use and runoff characterizations based on the Natural Resource Conservation Service Technical Release 55, *Urban Hydrology for Small Watersheds* (NRCS 1986). All inflow from adjacent areas is assumed to be sheet flow. PICP surface infiltration rates can be input by the user based on test results data and/or experience.

Rainfall - Rainfall events can be selected from 2 year to 100 year storm events. The software contains a library of storm events for Canada and the United States, and allows for additional rainfall events and sites to be manually entered. Rainfall timing can be important when evaluating PICP potential to infiltrate water from surrounding areas. The time delay between the rainfall on these areas (with some infiltration) and the time the water enters the PICP surface during the peak rainfall intensity can also reduce the peak outflow, thereby conserving the need for larger storm sewer pipes and reducing potential downstream erosion.

Water Outflow - Stormwater exits PICP via groundwater recharge (soil subgrade infiltration), subdrains (generally perforated pipes) and through evaporation/ transpiration. *Permeable Design Pro* estimates the water infiltrating into the soil subgrade and into pipe subdrains. The drains are typically used with low infiltration soils and the user can specify the pipe size, slope, horizontal spacing and height above the soil subgrade. The latter can be important to creating some water detention in the base for infiltration and nutrient reduction. Besides modeling complexities, evaporation and transpiration are considered insignificant and are not part of the program.

Groundwater Recharge (subgrade soil infiltration) - Based on the user selected soil subgrade permeability, the program assumes saturated conductivity and calculates infiltration over time using Darcy's Law (Cedegren 1989). Since the water table is typically some distance below the base/subbase layer, the hydraulic gradient can be assumed to be 1.0 as the drop in elevation causes downward flow. The program assumes that drainage occurs uniformly across the bottom of the pavement as the base/subbase becomes saturated. Specifically:

$$Q_{Groundwater} = k_{Subgrade} \cdot \frac{Depth\ of\ Water\ in\ Pavement}{Thickness\ of\ Pavement} \cdot Subgrade\ Infiltration\ Factor$$

Where:
$Q_{Groundwater}$: Flow rate of water into groundwater recharge (m/day, ft/day)
$k_{Subgrade}$: Hydraulic conductivity of the subgrade material (m/day, ft/day)
Subgrade Infiltration Factor: Expected reduction in subgrade permeability due to clogging

Since predicting sediment loading within the base/subbase is practically impossible, a subgrade infiltration reduction factor can be applied to conservatively account for potential clogging and reduction of the soil subgrade infiltration rate. The base/subbase water depth changes and as this factor increases, and the static pressure increases affecting the drainage rate.

PICP may be designed to detain water which can assist in nutrient reduction. This approach is more amenable in low-infiltration rate clay soils. In such cases, detention pond design principles can be applied to inflow, storage and outflow calculations. The maximum resident time for water should not exceed 72 hours. Excess water that cannot be contained by the base is allowed to exit via swales or to adjacent bioretention areas, through pipes in the base, and/or into catch basins.

Structural Design – To integrate hydrological and structural design, the base/subbase thickness is determined for hydrological and structural (traffic loading) needs, and the thicker section is selected. Hydrological design is a straightforward task for stormwater managers, but structural (base thickness) design is not, due to inexperience and a lack of information on the structural performance of open-graded bases used in them. This information is essential to providing durable designs that can withstand repeated vehicular traffic.

For structural design of impervious (conventional) roads and base, many local, state and provincial agencies use design methods published by AASHTO. While the AASHTO methodology is familiar to many civil engineers, stormwater agency personnel who do not deal with pavement design are encouraged to become more familiar with them and reference them in permeable pavement design recommendations for local, state or provincial BMP and LID manuals, and regulatory documents.

Highway engineers are increasingly using AASHTO *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures* (2004) which relies on mechanistic design and modeling, i.e., analysis of loads and resultant stresses and strains on materials and the soil subgrade. The AASHTO mechanistic design model was developed and calibrated by state, provincial and federal highway agencies across a wide range of highway loads, load testing, soil types and climatic conditions. This model has not been calibrated for permeable pavements (subject to significantly less traffic loads) constructed with open-graded, crushed stone bases.

Many local transportation agencies use the empirically-based AASHTO 1993 *Guide for Design of Pavement Structures* (AASHTO 1993) whose underlying concepts emerged from test pavements in the 1950s repeatedly trafficked by trucks that established relationships among materials types, loads and serviceability. The AASHTO equation in the 1993 *Guide* calculates a Structural Number or SN given traffic loads, soil type, climatic and moisture conditions. The designer then finds the appropriate combination of pavement surfacing and base materials to meet or exceed the Structural Number. This empirical design approach appears to be applicable to permeable pavements with consideration given to input variables.

Due to their load distribution means PICP is considered a flexible pavement system. The previously mentioned ICPI manual provides a base/subbase thickness design chart given axle loads, soils and frost considerations. Since PICP is a flexible pavement, design concepts in AASHTO can be applied to it. A key input for flexible pavement design is the layer coefficient which characterizes each pavement layer with a number. The higher the coefficient, the stiffer the material and the coefficient is expressed per inch or per millimeter of pavement layer thickness. The thickness of each material is multiplied by the layer coefficients and all coefficients are added to equal or exceed the Structural Number.

For example, given site specific inputs on subgrade soil strength, climate, moisture and traffic loads into the AASHTO equation yields a required structural number of 2.5. The designer then identifies the combination of pavement layer materials whose layer coefficients total at least 2.5. In this illustration, a compacted, dense-graded crushed stone base typically has a layer coefficient of 0.14. Asphalt typically has a layer coefficient of 0.44. If 3 in. (75 mm) of asphalt are selected, then the SN for this layer is 0.44 x 3 = 1.32. The base layer thickness required would then be 2.5 – 1.32 = 1.18/0.14 = 8.4 or about 9 in. (225 mm) which satisfies the required Structural Number.

The layer coefficients of dense-graded bases generally range from 0.10 to 0.14 per inch or 25 mm of material thickness. The layer coefficients of open-graded crushed stone aggregates such as ASTM No. 57 and ASTM No. 2 stone are not well understood nor has there been significant research defining their structural capacity using empirical means or mechanistic analysis. A preliminary, yet to be published mechanistic study has been conducted by Caltrans for pervious concrete and porous asphalt as well as ongoing in-situ research by the Minnesota Department of Transportation (MnRoad).

There is general agreement that layer coefficients for open-graded materials are lower than that used for dense-graded materials. Some designers decrease layer coefficients for open-graded bases by 40% to 50% to account for lower strengths. This considers saturated conditions as well as less mass (i.e. 30%-40% void space) available to generate shear transfer of applied loads. There is a substantial need for in-situ measurements of stiffness and resilient modulus of open-graded bases under PICP to apply to mechanistic design as well as to better understand their highly stress-dependent nature. In the meantime, thick open-graded bases as a result of conservative structural design serve the hydrological needs for water storage and infiltration of some or all of the water, as well as provide for unpredictable decreases in soil subgrade infiltration from long-term sedimentation.

Many studies have defined the layer coefficient of interlocking concrete pavements and bedding sand layer as equal to or higher than an equivalent thickness of asphalt, typically 0.44 per inch (or 25 mm) of thickness. These values have been verified with years of laboratory and in-situ testing. In contrast, a very limited number of studies have conservatively defined the layer coefficient as 0.30 for the PICP surface layers, i.e., 3.125 in. (80 mm) thick and a 2 in. (50 mm) thick bedding layer of typical ASTM No. 8 bedding stone directly under permeable interlocking concrete paving units. Additional full-scale accelerated traffic load studies are needed to better define the layer coefficient and stiffness or elastic modulus of these layers.

Characterizing Traffic Loads - When a vehicle passes over a pavement, it damages it. The cumulative effects of many passes eventually causes ruts or cracks making the pavement unserviceable and needing rehabilitation. Vehicles passing over a pavement exert a wide range of loads. Compared to cars, trucks and busses do the most damage to pavements because their wheel loads and tire pressures are much heavier and higher than cars. One pass of a fully loaded truck will do more damage to pavement than several thousand cars passing over it. The AASHTO *Guide* characterizes traffic loads as the number of 80 kN or 18,000 lbs equivalent single axle loads or ESALs. The 80 kN (18,000 lbs) load emerged from the AASHTO road tests conducted in the 1950s and has remained as a convenient means to quantify loads.

The number of ESALs is determined by the weight of each of the axles and dividing them by a ‘standard’ ESAL of 80 kN (18,000 lbs). A five axle tractor-trailer truck provides an example: two rear axles on the trailer each exert 80 kN 18,000 lbs; two on the back of the truck at 70 kN 15,800 lbs; and one in the front (steering) at 50 kN (11,000 lbs). AASHTO uses the following relationships called

load equivalency factors or LEFs for each axle to estimate ESALs. LEF and ESALs for this truck are as follows:
Trailer: $(80/80)^4$ = 1 (x 2 axles) = 2 ESALs
Truck rear: $(70/80)^4$ = 0.6 (x 2 axles) = 1.2 ESALs
Truck front: $(50/80)^4$ = 0.15 ESALs

When added together, all LEFs = 3.35 ESALs. For every pass across a pavement, this truck exerts 3.35 80 kN (18,000 lbs) ESALs. To put automobile axle loads into perspective, the weight of one passenger car placed into the formula yields about 0.0002 ESALs. Therefore, pavement design primarily considers trucks because they exert the highest loads and most damage. In contrast, thousands of cars are required to apply the same loading and damage as one passage of a truck.

Permeable Design Pro software can design to 600,000 lifetime ESALs with allowance up to 1 million ESALs. These loads are those found on most parking lots and low-speed residential collector streets. The California Department of Transportation uses Traffic Index or TI to characterize axle loads. Using this approach, PICP can be designed for a TI of 8.5.

DESIGN EXAMPLE

The following example illustrates how PICP reduces runoff and peak flows. The project is a parking lot near Omaha, Nebraska USA. The parking is 580 m^2 (6,243 sf) of PICP set within a 2,600 m^2 (27,986 sf) traditional impermeable pavement parking lot. This site is bordered by an upslope grassed area that allows stormwater runoff onto the pavement. Drainage ditches adjacent to the PICP handle water volumes when PICP storage and the soil subgrade infiltration capacities are exceeded.

For structural capacity, the design traffic was estimated at 91,000 ESALs over the life of the pavement (typically 20 years). The local subgrade material is low plasticity clay with low permeability and California Bearing Ratio (CBR) of 3%. This requires a pavement structure consisting of the paving units and bedding material over 100 mm of ASTM No. 57 stone and 450 mm of ASTM No. 2 stone.

For this area of Nebraska, rainfall intensities typically start low, have short periods of high intensity and then slow near the end of the storm. This rapid water inflow from intense rainfall onto impervious surfaces tends to deliver water quickly into the PICP. This site has a low permeability per soil infiltration tests and the infiltration rate is entered into the program by the user. Stormwater management, however, can be improved by storing the water in the PICP base, allowing for a modest amount of infiltration and slowly draining the remainder over two days. This is a substantial improvement over two hours required to drain the water from a completely impervious pavement.

For this example, water released from PICP base/subbase when full will enter drainage ditches using subdrain pipes to control the flow. Using the software program, three 100 mm (4 in.) diameter perforated pipe subdrains placed at the bottom of the pavement subbase at equal spacing enables water to slowly drain out within two days. The difference in inflow and outflow illustrated in Figure 4 indicates some infiltration and a delay in peak flow.

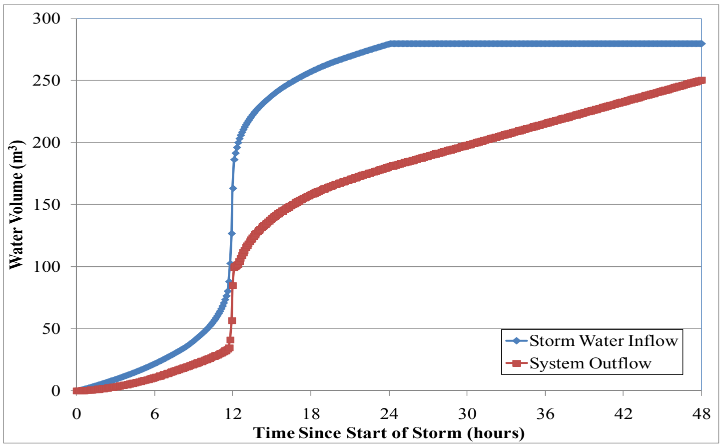

Figure 4. Comparison of PICP inflow vs. outflow

As shown in Figure 4, the rate of water inflow is very rapid with most occurring at the 12 hour mark. With the planned design layout, the entire pavement structure is sloped towards the drainage ditches. The design forces the runoff to flow into the PICP surface and slowly release the water over time. This causes the peak inflow to be reduced by about 50 percent and for the remaining water to be drained over an additional 24 to 48 hours, depending on the storm intensity. Obviously, with design software, other base design scenarios can be modeled by changing the soil infiltration rate, traffic and soil strength as well as rainfall patterns.

MAINTENANCE

The site location for any PICPI project greatly influences the amount of maintenance required. Inspection and maintenance schedules should be determined early. PICP maintenance tasks can be incorporated into routine site inspection and maintenance programs (such as commercial parking sweeping), or into maintenance agreements between the owner and municipality that could identify the following:

Inspections – These should be conducted several times following initial installation and annually thereafter. Inspections monitor and prevent clogging that helps ensure proper surface and subsurface drainage, as well as maintaining an undamaged surface.

Surface Permeability - The most prevalent maintenance concern is the potential clogging of the openings and joints between the pavers. Fine particles that can clog the openings are deposited on the surface from vehicles, the atmosphere, and runoff from adjacent land surfaces. Clogging will increase with age and use; but while more particles become trapped in the pavement surface, it does not become impermeable. Regular street sweeping on the PICP and in the site's drainage area can prolong functioning permeable pavements. If the surface infiltration rate requires measurement, ASTM C 1701 (ASTM 2009) can be used for PICP.

Studies by Borgwardt (2006) of the long term surface permeability of PICP and other permeable pavements have found high infiltration rates initially, a decrease, and then a leveling off with time typically 5 to 7 years. With initial infiltration rates of hundreds of centimeters or inches per hour, the long term infiltration capacity remains high even with clogging. When substantially clogged, surface infiltration rates usually well exceed 25 mm/hr (1 in./hr), sufficient in most circumstances to infiltrate rainfall and manage stormwater.

Surface permeability can be increased with vacuum sweeping. Industry experience has shown the street sweeping combined with vacuuming (without water) biannually ensures permeability and minimizes sediment accumulation in the joints and openings. In extreme circumstances where surface infiltration requires restoration such as that shown in Figure 5, selected vacuum equipment such as that shown in Figure 6 can withdraw the layer of sediment (approximately 15-25 mm) that often collects in the openings of unmaintained PICP over several years. The voided openings can be refilled with stone. This will also help restore a higher surface infiltration rate.

Figure 5. Six year-old paving blocks are removed from the heavily-used and never-previously-cleaned PICP parking lot at Morton Arboretum in Lisle, Illinois. Note the sediment trapped by the stone in the openings. The picture also illustrates PICP's modular construction that facilitates surface repair and access to underground utilities.

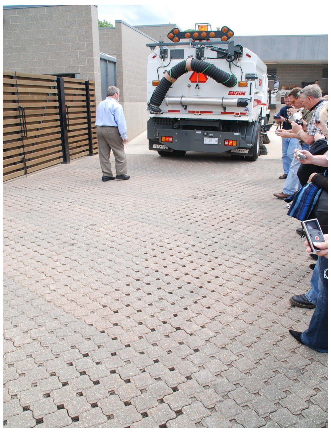

Figure 6. Vacuum cleaning of surface sediment at Morton Arboretum precedes filling the openings with stones to as a means to increase surface infiltration.

Sand should not be applied for snow or ice conditions and snow plowing can proceed as with other pavements. If traction is required, the surface can receive the same stone material in the joints. PICP has been found to work well with no heaving in cold climates and without a frost protection layer in the structure. The stability of the base and soil subgrade is due to adequate drainage prior to reaching freezing temperatures. In addition, warmth from the earth and insulating effects of the air between the aggregate particles in the base slow or prevent freezing of the base in some situations.

The rapid drainage of the surface reduces the occurrence of freezing puddles and black ice. Experience with over 500,000 m^2 (5 million sf) of PICP in the Chicago area over the past five years has demonstrated that PICP is plowed like conventional pavements; no special plow blades are required. Plowed snow piles should not be left to melt over the paver joints and openings as they can receive high sediment concentrations that can clog them more quickly.

While all permeable pavements do not treat chlorides from road salts, deicing material use can be reduced with PICP as previously noted. In addition, snow plowing is reduced due to surface snow melting and infiltrating. By eliminating ice forming, there can be a reduction in potential liability from slips and falls.

COSTS

Several factors influence the overall PICP costs:

- Material availability and transport – time and distance for delivery
- Site conditions – accessibility by construction equipment, slope, existing buildings and uses
- Subgrade – Soils such as clay may result in additional base material for structural support or added stormwater storage volume.
- Stormwater management requirements – The level of control required for the volume, rate or quality of stormwater discharges will impact the volume of treatment needed and the subbase thickness.
- Project size – Larger PICP areas tend to have lower costs due to construction efficiencies. Mechanized installation of the paving units (shown in Figure 7) is often used thereby reducing construction time.

Figure 7. Mechanized PICP installation is increasingly used to decrease time and installation costs compared to manual installation.

Installation costs of permeable paving are typically higher than conventional asphalt or concrete. However, significant savings can be realized by reducing or eliminating off-site detention/retention facilities. In some instances savings can offset the initial cost difference between conventional pavements and PICP. Additional land utilization (or conservation) from reduced or eliminated detention ponds can also offset initial PICP costs. This has been the case in many PICP applications. In addition, PICP does not require periodic surface maintenance and rehabilitation (and related costs) like conventional asphalt. A recent study by the US Army Corps of Engineers of a demonstration project in Ft. Stewart, Georgia demonstrated the lower life-cycle costs for PICP compared to conventional asphalt and stormwater drainage (US Corps of Engineers 2009).

CONCLUSIONS

PICP design requires the uniting of two formerly separate spheres---hydrological design and pavement design. Hydrological methods are familiar to stormwater managers but they likely need additional information on structural design to further the use of PICP among pavement engineers. The AASHTO 1993 design procedure for flexible pavement can be applied to structural design with modified layer coefficients for the open-graded base materials and for the pavers and stone bedding layer compared to that used for dense-graded bases under conventional interlocking concrete pavers and beddings sand. The design considerations in this paper and supporting research, monitoring and maintenance experiences will be included in the emerging permeable pavements technical guide underway by the ASCE Permeable Pavements Technical Committee.

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Laboratory Evaluation of HMA Containing RAP and PMB

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Abstract
Sustainable pavement designs call for energy-efficient and durable materials that lead to long-lasting, safe and economical highways. This paper presents the results of the laboratory study on rutting susceptibility of the Hot-Mix Asphalt (HMA) mixes used in the North East region of the US. A total of 40 different HMA combinations were included in this study. The HMA mixes were prepared with five different Polymer Modified Binders (PMB): 70-28, 76-22, 64-28, 64-28PPA, and 58-34. These binders were combined with four Reclaimed Asphalt Pavement (RAP) sources in two different ways. In the control mixes, the RAP was first burned to remove the RAP binder and only the RAP aggregate was added to the base batch of a virgin binder and aggregate. In the second set of mixes, the RAP was added at 10 percent of the total mix weight. The RAP sources differed in the mineralogical origin of their aggregates. Each of the four RAPs consisted primarily of one of the following minerals: granite, basalt, schist, and limestone. All 40 mixes were compacted according to the mix design with 12.5 mm Nominal Maximum Aggregate Size (NMAS) using the one virgin aggregate source. In order to evaluate rutting susceptibility, mixes were tested in the Asphalt Pavement Analyzer (APA) at the high PG grade temperature of the corresponding binder with the rate of 60 cycles per minute. This paper outlines the methodology, presents experimental data and includes statistical analysis of the APA results.

KEYWORDS: Asphalt Pavement Analyzer, hot mix asphalt, polymer-modified binders, reclaimed asphalt pavement, rutting.

Introduction

Construction of Hot-Mix Asphalt (HMA) pavements requires significant amounts of virgin aggregate and asphalt binder. According to EAPA 2007, total production of HMA in 2007 reached 500 million tons in the US and 342 million tons in Europe. Although such quantities are necessary to maintain current infrastructure and build new highways, it is critical to consider the future re-usage of these materials. Recycling deteriorated HMA results in a reusable mixture of aggregate and asphalt binder known as Reclaimed Asphalt Pavement (RAP). The increasing costs of crude oil and, thus, virgin binders, the lack of quality aggregates in some parts of the world, and the increasing concern about the environment make RAP a favorable construction material, motivating many research efforts to investigate its feasibility when mixed with virgin materials.

Asphalt modifications are intended to enhance liquid asphalt binder properties such that they will meet standard requirements and perform well under given environmental and loading conditions. Polymer modifications come in several forms from latex and acids (elastomers) to synthetic polymers (plastomers) intended to enhance the placement, serviceability and performance characteristics of the pavement (MS-4 2007.)

Because of the numerous different constituent possibilities involved with the production of a pavement, there are many possible stability issues among these different materials which, if exist, need to be addressed. An annual survey conducted by the Association of Modified Asphalt Producers (AMAP) indicates that modified binders used annually in the United States are consistently 25% of the total binder used despite fluctuations in total quantities (Casola 2008).

This paper discusses the results of the research performed recently by the University of Connecticut. The main objective of this study was to investigate the effect of RAP constituents and polymer modified binder interactions on rutting resistance. The paper presents background information on the RAP and binder interaction other studies have investigated, describes experimental design and testing procedures used in this research, and analyzes the statistical significance of the experimental results.

Background

Reclaimed asphalt pavement (RAP) is seen as a quality construction material by many agencies and industry officials. The use of RAP in new pavements has positive implications from both economical and environmental viewpoints. When RAP is incorporated into a pavement, the volume of virgin raw materials needed to be excavated, manufactured and/or purchased is reduced. The shortcoming of RAP is the inconsistency of the binders in recycled RAP. Having undergone a service life of oxidation aging, and potentially containing unknown modifiers, RAP binder can adversely interact with virgin binder during mixing.

As the world's most recycled material, asphalt pavements are continually changing in constituency. Understanding the interaction of virgin materials and RAP is necessary for predicting and determining a pavement's ability to meet serviceability requirements and withstand loading from both traffic and environmental conditions. The asphaltenes, saturates, aromatics and resin which comprise the asphalt derived from vacuum distillation of crude oil have unique interactions with both modifiers added to the binder, and RAP binder that blends with the virgin binder during the mixing process. With the addition of RAP binder, the ratios of the asphalt constituents change, which can lead to unstable behavior (Polacco 2006.) The increasing use and incorporation of RAP into asphalt pavements adds to the complexity of examining when PG binder modification along with the use of different aggregates will have a positive or negative effect on the performance of a pavement.

Modified virgin asphalt binders are becoming increasingly standard in many areas of the country. In a report Foreword by T. Paul Teng from FHWA Office of Infrastructure Research and Development, he states that the use of polymer modified asphalt binder is increasing and it is expected that it will continue to increase (Stuart, 2001).

Modifiers added to asphalt binder are intended to increase the durability of hot mix asphalt. Different additives can have minimal or adverse effects in particular applications. In most circumstances, modified asphalt mixes have higher reported strengths and plastic deformation resistance (Tayfur 2005.) One such example of a possible compatibility issue is the use of polyphosphoric acid (PPA) modification in conjunction with limestone aggregates. Limestone is made of calcium carbonate ($CaCO_3$) which will dissolve in the presence of acid. Polyphosphoric acid is an inorganic polymer which is incorporated into virgin asphalt binders as a means of increasing the high temperature performance grade without affecting the low temperature. PPA also helps to mitigate susceptibility to aging and storage stability at high temperatures (Daranga 2009.)

Styrene-butadiene-styrene (SBS) modification of asphalt is the most common asphalt modification used in the United States (Casola 2008.) The ability of SBS modified asphalt to remain ductile and flexible at low temperatures combined with its tendency to resist permanent deformation at high temperatures overcomes the increased cost of these modifications. Polymer modification has been reported to reduce required mat thickness, increase wear surface life, decrease maintenance costs and reduce aging (Polacco 2006.)

Florida DOT conducted a study that suggested RAP mixtures have shown good rutting resistance and mixes containing styrene-butadiene-styrene (SBS) polymer modified binders have shown both good rutting resistance as well as cracking resistance (Kim 2009.) In their research they investigated the performance of the RAP mixes combined with SBS polymer modified binders. These materials were investigated with respect to cracking, rutting and binder properties. Included RAP contained both limestone and granite. These mixes contained 0%, 15%, 25%, and 35% RAP.

The authors concluded that all of the RAP mixes containing SBS polymer modified binder performed well under the Superpave Indirect Tensile Test (IDT) as well as the APA (Asphalt Pavement Analyzer) which measures susceptibility to rutting. The report also concluded, that the amount of RAP binder blended with the modified binder had some effect on the performance parameters as measured with the Dynamic Shear Rheometer (DSR). The extent of this effect on mixture performance was not evident.

Rutting in HMA is defined as permanent deformation accumulated by traffic loading. This deformation can propagate into all the layers of a pavement structure (Tayfur 2005.) Tests to determine rutting susceptibility using the Advanced Pavement Analyzer, Hamburg Wheel Track Test or LCPC Wheel Tracker measure the resilience of an asphalt pavement mix as an entity. Evaluation of the mix as a whole effectively identifies constituent incompatibility between aggregate, binder and RAP should there be any instability. Material-specific testing is required to identify the sources of incompatibilities.

Methodology

Materials

HMA Specimens were fabricated using Superpave HMA mix design for a 12.5 mm Nominal Maximum Aggregate Size (NMAS). Virgin Aggregate was mixed with the selected virgin asphalt binders and RAP (from 4 sources in New England) in 40 combinations for testing. The asphalt binders tested were a PG 70-28, 76-22, 58-34, 58-34 and 64-28PPA. A PG 64-28 unmodified asphalt was used as a control binder. The virgin aggregate remained constant throughout testing to reduce variability in the specimens. Reclaimed Asphalt Pavement was used from 4 sources; a granite RAP from Vermont, a limestone RAP from Maine, a schist RAP from Connecticut [Torrington] and a basaltic RAP from Connecticut [Wallingford.] Summary of mix designs is presented in Table 1.

The test specimens had 10% RAP added by weight; this RAP was heated for 8 minutes in the oven before mixing with virgin constituents. Control specimens were made by removing the RAP binder from a sample of RAP 10% by weight of the batch using an ignition oven. The RAP aggregate was then mixed with virgin aggregate and binder adding compensatory virgin binder for that lost in the ignition oven.

All mixtures were short-term oven aged then compacted using a Pine AFGC125X gyratory compactor. Specimens were compacted in a 150mm diameter mold to a target height of 75mm. Upon cooling, each specimen's mean air voids were checked to ensure proper mix and compaction.

Table 1. Summary of Mix Design

Mixes With 10 % RAP	**Percent (%) Mix**			
	Wallingford (basalt)	**Vermont (granite)**	**Torrington (schist)**	**Maine (limestone)**
1/2"	20	19	22	18
3/8"	25	26	28	24
Stone Sand	35	35	35	38
Natural Sand	10	10	5	10
RAP	10	10	10	10
Pb	5.2	5.2	5.3	5.5
RAP Pb	5.2	5.3	5.1	5.2
Gsb	2.806	2.788	2.816	
Gmm:				
58-34	2.63	2.623	2.617	2.635
64-28	2.647	2.633	2.645	2.621
64-28 PPA	2.644	2.619	2.647	2.618
70-28	2.631	2.616	2.624	2.609
76-22	2.655	2.640	2.651	2.638

Control mixes	Percent (%) Mix			
	Wallingford (basalt)	Vermont (granite)	Torrington (schist)	Maine (limestone)
1/2"	21	16	20	17
3/8"	25	22	27	23
Stone Sand	34	37	35	38
Natural Sand	10	15	8	12
RAP	10	10	10	10
Pb	5.5	5.5	5.5	5.8
Gsb	2.807	2.771	2.807	2.778
Gmm:				
58-34	2.624	2.609	2.598	2.65
64-28	2.621	2.610	2.620	2.599
64-28 PPA	2.628	2.607	2.633	2.599
70-28	2.627	2.597	2.620	2.593
76-22	2.619	2.605	2.621	2.593

Testing

The HMA specimens were fabricated and then subjected to the Advanced Pavement Analyzer (APA) testing to establish any significant changes in the performance of HMA mixtures with the selected binders and RAPs. The rutting resistance was tested according to AASHTO method TP 63-07. This method uses 75-mm high HMA specimens that are subjected to repeated loading conditions in the APA. Before APA testing, the specimens were conditioned in the moulds at their high PG temperature for six hours, as specified by the AASHTO procedure. During the test, a concave wheel runs over pressurized rubber hosing that is set on top of the gyratory specimens in the temperature-controlled chamber. The rubber air lines on the load rack were pressurized to 0.69 ± 0.03 MPa and the load of wheel was set to 0.45 ± 0.02 KN. A total of 8,000 cycles of wheel loading were applied to the HMA specimens in the chamber. One cycle was equivalent to one forward pass and one backward pass over the specimens. The rut depth for each cycle was recorded in the raw data file by the acquisition system attached to the APA.

Results

The data collected in the laboratory testing presented above was analyzed and compared in several ways. First, the APA rutting curves for different mixes were qualitatively compared. In order to quantitatively estimate the rutting susceptibility, the rutting accumulated within first 4000 cycles and second 4000 cycles were calculated and compared separately for the control and 10%RAP mixes.
Next, the influence of the RAP binders and RAP aggregate on the rutting performance was carefully studied. The Analysis of Variance (ANOVA) and interaction plots were used to determine what factors are statistically significant and Bonferroni pairwise comparison was employed to distinguish between different levels of a given factor.

APA rutting development curves

Typical APA rutting curves measured in this study are shown in Figures 1 and 2. Figure 1 presents three replicates (left, center, right) for the 64-22PPA with basaltic RAP and binder at 10% RAP. For comparison, Figure 2 presents the same mix (binder and RAP aggregate) but without RAP binder. It can be observed that both groups represent significantly different behavior. For the mixes with 10% RAP, majority of rutting occurs in the first 4000 cycles and the curves levels off afterwards. For the control mixes, the rutting steadily continues to increase after first 4000 cycles which suggests softer mix with higher susceptibility to plastic deformations.

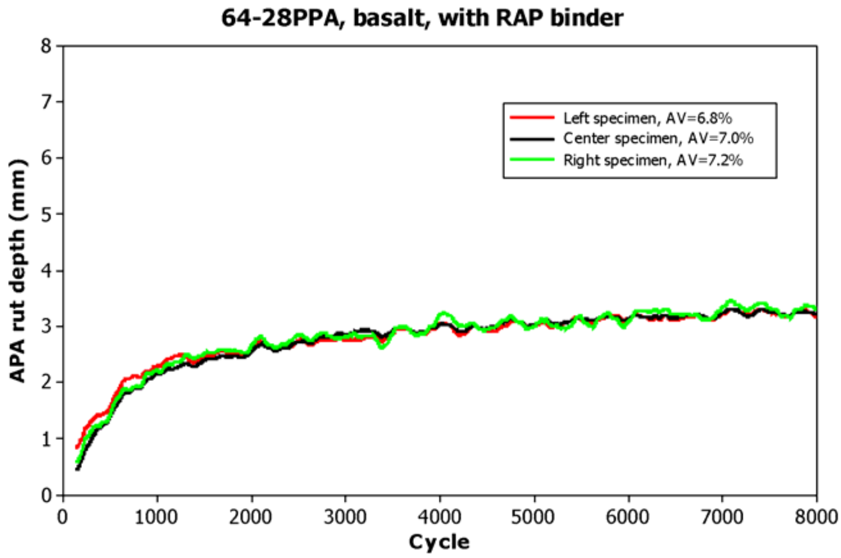

Figure 1. APA rutting curves for 10% RAP mix.

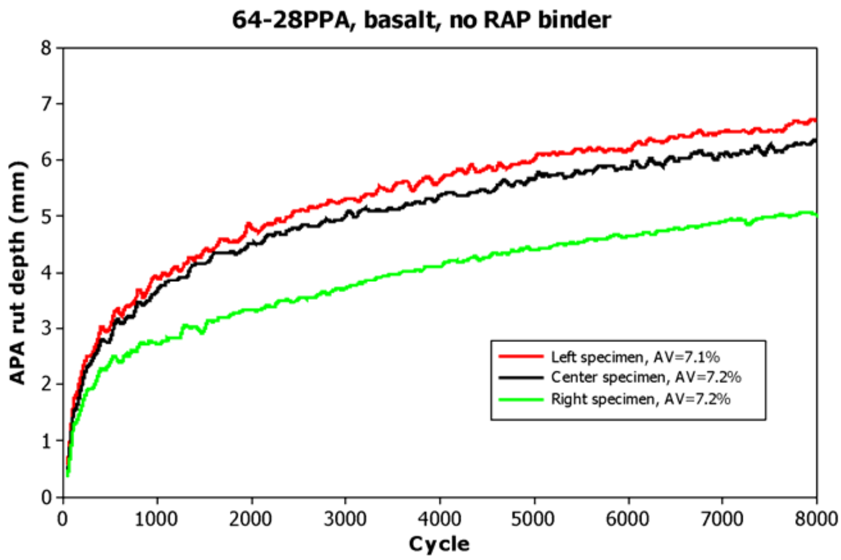

Figure 2. APA rutting curves for control mix.

In order to quantitatively evaluate the rutting development, two parameters were calculated: δ_{4000} and δ_{8000}. Both parameters calculate the fractions of the total rutting that accumulate in the first and the second part of the test, respectively. Figures … show the average δ_{4000} and δ_{8000} parameters for all mixes in this study. It can be observed that on average δ_{4000} for control mixtures is around 84.5% and for the 10% RAP mixtures is 86.5%. Similarly, δ_{8000} is equal to 15.5% for control and 13.5% for 10% RAP mixtures. The observations made in Figures 1 and 2 can be also followed in Figure 3. 10% RAP mixes with 64-28PPA binder and either basalt or schist aggregates deviate considerably from other mixes and accumulate approximately 95% of total rutting within first 4000 cycles. No other apparent and concise trend can be observed based on the Figures …. .

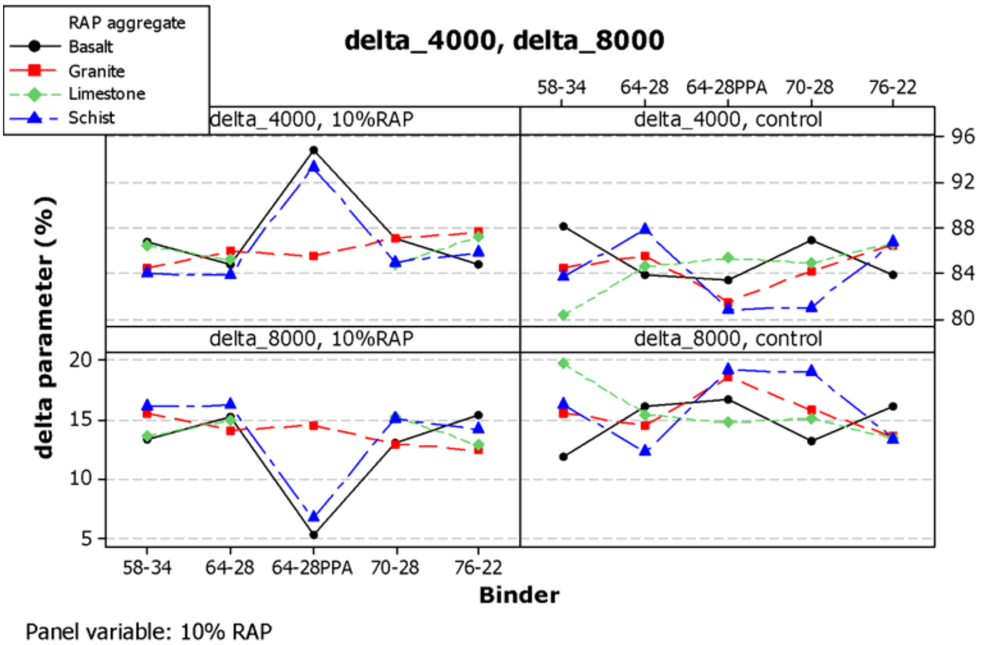

Figure 3. Interaction plot for δ_{4000} and δ_{8000} parameters.

Virgin binder and RAP aggregate effect

Figure 4 and 5 show the average rutting values measured at 8000 cycles. Both figures present the same data however each of them emphasizes different factor: Figure 4 highlights binder effect whereas Figure 5 underlines the RAP aggregate impact on the APA rutting. Based on both figures, the following observations can be made:

– Mixes with 58-34 binder produce the highest APA rutting for almost all combinations with RAP aggregates in both control and 10% RAP mixes.
– Presence of granite leads to the highest rutting in 10% RAP mixes; on the other hand, in control mixes there is no consistent trend on which RAP aggregate leads to the highest rutting.
– Limestone and schist show similar trends except when mixed with 76-22 and 10% RAP.
– 76-22 binder is highly reactive with different RAP aggregates which lead to a wide range of rutting depths for 76-22 mixes.

- For 58-34, 70-28, and 64-28PPA binders, addition of RAP binder did not significantly change the relative trends between different RAP aggregates – the corresponding curves in the Figure 4a and Figure 4b have similar shapes.
- 64-28 and 76-22 binders significantly change trends between control and 10% RAP mixes.
- On average, control mixes seem to produce higher APA rutting which is further investigated in the next section.

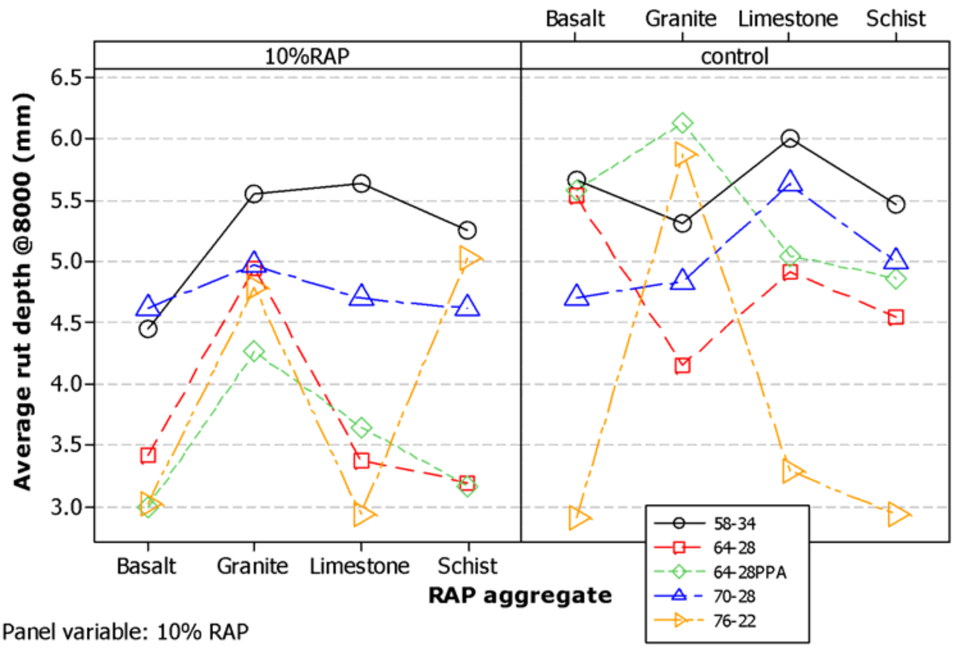

Figure 4. Virgin binder effect.

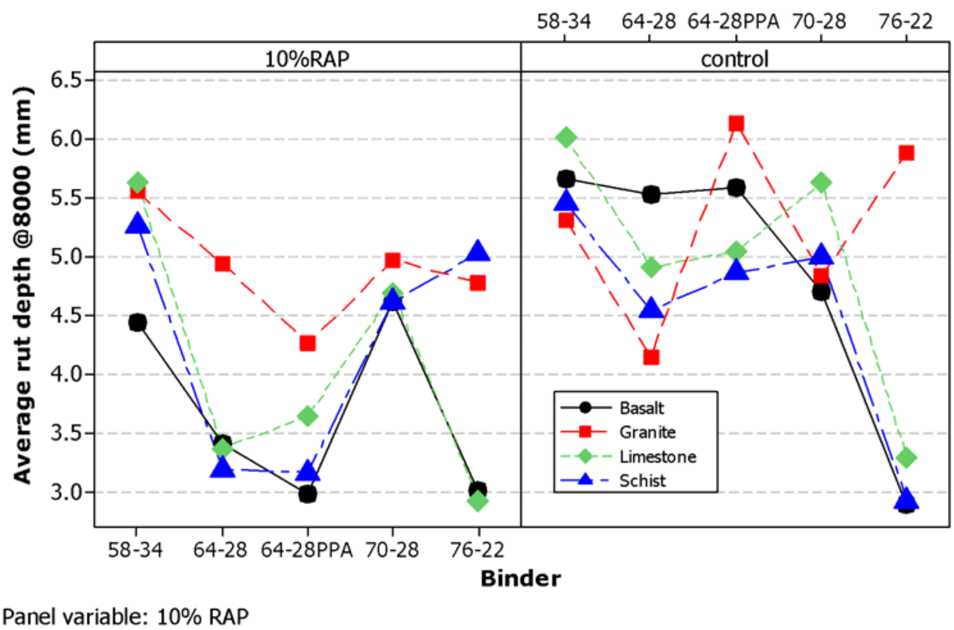

Figure 5. RAP aggregate effect.

The complete data at 8000 cycles from all replicates were statistically evaluated using Bonferroni pairwise comparison. The results are shown in Table 2 where X implies that the rutting between two mixes was statistically different. The upper right part of the matrix is based on the control mixes whereas the lower left is for the 10 %RAP mixes. It was concluded that 76-22 binder when mixed with basalt, limestone and schist produces statistically different (lower in this case) rut depths as compared to all other control mixes. For the 10% RAP mixes, the 58-34 binder batched with granite, limestone or schist gives statistically different (higher) rutting as compared to several other 10% RAP mixes. These conclusions agree with observations made from Figures 4 and 5, however only the most extreme differences in rutting were detected due to the statistical character of the results and objective evaluation of differences between rutting depths rather than visual observations.

Table 2. Statistical difference between rutting depths at 8000 cycles (upper right corner is for control mixes and lower left is for the 10 % RAP mixes).

		58-34				64-28				64-28PPA				70-28				76-22			
		B	G	L	S	B	G	L	S	B	G	L	S	B	G	L	S	B	G	L	S
58-34	B																	X		X	X
	G																	X		X	X
	L						X											X		X	X
	S																	X		X	X
64-28	B		X	X														X		X	X
	G										X										
	L		X	X														X			X
	S		X	X																	
64-28 PPA	B		X	X	X													X		X	X
	G																	X		X	X
	L																	X			X
	S		X	X														X			X
70-28	B																				
	G																	X			X
	L																	X		X	X
	S																	X			X
76-22	B		X	X	X														X		
	G																			X	X
	L		X	X	X																
	S																				

X - statistically different at p=0.05
B Basalt
G Granite
L Limestone
S Schist

RAP binder effect

The other important objective of this study was to investigate the effect of the RAP binders on the rutting performance. In order to quantitatively capture the RAP binder effect the following parameter was determined for all binder/RAP aggregate combinations:

$$RAP\ effect_i = \frac{d_{i8000}^{control} - d_{i8000}^{10\%RAP}}{d_{i8000}^{control}} 100\% \qquad (1)$$

Each binder/RAP aggregate combination had 3 replicates and their rutting d_{8000} values at 8000 cycles were assumed normally distributed. This allowed for determination of mean and standard deviation separately for all binder/RAP aggregate combinations in control mixes and for all corresponding combinations in 10% RAP mixes. A Monte Carlo simulation was used to randomly sample values from both distributions and re-calculate the *RAP effect* parameter according to Eq. (1). The calculation was repeated 10,000 times which produced the mean and standard deviation of the *RAP effect* for each binder/RAP aggregate combination. These results are graphically presented in Figure 6. If the *RAP effect* parameter is positive it suggests stiffening effect of the RAP binder and less APA rutting, and consequently if the *RAP effect* is negative it suggests softening influence and more rutting in the total mix. Examination of the Figure 6 leads to the following observations:

- 58-34 and 70-28 mixes oscillate around zero value which suggests no RAP binder effect on the APA rutting.
- 64-28 and 64-28PPA mixes show positive RAP binder effect (less rutting in 10% RAP mixes) with the exception of 64-28PPA with granite that shows negative RAP binder effect (but it has a large variability).
- All 76-22 mixes show minimal RAP binder effect but one – combination with schist aggregate produced significant negative RAP binder effect, i.e. 76-22 binder with 10% RAP and schist aggregate produced on average 76% more rutting than corresponding control mix.

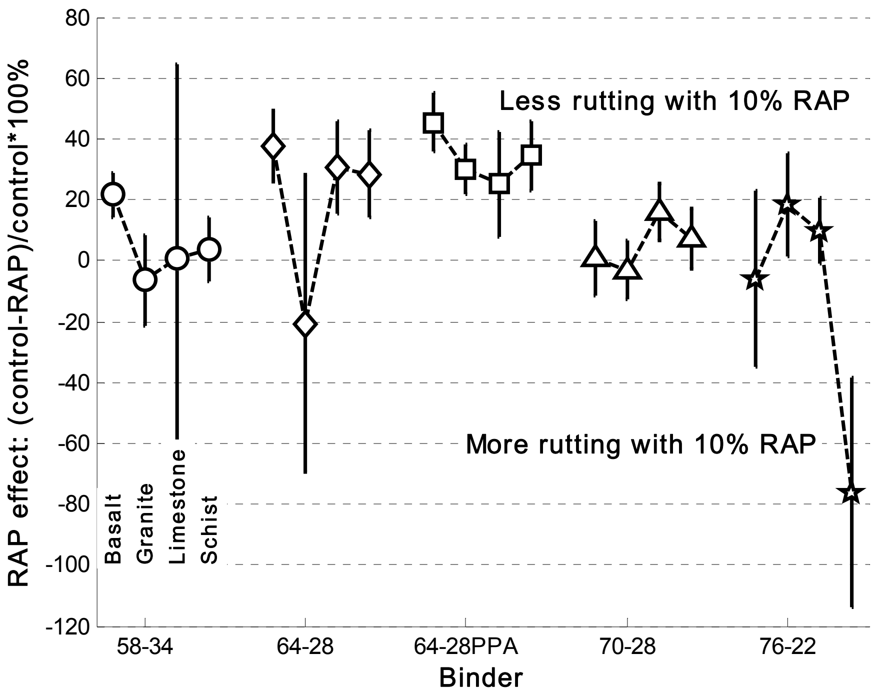

Figure 6. RAP binder effect (mean and one standard deviation).

The results presented in Figure 6 test the hypothesis that the RAP binder effect is statistically different than zero, i.e. no significant effect was observed. The results of testing such hypotheses for all mixes are shown in Figure 7. The bars represent the mean RAP binder effect and the bolded bars highlight the mixes for which the RAP binder effect is statistically different than zero. The conclusions are similar to those from Figure 6.

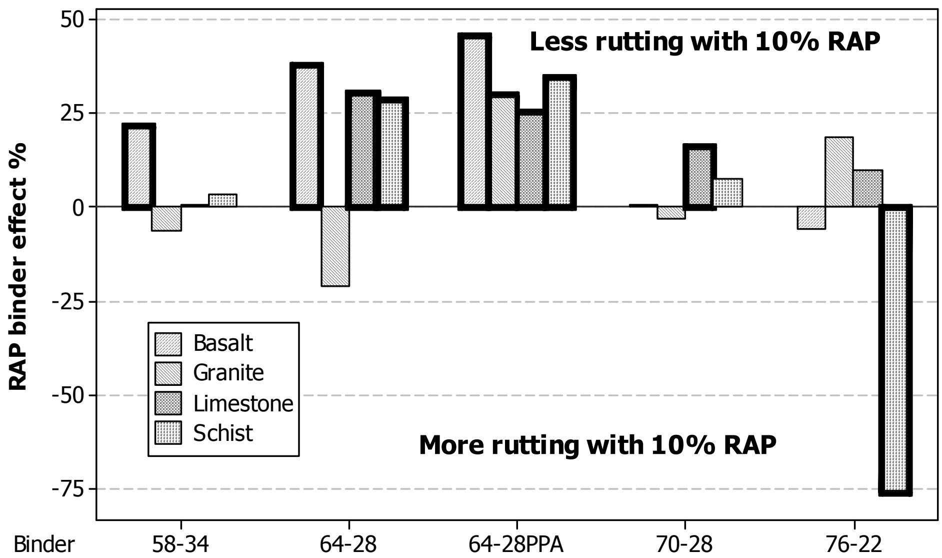

Figure 7. RAP binder effect (bolded bars imply that effect is statistically different than zero).

Conclusions

The following conclusions can be emphasized based on the APA testing conducted in this study:

1. There is a strong interaction of 76-22 binder and RAP aggregates.
2. Rutting of 58-34 mixes with 10% RAP is statistically different (higher) than other RAP mixes.
3. For 76-22 binder with schist aggregate, addition of 10% RAP leads to more rutting, i.e. RAP binder softens the 76-22 mix.
4. Adding RAP binder significantly stiffens 64-28 and 64-28PPA mixes.

The results presented in this paper are based only on the APA mix testing. To fully address the rutting performance and comprehensively interpret the APA results more research should be done. The following laboratory activities are planned by the authors for the near future:

- Evaluate virgin binders, RAP binders and their blends in the DSR (G* mastercurve and MSCRT tests).
- Measure and compare the amount of aging in the RAP binder sources (FT-IR).
- Verify the modification method of virgin binders (FT-IR and GPC).

Acknowledgments

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High Volume Fly Ash Concrete for Highway Pavements

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Abstract

This paper encompasses the evaluation and research of high-volume fly ash (HVFA) concrete. The primary objective of this study was to examine increased levels of cement replacement with Class F fly ash for concrete used in Colorado highways. Fly ash is a byproduct of the combustion of pulverized coal in electric power generating plants. The benefits of using fly ash in concrete include increased compressive strength and durability, and reduced sulfate attack, shrinkage, and cost.

Four HVFA concrete mixtures with 50%, 60%, 70%, and 80% Class F fly ash were designed and tested for compressive and tensile strength and permeability. Compressive strength tests were conducted at 3, 7, 28, and 56 days of age. The permeability and tensile strength of the mixtures were measured at 28 and 56 days of age. The Colorado Department of Transportation (CDOT) Class P mixture was used as the base mixture for this study. This class of concrete is specific for concrete pavements used for Colorado streets and highways. Required field compressive strength of Class P concrete is 29 MPa (4200 psi) at 28 days; a minimum cementitious content of 392kg/m^3 (660 lbs/cy); air content ranges between 4-8% and a maximum water/cementitious material ratio of 0.44 is specified by the CDOT.

The results of this study provide sufficient evidence that increased amounts of fly ash (above typical limits) can be incorporated into concrete mixtures for streets and highways.

Introduction

Concrete typically consists of gravel, sand, water, and portland cement. It is a versatile building material used extensively worldwide. However, significant environmental problems result from the manufacture of portland cement. It is known that the production of portland cement "accounts for 6-7% of the total carbon dioxide (CO_2) produced by humans, adding the greenhouse gas equivalent of 330 million cars driving 12,500 miles per year (Green Resource Center, 2010).

During cement production, four major chemical compounds are produced. Two of these compounds (tri-calcium silicate and di-calcium silicate) contribute specifically to the compressive strength of concrete due to the amount of calcium-silicate-hydrate that is produced during cement hydration. Fly ash, a by-product of the coal burning industry, is composed of high concentrations of silica that reacts with the calcium hydration (cement hydration product) to produce additional calcium-silica hydrate. Thus, fly ash produces a stronger, more durable product while reducing the environmental impact of concrete.

More than 12 million tons of coal fly ash is used in concrete structures each year in the United States [Aggregate Research, 2005]. In addition, the use of fly ash helps reduce greenhouse gas emissions, virgin material depletion, and landfill disposal of unused fly ash. For every ton of fly ash used in place of portland cement, twenty-four days of energy used by an average American home are saved, four hundred and fifty-five days of solid waste produced by an average American are avoided from landfill space, and two months of reduction in CO_2 emissions are saved from an automobile. Typical cement replacement percentages with fly ash are limited to no more than 30%. However, mixtures with increased percentages can meet structural performance criteria at a reduced material cost and environmental benefit.

This paper examines the performance of four HVFA concrete mixtures. Specifically, mixtures with cement replacement percentages of 50%, 60%, 70%, and 80% were evaluated for their fresh and hardened concrete properties. The Colorado Department of Transportation (CDOT) Class P concrete specification was utilized in this research. The CDOT Class P concrete is used in Colorado pavements. The mixture contains a minimum cementitious content of 392 kg/m^3 (660 lbs/yd^3) and a 30% maximum cement replacement with Class F fly ash.

The slump, air content, temperature, and unit weight were measured for each of the mixtures. The hardened concrete properties examined in this study included compressive strength, tensile strength, and permeability. The research presented herein demonstrates that higher cement replacement levels with fly ash may be utilized and meet the current Class P structural specifications.

Background

Cement may be substituted with supplementary cementitious materials (SCMs) such as fly ash, blast furnace slag, and silica fume up to certain replacement levels. These SCMs affect concrete's fresh and hardened behavior. High volume fly ash contents were examined in this research.

Fly Ash

Fly ash is a byproduct of the combustion of pulverized coal in electric power generating plants [Kosmatka and et. al., 2002]. The shape of fly ash is a solid sphere or hollow cenospheres with a size ranging from 1 micron to 100 microns. The particle mean size is 25 microns. As a pozzolan, fly ash possesses no cementitious value of its own. However, in the presence of water, it can chemically react with calcium hydroxide ($Ca(OH)_2$), a byproduct of cement hydration, to form calcium-silicate-hydrate (C-S-H). C-S-H is responsible for the strength and durability of concrete. As the amount of C-S-H increases, concrete compressive strength increases, permeability decreases, and durability increases. In addition, past research has shown that fly ash produces concrete with better freeze/thaw resistance, reduced sulfate attack, decreased shrinkage, reduced alkali-silica reaction, and lower heat of hydration.

Due to the spherical nature of the fly ash particles, the workability of the concrete mixture is increased. In addition, set time may be delayed. HVFA concrete is usually very cohesive and shows little or no bleeding and segregation. The hardened concrete properties for fly ash concrete include an increased compressive strength at later ages, a decreased one day compressive strength, and decreased permeability at later ages.

High Volume Fly Ash Concrete Mixture

It has been found that because of the increase in workability combined with a water-reducing admixture, the water to cementitious material (w/cm) ratios can be less than 0.35 for concrete mixtures with fly ash replacement. This offsets the presence of large quantities of unreacted fly ash. The leftover fly ash acts as a microfiller integrally bonded within the hydrated matrix (Mindess, et. al., 2003).

HVFA concrete research has shown that depending on the quality of the fly ash and the amount of cement replaced, there can be a reduction of up to 20% in water requirements. With this reduction of water, the drying shrinkage of concrete will be positively affected.

Experimental Design

Concrete Materials

Class P concrete from the Colorado Department of Transportation, CDOT, standard specifications was the base model for the design of the HVFA concrete mixtures. Class P concrete is designated for use in pavements and must consist of a minimum 55% AASHTO M43 size No. 57 or 67 coarse aggregate by weight of total aggregate. The total weight of cementitious material shall not be less than 392 kg/m^3 (660 lbs/yd^3). The required field compressive strength is 29.0 MPa (4200 psi) at 28 days. Finally, the maximum w/cm ratio is 0.44. The materials used in this study are discussed in greater detail in the following.

Cement

An ASTM Type I portland cement manufactured from Holcim, Inc. was used for this study. The specific gravity of this cement was 3.15 and the specific surface area (Blaine Fineness) was 398m^2/kg.

Fly Ash

Class F fly ash was used for this study for many reasons including the fact that Class C fly ash is typically not as effective as Class F in mitigating alkali silica reaction, ASR. ASR is a reaction that occurs in concrete over time and can cause the concrete to expand and crack, ultimately losing its strength. In addition, Class C is generally not as resistant to sulfate attack. Sulfate attack can result in expansion and cracking of the concrete, and softening and disintegration of the cement paste. On the other hand, Class C ash will normally generate more strength at early ages than Class F fly ash. The chemical and physical properties of the Class F fly ash are shown in Table 1.

Table 1 Chemical and Physical Fly Ash Properties

CHEMICAL TESTS	Fly Ash	ASTM C 618 CLASS F/C
Silicon Dioxide (SiO_2), %	55.45	
Aluminum Oxide (Al_2O_3), %	21.06	
Iron Oxide (Fe_2O_3), %	4.12	
Sum of SiO_2, Al_2O_3, Fe_2O_3, %	81.63	70.0/50.0 min.
Calcium Oxide (CaO), %	10.83	
Magnesium Oxide (MgO), %	2.29	
Sulfur Trioxide (SO_3), %	0.43	5.0 max.
Sodium Oxide (Na_2O), %	0.77	
Potassium Oxide (K_2O), %	1.03	
Loss on ignition, %	0.67	5.0 max
Specific Gravity	2.37	

The amount of Class F fly ash used in the four mixtures was 196 kg/m^3, 235 kg/m^3, 275 kg/m^3, and 314 kg/m^3, for the 50%, 60%, 70%, and 80% replacements, respectively.

Aggregates

The coarse aggregate met ASTM C33 Size Number 57 and 67 gradation requirements. The graded coarse aggregate had a maximum aggregate size (MAS) of 25.4mm (1.0in.) and a nominal maximum aggregate size (NMAS) of 19mm (0.75 in.). The fine aggregate met ASTM C33 gradation requirement for concrete fine aggregate. The fineness modulus of the fine aggregate was 2.74.

The percent of coarse aggregate used per weight of total aggregate was 63%, 62%, 63%, and 63% for the 50%, 60%, 70%, and 80% fly ash concrete mixtures, respectively. These values are well above the CDOT requirement of 55%.

Mixture Design

Four HVFA concrete mixtures were designed, batched, and tested for performance. Concrete mixtures with 50%, 60%, 70%, and 80% cement replacement with Class F fly ash were evaluated. Table 2 provides the saturated surface dry (SSD) mixture proportions for each design.

Table 2 Mixture Proportions (SSD)

Materials	50% Fly Ash	60% Fly Ash	70% Fly Ash	80% Fly Ash
Cement (kg/m3)	196	157	117	78
Class F Fly Ash (kg/m3)	196	235	274	313
Coarse Aggregate (kg/m3)	1056	1056	1056	1056
Fine Aggregate (kg/m3)	602	591	580	570
Water (kg/m3)	157	157	157	157
w/c	0.4	0.4	0.4	0.4

Each HVFA concrete was mixed continuously for approximately 10 minutes. Both high range water reducing admixtures, HRWRA, and air-entrainment admixtures, AEA, were incorporated into the mixtures. A HRWRA lowers the water required to attain a certain slump or workability. It reduces the water demand of the concrete making it more pliable and easier to manipulate. An AEA increases the amount of air that is incorporated into concrete during mixing. This admixture aids in reducing the susceptibility of concrete to freeze-thaw cycles.

Results

Fresh Concrete Properties

The fresh concrete properties measured included slump, ambient and concrete temperature, air content and unit weight. Table 3 lists the properties of the four mixtures.

Table 3 Fresh Concrete Properties

Properties	50% Fly Ash	60% Fly Ash	70% Fly Ash	80% Fly Ash
Ambient Temperature, °C	19	18	12	13
Concrete Temperature, °C	21	16	16	16
Slump, cm.	1.27	0	0	13.97
Air Content, %	3.1	3	2.5	3.1
Unit Weight, kg/m3	2345	2352	2352	2297

Slump

The slump test provides an indication of the degree of concrete workability. In addition, it acts as a quality-control tool for engineers [Mindess et. al., 2003]. The slump/workability of the mixtures should increase with an increase of fly ash. Fly ash is roughly the same size as portland cement, but due to its spherical regularity, fly ash particles act as small ball bearings that reduce interparticle friction and aid in the placement of concrete into formwork and around reinforcing steel. Less water is typically needed when high volumes of fly ash are used in concrete.

During the batching of the 60% and 70% HVFA mixtures, increased amounts of high range water reducing admixture (HRWRA) were introduced because the concrete was not seen to have an acceptable workablility behavior. Even with the addition of the

HRWRA, a slump of 0 cm for both mixtures were experienced. The slump for the 50% and 80% batches were much more reasonable with 1.27 cm and 13.97 cm, respectively.

Temperature

The temperature of concrete mixtures fluctuates due to the chemical reactions (which produce heat) occurring during cement hydration. Mineral admixtures, such as fly ash, reduce the heat of hydration. Therefore, concrete mixed with fly ash will record a lower temperature during the hydration phase compared to a concrete mixed purely with portland cement. The temperature of the concrete mixtures ranged from 16 - 21ºC (61 - 70ºF).

Air Content

The air contents were 3.1%, 3.0%, 2.5%, and 3.1% for the 50%, 60%, 70%, and 80% fly ash concrete mixtures, respectively. These values are not within the required range of 4-8% for Class P concrete; however, a slight increase in AEA dosage should increase the air content within the specified range. It is suspected whether the HRWRA affected the AEA during batching of the concrete.

Unit Weight

The unit weight was expected to decrease as the cement replacement percentage increased. This is a result of the fly ash having a lower specific gravity than the cement. The measured unit weights for the 50%, 60%, and 70% fly ash concrete mixtures were similar. The unit weight of the 80% fly ash concrete was lower than the other three. The unit weight values ranged from 2297 – 2352 kg/m^3 (143.6 – 147.1 lb/ft^3).

Hardened Concrete Properties

The hardened concrete properties tested were compressive strength, split tension and permeability. Each of these properties and results are discussed in greater detail in the following.

Compressive Strength

The compressive strength of the HVFA concrete mixtures was determined at 7, 28, and 56 days of age on 10.2 x 20.3cm (4 x 8 in) cylinders. Table 4 provides the average compressive strength versus time. The mixture with 50% fly ash resulted in the highest compressive strength at all days of age. The 50% fly ash concrete mixture almost reached the required strength of 29.0 MPa (4,200 psi) at seven days of age. The 70% fly ash concrete mixture reached 27.7 MPa (4018 psi) and 30.9 MPa (4409 psi) at 28 and 56 days of age. Thus, the 70% fly ash concrete mixture meets the CDOT Class P structural compressive strength requirement at 56 days of age. Thus, if longer times are allowed in order to reach the ultimate compressive strength, increased cement replacement with fly ash is possible and still meet structural requirements.

The 60% fly ash concrete mixture experienced similar compressive strengths to the 70% at 7 and 28 days of age; however, approximately 5 MPa (725 psi) less strength at 56 days of age. It is believed that not enough HRWRA was added to the 60% mixture during batching (ie. the workability was poor resulting in decreased consolidation of the concrete cylinders). Of note is the increased rate of strength gain of the 70% fly ash concrete mixture between 28 and 56 days of age. This is a result of the pozzolanic reaction. The pozzolanic reaction is the reaction between the silica in the fly ash and the calcium hydroxide produced from cement hydration. It is evident that the mixture with 80% fly ash performed the worst in the compressive strength test at all ages. It never reached half the required compressive strength for Class P concrete.

Table 3 Compressive Strength

Day	50% FA Content	60% FA Content	70% FA Content	80% FA Content
	MPa	MPa	MPa	MPa
7	27.9	19	20.3	7.01
28	41.3	25.9	27.7	10.8
56	43.1	25.6	30.4	12.6

A plot of the compressive strength versus age is shown in Figure 1. The mixture with 50% replacement of fly ash has the largest compressive strength. The slope of the lines represents the rate of strength gain for the mixtures. The majority of strength is developed within the first 7 days of age. However, the fly ash concrete mixtures demonstrate additional strength gain beyond 28 days of age as a result of the pozzolanic reaction.

Split Tension

The split tension test was conducted on the four mixtures at 28 and 56 days of age. ASTM C496 was followed during testing. The split tension provides an indirect measure of concrete's tensile strength. The tensile capacity of the concrete is important for highway pavements as traffic induces bending stresses on the concrete slab. Table 4 provides the tensile strength results.

Table 4 Split Tension Results

Day	50% FA Content	60% FA Content	70% FA Content	80% FA Content
	MPa	MPa	MPa	MPa
28	2.85	2.84	1.95	1.22
56	2.75	2.39	2.27	1.34

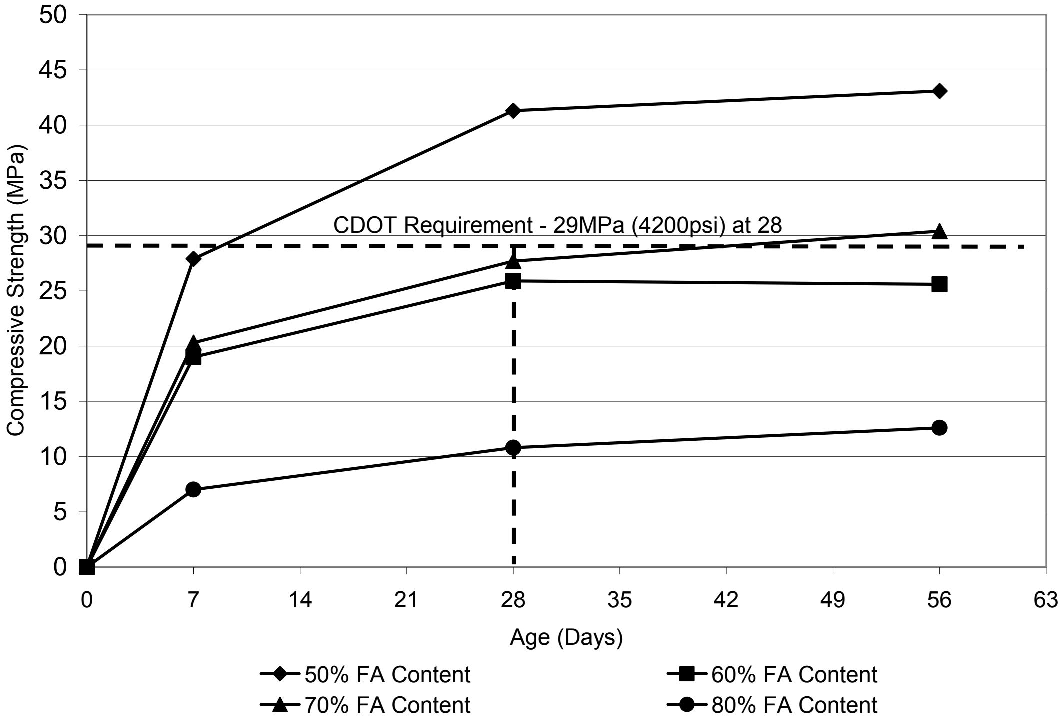

Figure 1 Compressive Strength vs. Age

At 28 days of age, the 50% and 60% fly ash concrete mixtures had similar results. The 70% and 80% fly ash concrete mixtures had significantly less tensile strength than the 50% and 60% at 28 days of age. At 28 and 56 days of age, the tensile strength of the concrete decreases as fly ash content increases. The tensile strength of concrete is much lower than the compressive strength because of the ease at which cracks can form under tensile loads. The ratio of tension strength to compressive strength ranges from 0.06 to 0.11. Typically concrete's tensile strength is assumed to be approximately 0.07 – 0.11 of the compressive strength. Thus, the data measured in this study falls within typical expectations. Table 5 provides the ratios from these test results.

Table 5 Ratio of Split Tensile Strength to Compressive Strength

Day	50% FA Content	60% FA Content	70% FA Content	80% FA Content
	MPa	MPa	MPa	MPa
28	0.07	0.11	0.07	0.11
56	0.06	0.09	0.07	0.11

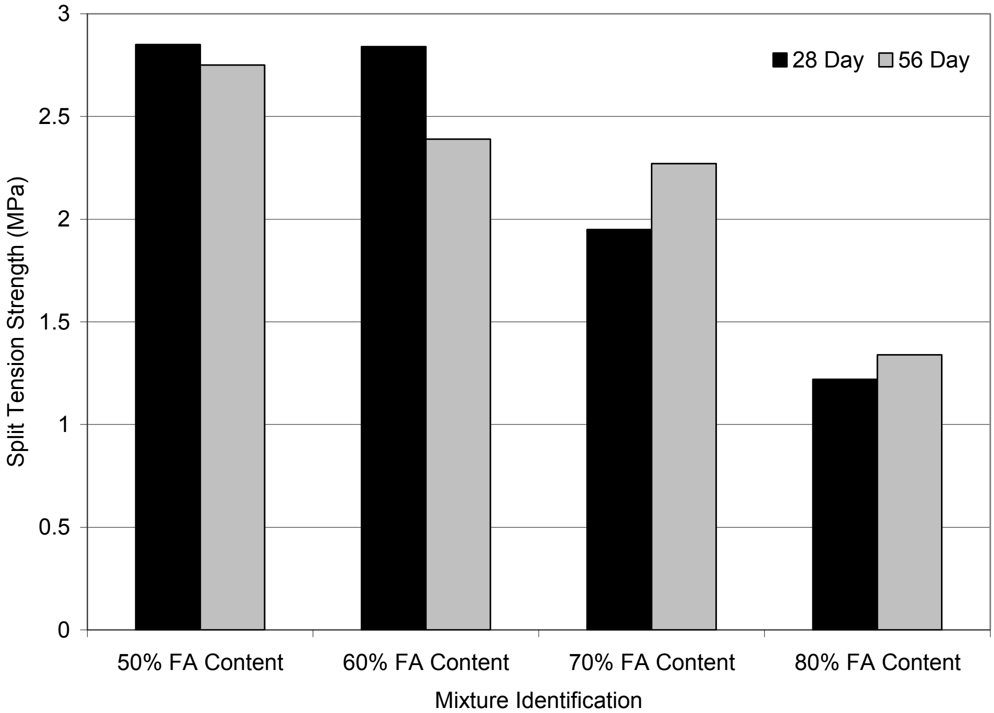

Figure 2 Tensile Strength of HVFA Concrete Mixtures

Permeability

Permeability plays an important role in the durability of concrete because it controls the rate of entry for chlorides, sulfates, and other aggressive and detrimental substances. The more permeable the concrete, the higher susceptibility to freeze-thaw cycles and sulfate attack. The Rapid Chloride Permeability Test, RCPT, (ASTM C1202) was used to measure the permeability of the concrete mixtures. Two specimens were tested for each mixture at 28 and 56 days of age. The results of the four fly ash concrete mixtures are shown in Table 6 and Figure 3.

Table 6 Permeability

Day	50% FA Content	60% FA Content	70% FA Content	80% FA Content
	Coulombs	Coulombs	Coulombs	Coulombs
28	1365	924	1541	3229
56	756	603	1223	3092

The 50% and 70% fly ash concrete mixtures exhibited low permeability while the 60% fly ash concrete mixture experienced very low permeability at 28 days of age. At 56 days, both the 50% and 60% samples conducted between 100 and 1000 Coulombs, resulting in a very low permeability classification. The samples with 70% fly ash averaged 1223 Coulombs (low permeability) at 56 days. The 80% fly ash concrete mixture experienced moderate permeability with Coulombs of 3229 and 3092 at 28 and 56 days of age, respectively. Figure 3 shows the decrease in permeability between 28 and 56 days of age. The 50% fly ash concrete mixture demonstrated a significant decrease in permeability between the test dates.

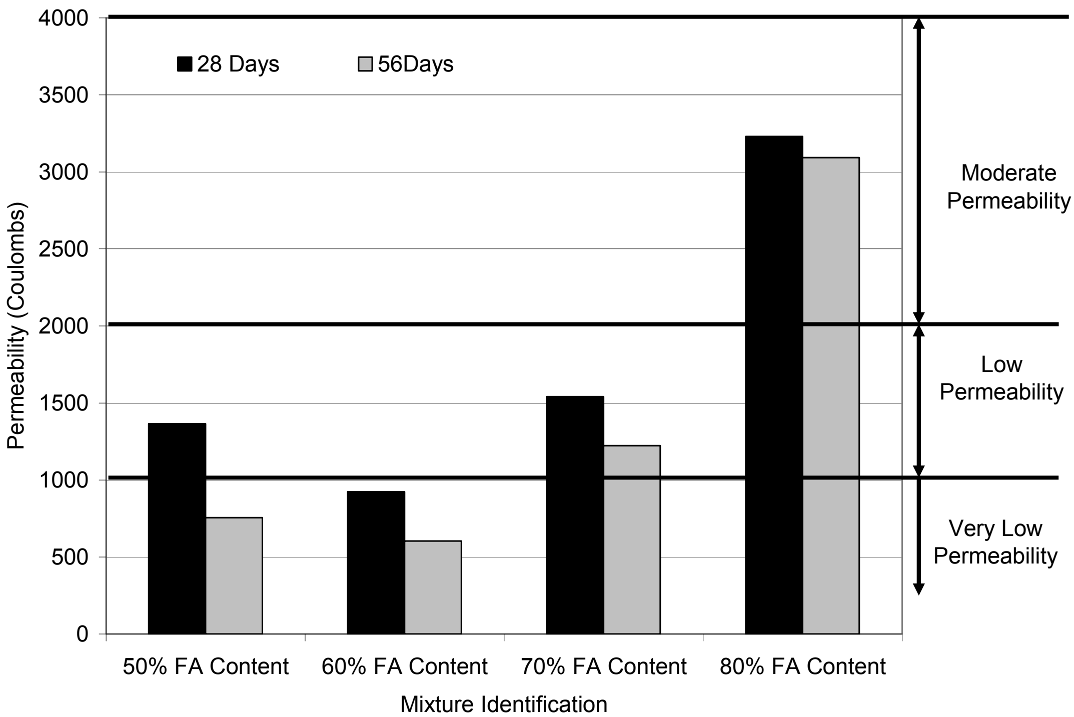

Figure 3 Permeability at 28 and 56 Days of Age

Conclusions and Recommendations

The results of this study found:

- The 50% replacement concrete met the current CDOT compressive strength requirements at 28 days of age. The 70% fly ash concrete met the required 29.0 MPa (4200 psi) compressive strength at 56 days of age.
- If ultimate strength is specified at later ages (ie. 56 days of age) replacement rates up to 70% could be used in the CDOT Class P concrete.
- The tensile strength of the fly ash concrete mixtures decreased with increased percentages of fly ash.
- The tensile strength for the four mixtures were within 7-11% of the compressive strength.
- Mixtures containing 50% and 60% fly ash experienced very low permeability at 56 days of age. The 70% fly ash concrete mixtures produced low permeability at 56 days of age.

The recommendations of this paper include (1) up to 50% of the cement can be replaced with Class F fly ash and meet the current CDOT Class P compressive strength requirement at 28 days of age with very low permeability at 56 days of age and (2) up to 70% fly ash may be included if the ultimate compressive strength can be specified at 56 days of age.

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SUSTAINABLE CONCRETE FOR THE URBAN ENVIRONMENT: A PROPOSAL TO INCREASE FLY ASH USE IN CONCRETE

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ABSTRACT

Sustainable concrete described as concrete incorporating by-products or waste materials is not a new topic. In fact, published research on the use of fly ash, as a replacement for cement in concrete dates back to the 1930s. Additionally, a considerable amount of research supports the use of sustainable concrete in pavements and/or structural components with beneficial results pertaining to reduction in CO_2 emissions, reduction in cost, and achievements in strength and durability. Despite positive research, achieving a more permanent use of sustainable concrete in street and highway projects may require the advocacy for increased utilization of fly ash concrete. This paper argues that increased use of fly ash concrete can occur through continuing fly ash concrete research, motivating public policy efforts and, and furthering technology transfer. Additionally these strategies could contribute to a more committed application of sustainable concrete in street and highway projects.

INTRODUCTION

The Importance and Definition of Sustainable Concrete

In an article by Reiner, Rens, and Ramaswami (2006), sustainability of the built environment requires examination of dominant materials needed for the construction of the urban environment. Of equal importance to the future of the urban environment is the behavior and demands of the population. According to the United Nations, 50% of the world's population resides in cities (Reiner, Rens, and Ramaswami 2006) and with increased urbanization arrives the need for more infrastructure .

Concrete is both dominant as a construction material and contributor to greenhouse gas emissions due to cement manufacturing. With growing concern over environmental impact, meeting people's needs, and advancing technology, there is an increased interest in developing sustainable materials as one solution for these concerns (Mehta 2002). But what is a sustainable material or what is sustainable concrete? Various definitions exist for sustainable concrete and perhaps this is due to the debate over the definition of "sustainability." Some definitions of sustainable concrete have been associated with greening the concrete industry, creating an environmentally friendly material, or providing more durable and optimized concrete. Yet, in the Concrete Joint Sustainability Initiative all of these definitions and more are used to indicate that sustainable concrete can contribute to resource efficiency, safety/protection, economical savings, durability, waste and by-product reduction, and aesthetics. In this paper sustainable concrete is simply defined as the use of by-products such as fly ash in concrete in order to reduce environmental impact while meeting or exceeding structural and durability requirements Furthermore, the benefits of fly ash concrete have been shown to meet all these various "sustainable concrete" definitions.

Revisiting the Benefits of Fly Ash Concrete for Streets and Highways

Asphalt has been the primary material for pavements in the US; however, since the presumable first inception of concrete pavements in 1894 and with continuous research on concrete pavement durability, design, and economical savings the popularity of concrete pavements has increased (Pasko, 1997). Concrete pavements can maintain a competitive edge to asphalt if research focuses on concrete pavements through a materials, construction, urban ecology and urban growth point of view (Pasko 1997; & Mehta 2002). Based on the needs of concrete pavement research and sustainable material development, fly ash concrete has a rich history and promising future to meet these needs and pave the way for other sustainable materials.

States in the U.S. have been encouraged by the Federal Highway Administration (FHWA) to use fly ash in concrete pavements since 1974. In collaboration with organizations such as the American Coal Ash Association (ACAA) and Environmental Protection Agency (EPA), the FHWA has produced updated guidelines for the use of fly ash in concrete highway projects (ACAA 2003). Fly ash (a by product of coal fired power plants) in concrete has been proven to be a beneficial material since the 1930s with one of the first studies performed by R. E. Davis (FHWA 1999). Extensive research since the 1930s have shown that fly ash in concrete can provide some of the following performance benefits (ACAA 2003; EPA 2005):

- Improved workability
- High ultimate strengths
- Reduced bleeding
- Improved durability through reduced permeability
- Reduced heat of hydration
- Increased resistance to sulfate attack, alkali-silica reactivity (ASR), and other forms of deterioration
- Reduced shrinkage

Additionally, fly ash concrete has been associated with economic and environmental benefits. Improved durability and replacement of cement can lead to decreased maintenance costs, longer life cycle and reduced material costs. In a study by P.K. Mehta embodied energy and CO_2 emissions from concrete were found to be largely an effect of the production of portland cement (Reiner, Rens, & Ramaswami 2006). 93% of concrete's embodied energy and 6% to 7% of the world's greenhouse gas (CO_2) emissions can be accounted for through the production of portland cement (with certain assumptions made about transportation and materials content). Typically 1 tonne (1.1 US ton) of portland cement produced releases 1 tonne (1.1 US ton) of CO_2 emissions. Replacement of portland cement with fly ash can reduce energy use and greenhouse gas emissions from the cement industry. One tonne (1.1 US ton) replacement of cement with fly ash can save landfill space, is a reduction comparable to replacing two months of automobile CO_2 emissions, and can save up to half a month of electricity for the average American home (EPA 2005). Lastly, fly ash use in concrete can encourage conservation of natural resources and other materials.

An Indicator That Sustainable Concrete Might Not Be Achievable

The EPA, FHWA, the Utilities Solid Waste Activities Group, Department of Energy and ACAA provide successful case studies on the application of fly ash concrete in various projects throughout the U.S. (EPA 2005). Despite the ability to achieve various benefits, the ACAA reports that the average rate of cement replacement with fly ash in concrete, although has increased over the years, has been maintained between 10% and 20% (Reiner, Rens, & Ramaswami 2006). In Table 1, data gathered from an ACAA 2008 report showed that only 41.6% of the total fly ash produced is being used either in concrete, raw for clinker, flowable fill, embankments, road based, soil modification, filler in asphalt, snow and ice control, blasting grit, mining applications, gypsum products, waste stabilization, agriculture, aggregate, and/or miscellaneous activities. Although, most of the fly ash is used in concrete, fly ash concrete (i.e. concrete for highways, buildings, and other structural components) only accounts for 17.4% of the total production used.

Perhaps certain lingering limitations pertaining to fly ash have led to hesitation in a constant use of fly ash concrete. These limitations are associated with low early strength gain, the need to classify fly ash because of its varying properties due to different types of coal and burning conditions in the power plant, high transportation costs, and the need to study different mixture proportions. Another reason fly ash might not replace cement more frequently is because states within the U.S. are allowed to establish laws, regulations, and policies on the use of fly ash in highway construction on top of already established common standards such as ASTM C 618 (EPA 2005). These various guiding principles are not necessarily unmanageable but can cause confusion and limit states from experiencing the overall benefits of fly ash concrete (Reiner, Rens, and Ramaswami 2006).

Table 1. 2008 Fly Ash Production and Use in the U.S.(ACAA 2008)

By Product	Fly Ash
Total Produced (tonne)	65,729,371
Total Used (tonne)	27,344,611
Fly Used in Concrete (tonne)	11,423,492
Fly Ash Used in Concrete Production (%)	17.4
Beneficial Use of Fly Ash (%)	41.6

However, it is important to note that fly ash concrete is still an emerging research area and there are studies that have attempted to address fly ash limitations with successful results. A list of some authors who have worked towards solving fly ash concrete issues for pavements and structures are listed in Table 2.

Table 2. Past Research on Fly Ash Concrete Issues for Pavements and Structures

Improving Air Entraining	Applications of Various Fly Ashes	Transportation Costs of Fly Ash	High Early Strength Gain
Wang, L. Song S., 2009; Pigeon, M., Malhotra, M. V., 1995	Electric Power Research Institute [EPRI], Coal Combustion Systems Division [CS], 1986; Borrachero, M.V., Monzon, J., Persimora, E. Amahjout, F., 2001	Worrell, E. 2001; Papayianni, I., Anastasiou, E., 2006	Kang, J., Jin, Q., Wang, J., Liu, X., 2005; Naik, T. R., Ramme, B. W., 1990

If improving air entrainment, providing applications of various fly ashes, improving transportation costs of fly ash, and attaining high early strength for fly ash concrete are no longer the issues for fly ash concrete then it might be possible that 58.4% of fly ash that is not being used is due to contrasting state regulations with national regulations and a lack of understanding and communication among all stakeholders (policy makers, public practitioners, researchers, and the public) of concrete. Nevertheless, if 80+ years of extensive research, successful case studies, encouraging guidelines, and various organizational support, still, cannot guarantee increased use of fly ash in concrete streets and highways then impassible hardships lie ahead for achieving permanent use of any sustainable material. Of particular note no other use of sustainable material surpasses fly ash concrete today.

TOWARDS A SUSTAINABLE CONCRETE FUTURE

Despite present conditions of fly ash concrete this paper proposes that barriers to increased utilization can be lifted through continued research, implementation of policy or regional pathways, and technology transfer.

The Importance of Continuing Research of Fly Ash Concrete

There is a possibility that research and innovation might present better options for renewable energy and our dependence on coal based electricity will decrease. However, there presently exists the million tonnes of fly ash that has not been used and is landfilled. Direct landfill of fly ash leads to the issue of leaching metals in groundwater, increased need for land, and the need for monitoring and evaluation of these landfills. Although, fly ash concrete will eventually reach an end-of-life phase, research has shown that trace metals in landfilled fly ash concrete are stable or at least fall under the EPA regulatory levels (Zhang, Blanchette, and Malhotra, 2001). So should the following question be proposed? Are we generating more waste than the replenishment of our resources? If the answer is yes then we certainly must recognize that fly ash is not the only waste material that is generated every day, thus presenting a need for research in the recycle/reuse of materials. Lastly there is still the need for improving the durability, strength, and life span of materials for infrastructure and if waste materials such as fly ash can provide these properties then continued research can help to discover these possibilities.

Policy and Regional Pathways

There is little or no documentation of whether local or regional governments are using fly ash concrete. Increased utilization of fly ash concrete does not have to depend on state initiatives and there is training and guidelines, offered by local ready mixed companies, and professional organizations (i.e. American Concrete Institute, AASHTO, FHWA) to help implementation of fly ash concrete regionally.

Local Agenda 21 and the U.S. Conference of Mayors Climate Protection Agreement are a couple of common examples of implementing change by having local or regional governments take the lead over state and federal governments. Local governments know the needs of their community and have the power to focus on these needs by influencing state and federal government to enact policy changes. According to a study by Ramaswami, Hillman, Janson, Reiner, and Thomas (2008) greenhouse gas emissions research for the city of Denver was used in implementing a "green concrete" policy requiring all new public and private concrete projects to have a percentage of fly ash in the concrete. This policy is emphasized in Denver's climate action plan.

Transferring Technology

As previously mentioned a lack of understanding and communication among all stakeholders (policy makers, public practitioners, researchers, and the public) of the concrete industry could possibly be preventing increased fly ash concrete utilization. But proof of such a statement could require surveying all stakeholders in order to gauge their understanding of fly ash concrete. However, through a brief observance of comments and letters to the EPA regarding the EPA's proposed regulation of fly ash (a result of the failed fly ash impoundment in Tennessee) there is a definite disagreement on fly ash use in general which poses doubts in fly ash use in concrete. There is need to consistently bridge the gap of these varied perspectives. Bridging might need to start with research. If there are weak attempts at communicating research, the proposed policy and regional pathways for fly ash concrete will not be thoroughly considered, and there will undoubtedly be challenges in achieving sustainable concrete. Communication has to reach a broad audience and this is possible through strategies such as peer reviewed literature, magazine articles, a news broadcast, conferences, and attendance in city planning or council meetings.

CONCLUSION

Moving towards a sustainable urban environment can begin with knowing the past, present and future of fly ash concrete for streets and highways. There is an enormous amount of supporting data and interest in fly ash concrete by the research and concrete industry community. Yet 80 years of trying to understand the potential of fly ach concrete has not fully closed the knowledge gap between academia/industry and the government/public. To ensure a future in sustainable urban environments we need to determine the future of one of the oldest sustainable materials and that is fly ash concrete.

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Durable "Green" Concrete from Activated Pozzolan Cement

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Abstract

Concrete is the most widely used man-made material, and the manufacture of portland cement - the active ingredient of concrete - accounts for 6 to 8 percent worldwide of all anthropogenic emissions of carbon dioxide, a leading greenhouse gas involved in global warming.

Globally, nearly 2.77 billion metric tons (t) (3.05 billion st) of portland and hydraulic cement was produced in 2007. The concrete construction sector has a responsibility to take immediate action to reduce its environmental impacts, including the generation reduction of CO2. This responsibility also brings the opportunity to develop innovative technologies, including use of materials from Coal Combustion Products (CCP's).

These newly developed activated fly ash based products leave virtually no carbon footprint. Updated cementitious binder technology eliminates approximately 0.9 t (1 st) of CO_2 emitted into the atmosphere per ton of portland cement produced. These cements have been engineered for use in fast track concrete repairs and construction, conventional paving, walls and concrete block masonry, new construction and repair projects.

Activated pozzolanic material cements and resulting products are comprised of up to 95 percent green sustainable industrial waste stream materials, primarily fly ash. They are manufactured via a low energy, powder blending process. Key to green cement development was creating a material matrix that has a very dense crystal structure. This green cement technology possesses excellent performance and durability characteristics, including high early strengths and 28-day strengths over 70 MPa (10,000 psi). Moreover, they can be placed effectively with ambient temperatures ranging from -1°C to 49°C (30°F to 120°F).

1. Introduction

Coal is a relatively abundant, reliable and inexpensive energy source for worldwide power generation. However, it is also one of the main producers of Carbon Dioxide (CO_2). Fossil-fuel combustion in power plants, vehicles and heaters around the planet released 31.5 billion t (34.7 billion st) of the greenhouse gas (Bloomberg, 2009). The U.S. alone produces approximately 1.5 billion tons of CO_2 annually from all sources; globally, coal is attributed to one third of all CO_2 emissions (USEPA, 2009).

Coal when used as a fuel, is also one of the main producers of Carbon Dioxide (CO_2). Coal combustion has been brought into question regarding other noxious waste products like Mercury, Nitrogen Oxide and Sulphur Dioxide. Economically and technically, viable mitigation technologies exist for the above mentioned pollutants with the exception of CO_2 (Hicks, et. al. 2009).

Another large producer of CO_2 emissions is portland cement kilns. For instance, the use of fly ash (a by-product of coal burning in power generation and most common CCP) in the cement-making process could reduce substantial amounts of CO_2 emitted by a cement kiln. Worldwide, the production of portland cement alone accounts for 6 to 8 percent of all human generated CO_2 greenhouse gases (Huntzinger, Deborah N. and Eatmon, Thomas D., 2009). Portland cement production is not only a source of combustion-related CO2 emissions, but it is also one of the largest sources of industrial process-related emissions in the United States. Combustion related emissions from the U.S. [portland] cement industry were estimated at approximately 36 Tg of CO_2 accounting for approximately 3.7 percent of combustion-related emissions in the U.S. industrial sector in 2001 (USGS, 2002)

In 2007, a survey of 161 US coal-fired power plants (out of 500 operating coal fired power plants) showed production of 118 million t (131 million st) of CCP's. Of this amount, only 12.4 million t (13.7 million st) were used in concrete or as a concrete product. The survey reported that more than 45.4 million t (50 million st) of fly ash is still being disposed of in US landfills annually. (ACAA, 2008) Clearly, the use of otherwise waste materials for beneficial use can reduce the need for more landfills and the amount of CO2 produced.

Extensive research is underway to find more economically feasible alternatives for carbon dioxide capture and storage (CCS). However, until financially and environmentally sustainable alternatives are in use, the byproducts of pulverized coal-based power generation (conventional) will be an issue for decades to come. A successful CO_2 mitigation process presently lies in private-public strategy that combines existing power plants (revamped to capture, geologically store and/or enhance oil recovery), and new ones using more advanced coal power generation technologies like the Integrated Coal Gasification Combined Cycle (IGCC). These approaches alongside proactive regulation could build a relatively sustainable alternative for the future (Floris, Vinio, 2009).

Not all current power plants will be refurbished as mentioned above; yet CCP's from plants that do not convert to CCS technologies could still be put to good use through innovative ways in order to assist in the decrease of greenhouse gases. For instance, fly ash (a by-product that largely ends up in landfills) can substitute for portland cement and improve structural changes to the end product (concrete and others). The use of one unit of fly ash reduces approximately one unit of CO_2 emitted by a cement kiln. Fly ash and other CCP's in the cement-making process could also avoid the use of the high energy requirement and significantly reduce the volume of useable material taken to waste management sites (Floris, Vinio and Hicks James K., 2009).

Governments and corporations are beginning to see the benefits of using CCP's for mitigating greenhouse emissions. For instance, in the State of California California Assembly Bill 32 (AB 32) was signed into law in 2006. AB 32 is seeking reductions in greenhouse gas emissions from the production of portland cement, primarily carbon dioxide. The California Air Resources Board has already passed regulations requiring annual reporting of greenhouse gases-related emissions data from portland cement manufacturing plants. California expects a potential 1.1 million tons reduction in CO_2 emissions by 2020 from cement manufacturing (with a 9% reduction by 2011) and a potential 0.54 to 1.6 million t (0.6 to 1.8 million st) reduction in CO_2 emissions by 2020 from concrete manufacturing (with 9 percent to 27 percent replacement of portland cement with CCP's). By 2050 an 80 percent reduction in greenhouse gas emissions below 1990 levels is targeted. (www.arb.ca.gov/climatechange).

Fly ash can be used as a component in the manufacture of cement while improving the end products of concrete, mortars and grouts (NRMCA and PCA, 2006). Use of fly ash allows their durability factors to be substantially improved. Although fly ash is a very good substitute for cement when used as a pozzolan in portland cement concrete and other cementitious products, importantly, fly ash can be used in very high quantities with activated fly ash cements. These cements have been engineered for use in conventional paving, walls and concrete block masonry, new construction and repair projects.

2. Coal-based Power Generation

Around the world, coal is primarily used as a solid fuel to produce electricity and heat through combustion. Globally, 25% of total energy sources come from coal while in the US it is about 50%. Approximately, 82 percent of coal reserves (data of 2008) were concentrated in six countries (in descending order: USA, Russia, China, India, Australia, and South Africa). The US has 29% of the reserves, 216,189 million t (238,308 million st), while Russia and China hold 19% and 14%, respectively. The US produced 20% of the world's total in 2008 while China and India produced 2.8 billion and 512 million tons, respectively. China is currently the largest producer of mined coal (41% of the world's total). (British Petroleum, 2009)

Global coal consumption is projected to jump nearly 50% by 2030. On a tonnage basis, world coal consumption is projected to grow 47% from 6,117 Mt in 2006 to 8,995 Mt in 2030, an average annual growth rate of 1.6%. The dramatic increase in global use of coal is the result of a predicted 44% jump in world energy consumption (2006-2030). 73% of that projected increase in world energy consumption is the result of expected strong economic growth in non-Organization for Economic Co-operation and Development (OECD) countries. Despite the current near-term economic slump, EIA expects demand for energy for manufacturing and consumer products to rebound□ after 2010. EIA anticipates a 15% growth rate in OECD countries during the same period. (EIA, 2009)

Coal prices have significantly risen since the 1980s after decades of steady pricing. Appendix Figure 1 shows coal prices (US$/st) for Northwest Europe, Central Appalachian US and Japan. US prices were about US $70/st in early 2009. Coal is, compared to other energy sources, the least expensive commodity for power generation. (ACAA Fact Sheet)

In 2006, there were 1,493 coal-powered units at electrical utilities across the US with a total nominal capacity of 335.8 GW The US generated annual power from coal (in 2006) was 227.1 GW. In 2006, China produced 195 GW and it is estimated that it has currently surpassed the US (USEPA, 2006).

Without any global climate policies, it is expected that coal production (mainly driven by Australia, China, Russia, Ukraine, Kazakhstan and South Africa) and consumption may increase 30 to 50% by year 2025 (from 2007 data) (US Energy Information Administration, 2009).

Until more economically feasible alternatives are developed for capturing and sequestering CO_2, conventional coal-based power generation will continue for decades to come. New electric power production technologies and a resurgence in nuclear power electric likely will begin to effect the reductions in CO_2 emissions.

3. Problems, U. Environmental Protection Agency (EPA) and Fly Ash

In 1980, Congress charged the EPA to prepare a detailed study of the health and environmental impact of coal ash. The report was presented in Year 2000 and after discussion at different levels EPA determined that it did not warrant regulations as a hazardous waste under the provisions of the Resource Conservation Recovery Act.

After studying coal-fired utility wastes in 1993, the EPA decided to permanently exclude large volume coal fired utility wastes, including fly ash, bottom ash, boiler slag and flue gas emission control waste from the definition of hazardous waste. Studies have shown that although trace elements may leach from coal ash in prolonged contact with the water table, they do not migrate far from the ash site and are present in very low concentrations, and therefore do not present a health threat.

The 2008, a large Kingston, Tennessee TVA coal combustion residue containment structure collapse opened the discussion considering the amounts of arsenic, lead, barium, chromium and manganese found on that pond (Schlesinger, 2009). However, the ranges of major elements in coal fly ash and soils have been evaluated and are available in National Bureau of Standards Certificate of Analysis (Standard Reference Material 1633a, January 5, 1985). The comparison shows that the constituents in coal fly ash fall within the typical ranges of those in soils found across the U.S. Furthermore, fly ash is commonly used as an additive to concrete building products, not significantly different from that of more conventional concrete additives or other building materials such as granite and red brick.

CCP are considered a waste product for power generation facilities. Waste material, however, should be removed and land filled appropriately. The authors have witnessed well-run facilities that do not pose any threats to health and the environment. Stringent regulations likely will move in that direction, but should not to the point to make the product a hazardous material. Such an outcome would seriously affect (and most likely end) the cement/concrete, road base and gypsum board industry that is providing a significant benefit to the environment. Even so, utilizing the fly ash in a positive manner such an blending to become hydraulic cement utilizes those otherwise discarded materials.

4. Cement and Concrete

Concrete is the most widely used man-made material in the world. In 2008 nearly 2.6 billion t (3 billion st) of portland and hydraulic cement was produced worldwide (PCA, 2009). Cement production generates carbon-dioxide emissions because it requires fossil fuels to heat the powdered mixture of limestone, clay, ferrous and siliceous materials to temperatures of 1,500ºC (2700°F). Limestone (Calcium Carbonate - $CaCO_3$) is the principle ingredient of cement. During the portland cement clinker calcining process, $CaCO_3$ is changed to CaO. This conversion releases one mole of CO_2 (carbon dioxide) for every mole of $CaCO_3$ consumed in the production process. Approximately one ton of CO_2 is released in the production of one ton of portland cement. In the United States, portland cement production alone constitutes about 2-3 percent of CO_2 gasses generated annually. Given the impact that portland cement production has on the environment, it is incumbent on concrete manufacturers to actively pursue immediate programs and/or practices that reduce the generation of CO_2 emissions. The concrete industry shouldn't consider this obligation a negative, however, because this responsibility also brings the opportunity to develop innovative technological advances in both material and a production processes.

Portland cement has long been used in standard building materials. Over the years, various modifiers have been developed for cement formulations to provide particular properties or advantages, such as more rapid curing, compatibility with and resistance to certain materials, and varying strengths, etc. In the past, at times the modified formulations have worked at cross purposes, so that a cement formulation that initially cures more rapidly results in a final product with a lower ultimate strength, while the higher late strength portland cement formulations frequently cannot be demolded for substantial periods of time because there is not sufficient early strength.

Over the past thirty years, scientists have pursued various methods to produce a class of fly ash based cement known as geo-polymers. These early precursors to present products were found - even though mineral in composition - to provide many of the properties of molding resins, such as epoxies and polyurethanes.

Some geopolymeric cementitious products are in used still today in various parts of the world. Such geopolymers are described and claimed, for example, US Patents. (Davidovits, 1982). These geo-polymers are primarily composed of silicas and aluminas, mixed and reacted in particular ways to provide the desired structure. While, in general, these geopolymers are perfectly adequate for the purposes intended, as such, they do not always provide the types of strengths sought in a concrete composition. Furthermore, geopolymers typically require post reaction thermal processing for up to 24 hours in order to achieve desirable strengths.

Below is a recent historical summary of earlier versions of pozzolan based cements:

- Alkali activation of solid, non-portland cement precursors (usually high-calcium slags) was first demonstrated in reasonably modern times by Purdon in 1940, and was developed on a larger scale primarily in Eastern Europe in the succeeding decades, (vanDeventer, Jannie S.J. et. al, 2010)

- 1970's: Geo-polymers from fly ash, cements high in Al-Si. J. Davidovits makes references to their use in historical construction techniques.

- 1980's: Activated fly ashes blended with cement, e.g. mostly two step mixes unconditionally require addition of the activator at the jobsite.

- 1990's through mid-decade beginning in 2000: development of one step mixes, activator in product package or cement. The cementitious compositions typically consisted of harsh acids and bases such as citric acids (pH~2.2) and alkali metal activators including alkali hydroxides (pH~12-14) and metal carbonates (pH~11.6). These included patents by Gravitt, Kirkpatrick, Styron, Hicks and others. There were some drawbacks to these materials. The prior art required acid -base reactions. These reactions sometimes were non-uniform and difficult to control.

The art has needed and continued to seek a hydraulic cement composition, which provides for utilization in standard situations, while providing both a high early strength and an ultimate, very high strength. In particular, compositions having a minimum strength of 28 MPa (4,000 psi) at 4 hours, the release strength necessary for prestress work, have been sought.

5. The New Generation of Cement Technology

This new generation of fly ash based cements offers the user a unique set of mechanical and dimensional properties competitive in cost to current cementitious product offerings, providing the user with a value added alternative solution for today's most challenging construction cementitious repair, product and paving applications. The technology is built around a highly flexible chemistry that allows for the inclusion of a wide array of waste materials as part of its binder matrix, establishing it as a truly green sustainable construction material with unique performance and application advantages.

This new green cement technology is based upon an all fly ash cement design that requires no portland cement in its matrix. Through a detailed study of various types of chemistry and reactive fly ash-based cement pastes, key aspects of the mineralogy have been identified for determining the usefulness of various fly ash sources as high performance cements, including non acid-alkali activated cements.

Key to green cement development was creating a material matrix that had a very dense crystal structure eliminating the movement of water and other chemicals through the material matrix; water being the catalyst for many of the reactions that occur in the concrete matrix.

This is accomplished through the simultaneous dissolution and retardation of the Calcium Oxide phase to solubilize both the silicate and aluminate amorphous phases. The minerals recombine to the desired structure providing desired mechanical and dimensional properties.

Thusly, pozzolanic materials are modified with chemicals to produce the desired structure. This is denoted by the phase diagram in accompanying Figure 7. At the corners of the diagram are the key minerals that are found in typical cements.

The red-hatched zone in the upper half of the diagram represents what is theorized to be the perfect cement. It characterized by a very dense crystal structure exhibiting the optimum chemical ratio of calcium to silicates to aluminates.

The micro pore structure is very small, greatly limiting the movement of liquids within the material matrix.

The crystal structure of portland cement is dominated by Tricalcium Silicate (C_3S) and Dicalcium Silicate (C_2S) components producing a crystal structure that is not as dense leading to relatively a large voids structure within the material matrix. The chemical and mineralogical improvements, coupled with the much higher fineness of pozzolan based cements ground leads to much lower porosity in the concrete. The lower porosity provides for very low water to cementitious ratios and improved durability factors.

Having developed a technique to "fingerprint" raw materials as well as a "road map" of good fly ash sources, the new approach is able to maintain quality assurance on product lines using a broad array of fly ash sources, and blends of sources.

The improved activated hydraulic cement technology is the principal backbone chemistry for a range of product offerings from small area repair packaged goods to new construction concretes. Products from the non acid-alkali activated cements were developed specifically to satisfy user or application performance requirements. Each product is water mixed, single component activated, turnkey concrete, mortar or grout with flexible working times from 15 minutes to three hours. The products were engineered to allow for mixing, hauling, placing and finishing using standard industry equipment and practices. The products were designed for applications where speed, strength and durability were desirable performance characteristics. Compressive strengths of more than 17 MPa (2,500 psi) in as little as 60 minutes supported by bond strengths of over 21 MPa (3,000 psi) and flexural strengths over 10 MPa (1,500 psi) in 7 days frame the technology's mechanical properties. Dimensional stability is highlighted by shrinkage of less than 0.04% length change in 28 days.

Principle benefits of this new class of products include:

- Non-shrink.
- Exceptional sustained bond strengths (slant shear and direct tension).
- Low coefficient of thermal expansion.
- Modulus of elasticity consistent with Portland cement concrete.
- Low permeability.
- High resistance to freezing and thawing.
- High resistance to scaling. High resistance to sulfate and chemical attack.
- Exceptional durability.
- Placement temperature tolerant.
- No epoxy resins are contained.

Specific areas of products developed meeting objective criteria fall into several areas:

- Rapid Repair
- Ready Mix including paving
- Volumetric mixer concrete and mortar
- Concrete block/grout/mortar
- Precast
- High Temperature Resistant Materials.
- Chemical Resistant Materials

Some of the more specific examples descriptions are:

- Rapid repair products all have cementitious components greater than 90 percent coal ash, and contain no portland cement. Based upon the size of the repair, products range in working time from 15 to 45 minutes, offering return to service ranging from 1 to 4 hours (See Table 1). All products can be mixed with conventional mixing equipment and placed like portland cement products, however without the requirement of bond coats.

- Ready-mix truck delivery. For large placements such as roadway slabs, ash-based pozzolanic cements have been adapted to ready-mix batch plant/transit truck mixing and placement. These products are able to be site activated (up to 4 hours transit time), and adjusted to placement times from 1 to 3 hours. Return to service can be achieved in as little as 6 to 12 hours (See Table 2). Slump control can be adjusted to range from roller-compacted concrete (RCC) to a self-consolidating concrete (SCC).

- Volumetric mobile mixer use. The volumetric pozzolanic product utilizes the same backbone chemistry as the rapid repair products. For larger placements that also require fast return to service, the pozzolans have been adapted to work in a volumetric mixer, allowing from 20 to 50 minutes of placement time, with return to service in as little as 1 hour depending upon the user requirements. With DOT and DOD applications, the principal benefit of volumetric placement is the ability to place larger volumes while still taking advantage of the quick return to service. One version of this product can be used as a flowable grout capable of providing up to three hours of working time, yet providing up to 35 MPa (5000 psi) in compressive strength in 24 hours.

Among the general construction and precast benefits are:

- For vertical construction markets, including columns, flooring, and tilt-up construction, ash-based pozzolanic cements have been adapted to perform as self-consolidating concrete (SCC). These products permit easy pumping and long working times, yet can suspend aggregate, provide sufficient placement time, and offer early return to service. These are placed with a conventional batching and mixer system.
- Precast. Additional benefits of non acid-alkali activated ash-based pozzolanic cements also extend to precast concrete applications. Higher strength precast components can be developed, offering the ability to strip molds much earlier than with cement based concrete. This ability permits faster turn-around and throughput to the manufacturer.
- High Temperature Resistant Materials. A unique benefit of ash-based pozzolanic cements is their high temperature resistance capabilities. Ash-based cements are naturally refractory given their amorphous glass chemistry. Coupled with other high-temperature admixtures, these products are the only materials that have passed Mach 1 shock testing at 1700°F (927 ºC) for 300 cycles. This result has qualified the material for use as a run-up and takeoff pad for current emerging vertical takeoff aircraft (VTOL) including the AV-8, V-22 Osprey, and the new Joint Strike Fighter.

- Armor and Protective Materials. Non acid-alkali activated fly ash-based pozzolanic cements are not only able to achieve high-early strength, but very high strengths overall. In one development area, a class of cements has been developed capable of achieving over 69 MPa (10,000) psi in 24 hours, and up to 152 MPa (22,000 psi) within 28 days. These products are in development with the US Army Corps of Engineers as a field emplaced armor material capable of withstanding both blast and fragment penetration.
- Concrete block/grout/mortar. The non acid-alkali activated fly-ash based pozzolanic cements have also been optimized to product both normal strength and high strength concrete masonry units (CMUs). Products have been able to achieve strengths ranging from 14 to 69 MPa (2,000 to 10,000 psi) using conventional concrete block manufacturing facilities, techniques, and cement percentages equal to those used by conventional cement.

6. Conclusions

Despite all global warming concerns and being in the midst of a financial crisis, an approximate growth of 30-50 percent of coal power generation is expected between Years 2007 to 2025. The installed capacity would jump to approximately 2.1 million MW. Initial estimates were even higher but the US and Europe are scaling back due to strong environmental pressures. China alone would add approximately 350,000 MW during this period while India would follow with more than 100,000 MW.

As it was examined in Sections 2, 3 and 4, it is essential to emphasize that the use of CCP could make key reductions in CO_2 emissions by using byproducts to make cement, substituting for portland cement in concrete, and reducing energy given the energy-efficient nature of concrete structures. It is important to point out that the CCP option is only available for pulverized coal plants. IGCC units follow a different technique and do not produce any cementitious materials as by-products.

These cutting-edge, next-generation “green” non acid-alkali activated fly-ash based pozzolanic cements provide the construction a value added alternative to traditional cement product offers. The extent of engineering that has been done with the product offers widest range of end-use applications from any pozzolan, removing it from its previous limited use as a short-life rapid repair product only. Moreover, the amount of research that has been conducted on understanding fly-ash chemistry and mineralogy has extended the ability to use a much wider range of high calcium coal ash while maintaining predictable product performance. These truly green building materials are comprised largely of renewable, recyclable or reusable resources. They are the only cements in the world whose chemical matrix is comprised of more than 95% waste materials. See Figure 5.

This new generation of all ash-based pozzolanic cements also furthers the ability to utilize green building technology for the widest range of end-use markets, including most DOT, DOD, and building construction market applications while meeting International Building Code and ASTM Standards.

It is important to note that although the environmental and even economic benefits from using CCP's are apparent, they are still underutilized. The American Coal Ash Association reported that less than 40 percent of CCP are used. The Association only reports affiliated utilities. The authors estimate that less than those amounts are currently used and end up in landfills, creating a burden to the environment and the economy of different enterprises.

We all need to understand that we must adopt sustainable energy policies to avoid endangering energy security and control carbon emissions. Without any intervention, CO_2 could increase 42.4 Gigatons in 2035 from 29.7 in 2007 (EIA, 2010). This increase is a real and immense challenge that has to be managed promptly.

KEYWORDS: Recycled, cement, green, concrete, CO_2 reduction, CCP, Sustainable

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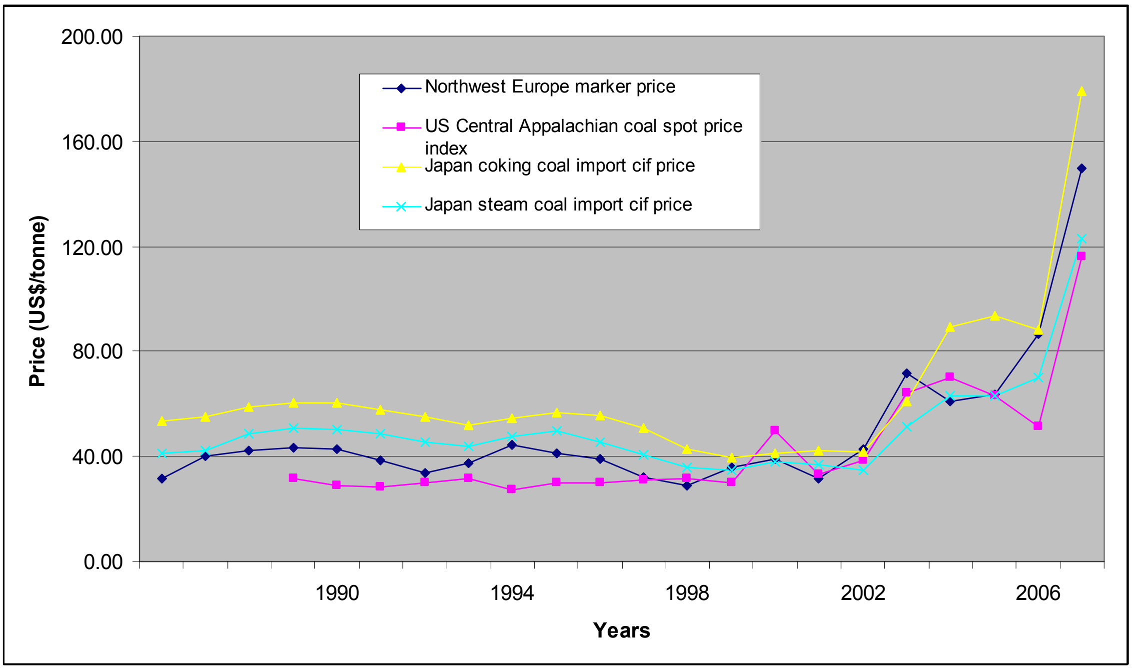

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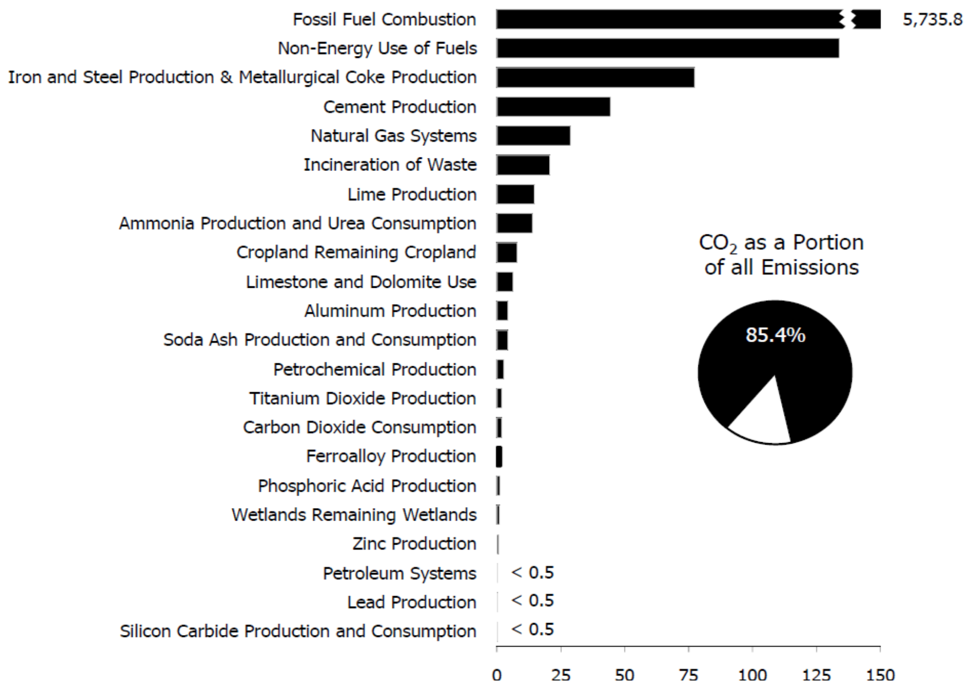

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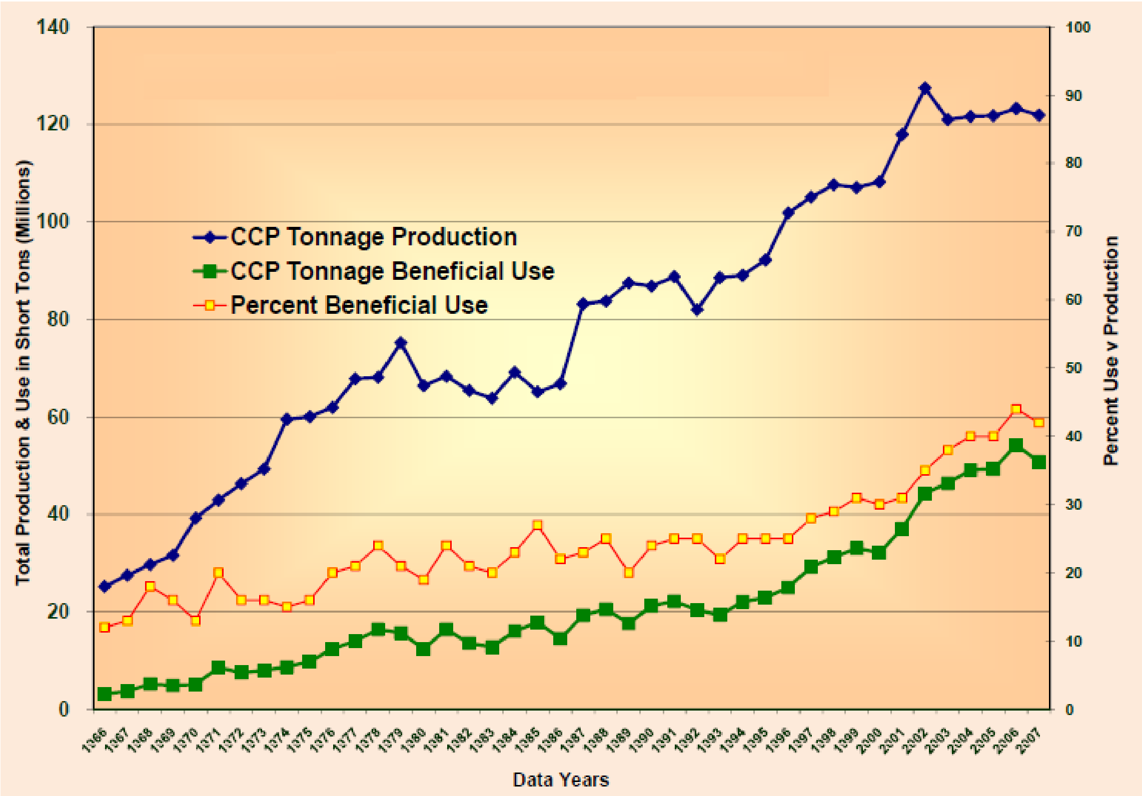

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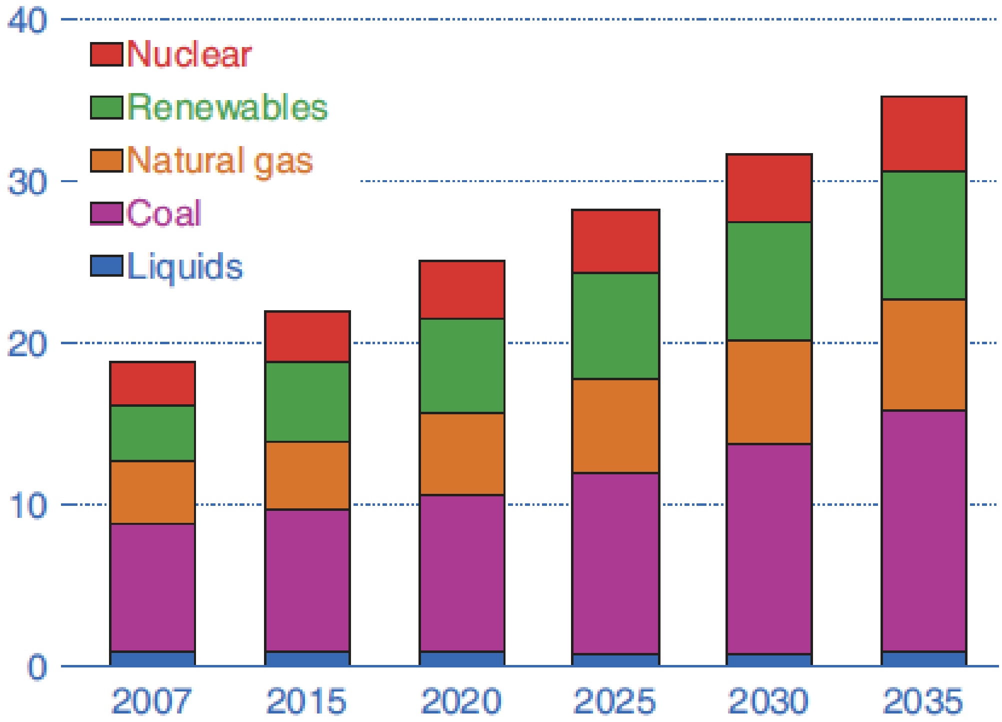

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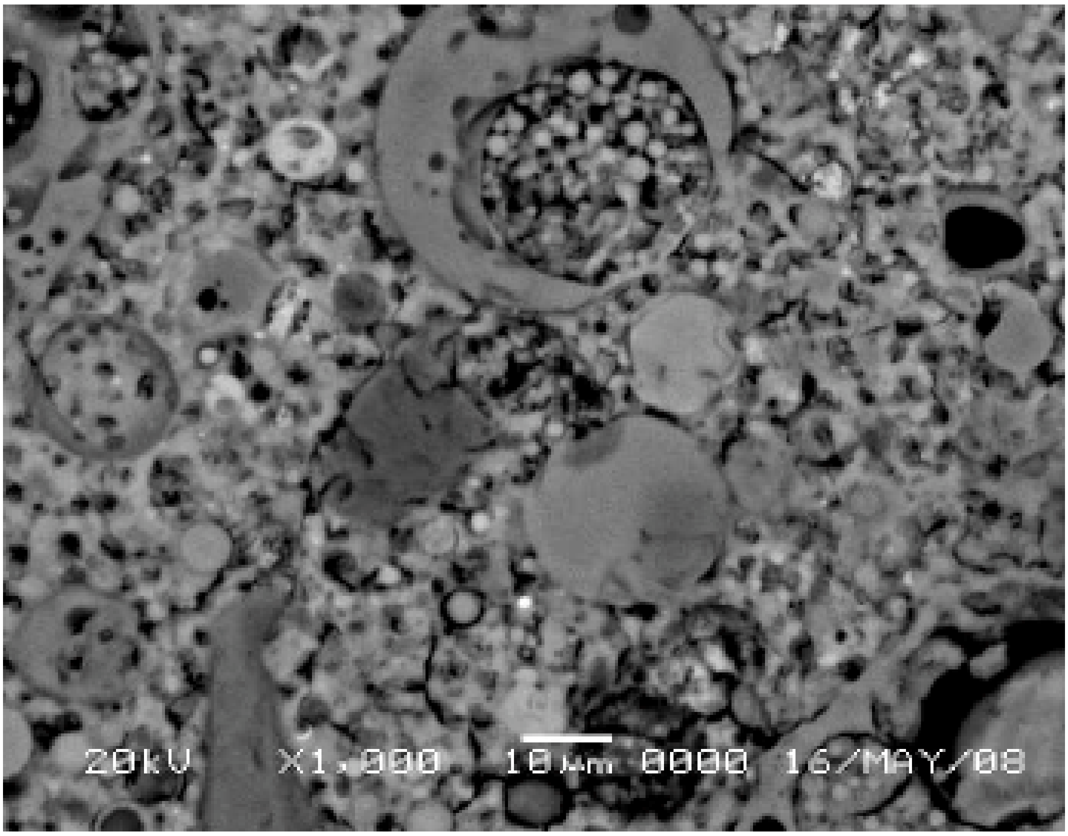

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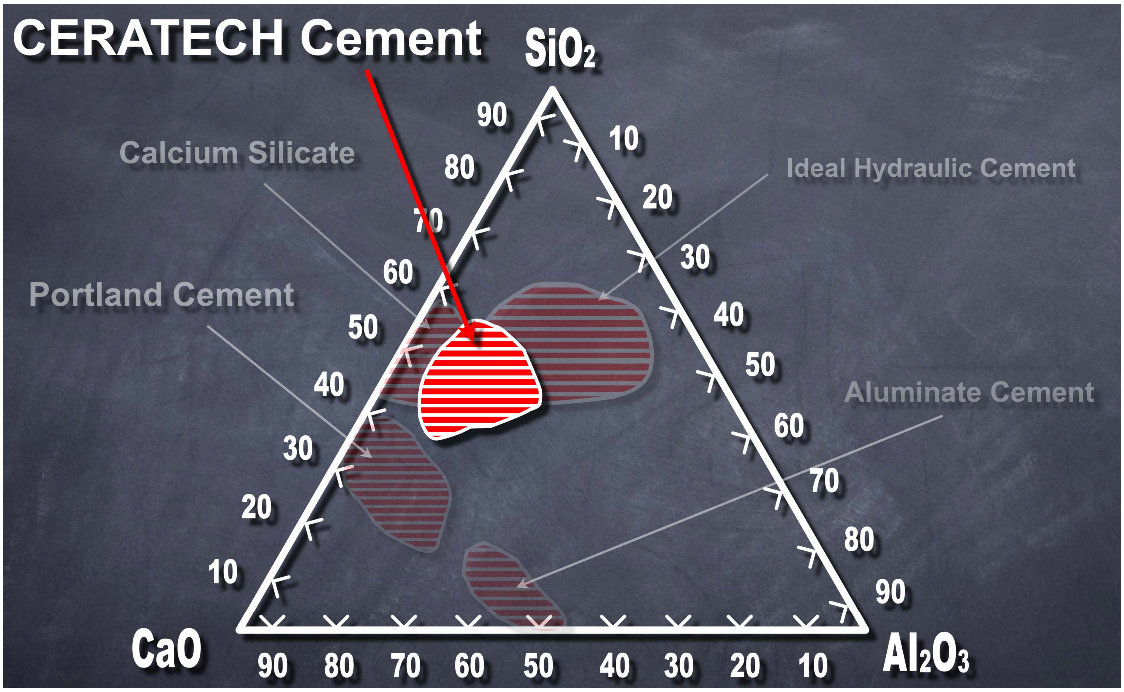
Source: James K. Hicks, et. al. (2009).



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Source: CeraTech, Inc.

Figure 8. Marine Corps Engineers training for fast track construction and repair prior to deployment. Marine Corps Base Concrete Installation

Source: James K. Hicks, et al (2009).

Table 1. Performance characteristics of an activated pozzolan based cement repair material. All testing was performed with air cured specimens.
Source: CeraTech, Inc.

Property	As Packaged 4 in. x 8 in. cylinders	Test Method
Compressive Strengths, psi (MPa)		
2 hours	2820 (19.4)	ASTM C 39
1 day - 24 hours	6115 (42.2)	ASTM C 39
7 days	9345 (64.4)	ASTM C 39
28 days	10,510 (72.5)	ASTM C 39
Flexural Strength, psi (MPa)		
1 day - 24 hours	690 (4.8)	ASTM C 78
7 days	945 (6.5)	ASTM C 78
28 days	1405 (9.7)	ASTM C 78
Splitting Tensile Strength, psi (MPa)		
28 days	590 (4.0)	ASTM C 496
Bond Strength, psi (MPa)		
1 day - 24 hours	1960 (13.6)	ASTM C 882
7 days	2745 (18.9)	ASTM C 882
Rapid Freeze Thaw Resistance (Durability Factor - Retained percentage of Dynamic Modulus)		
300 cycles	100%	ASTM C 666A
Scaling Resistance, lbs/ft² (kg/m²)		
50 cycles	0	ASTM C 672
Modulus of Elasticity, msi (GPa)		
28 days	5.2 (35.1)	ASTM C 469
Coefficient of Thermal Expansion, in/in/°F		
28 days	1.32	AASHTO TP 60
Length Change, % of total length		
28 days soak / 28 days dry	-0.052 /-0.041	ASTM C 157

Table 2. Characteristics of an activated pozzolan cement fast return to service ready mixed concrete[1]
Source, CeraTech, Inc.

Property	[1]Rapid Set	[1]Standard Set	Test Method
Compressive Strengths, **psi** (MPa) 4 in. x 8 in. cylinders			
6 hours	3500 (24.1)	NA	ASTM C 39
24 hours	3604 (24.9)	2497 (17.2)	ASTM C 39
3 day - 72 hour	4502 (31.0)	4193 (29.0)	ASTM C 39
7 days	6487 (44.7)	5998 (41.3)	ASTM C 39
28 days	8511 (58.7)	8502 (58.6)	ASTM C 39
Flexural Strength, **psi** (MPa)			
7 days	510 (3.5)	485 (3.3)	ASTM C 78
28 days	650 (4.5)	630 (4.3)	ASTM C 78
Splitting Tensile Strength, **psi** (MPa)			
28 days	720 (5.0)		ASTM C 496
Rapid Freeze Thaw Resistance (Durability Factor - Retained percentage of Dynamic Modulus)			
300 cycles	100%		ASTM C 666A
Scaling Resistance, **lbs/ft²** (kg/m²)			
50 cycles	0		ASTM C 672
Abrasion Resistance, Depth of wear, millimeters @ 28 day	0.14		ASTM C 944 (2005)
Modulus of Elasticity, **msi** (GPa)			
28 days	5.00 (34.0)		ASTM C 469
Coefficient of Thermal Expansion, **in/in/°F**			
28 days	4.6		AASHTO TP 60
Length Change, **% of total length**			
14 days	0.04		ASTM C 157
Creep (365 days) (µ Strain / psi) **Creep** Coefficient	1.91		ASTM C 512

Notes:

1. Strength development and working times can be adjusted by varying the cement ratio and by use of various proprietary activator admixtures.
2. Test results based on 846 lbs. of cement per cubic yard mix design and Fast Set Activator
3. Test results based on 564 lbs. of cement per cubic yard mix design and Fast Set Activator

Concrete in the Inner Circuit, a sustainable solution for Mexico City

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ABSTRACT

In one of the largest cities in the world, the concern to prevent and reverse the environmental damage caused by a disorganized and uncontrolled planning process, becomes a primary focus on the development of a city. The specific options that concrete gives us in terms of sustainability according to their physical and mechanical characteristics enabled the Government of Mexico City to create a sustainable solution for one of the largest thoroughfares of this city, the Inner Circuit. Sustainable benefits were reported in three areas, the social, economic and environmental improvement over other materials performance in durability, safety, energy conservation, heat island effect and others. The repaving project of Inner Circuit of Mexico City, not only involves the incorporation of a sustainable material in the pavement but all works carried out on alternate result of the project, such as empowerment of green areas, recreational areas along the 42 kilometers that make up the circuit, the use of sustainable alternatives and innovative recycled materials and waste. Now, the Inner Circuit in Mexico City is an example of sustainable project on highways and streets.

1. Introduction

Mexico City has presented a rapid growth of population and territorial extension over the past 50 years. Mexico City has become a giant city which demands major infrastructure projects to meet the demand of its population (Alba, 2004). Infrastructure also needs to be friendly with the environment and provide benefits and advantages over environmental problems such as noise, traffic pollution, lack of recreational facilities, lack of green space, etc. The road infrastructure of Mexico City has a length of 10 200 kilometers and consists of primary roads, road axis, secondary and tertiary roads or local. The Inner Circuit of Mexico City, today also called Bicentennial Circuit, is a main artery of 42 kilometers in length, with three high-speed central lanes in each direction plus two side lanes for heavy traffic. The Circuit is a concentric ring (see Figure 1) linking different areas of the city.

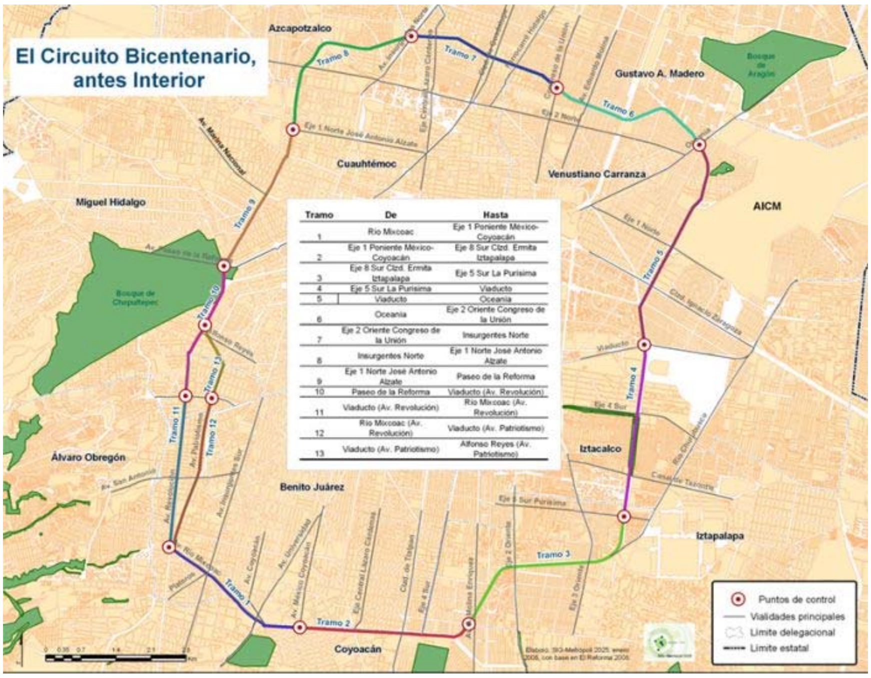

Figure 1. Configuration of Bicentennial Circuit/Inner Circuit.

The Government of Mexico City (GMC) used to spend recurring costs in maintenance of Inner Circuit due to it was built with asphalt roads which required continuous maintenance. Through a public tender in accordance with Mexican law, in January 2008, GMC employs CEMEX to provide long-term services for urban enhancement and maintenance of the Inner Circuit, which includes the bearing surface of the central and side rails to concrete base, a garrison, street lighting, signage, restoration of green areas, under bridges and renovation of pedestrian and vehicular bridges. The decision-making process was based on work done several years ago where it has shown the performance and benefits of concrete pavements on the asphalt, specifying the economic, environmental and in this project, social.

2. Sustainable Project Proposal

Urban planning and sustainability go hand in hand and for this marriage to be met these things should be taken into account: the creation, maintenance and improvement of roads, establishment of mechanisms for cleaning, sanitation, water management, waste treatment, urban management and regeneration and maintenance of green areas. (Gonzalez, 2009).

Within the three factors that make up sustainability: social, environmental and economic, different solutions were proposed that make the project a sustainable solution for Mexico City.

Initially, the rehabilitation process of Inner Circuit began with the demolition of the asphalt, which by this time consisted of eight layers of asphalt were given as maintenance since its construction.

After demolition, excavation was carried out because the thickness of the pavement was considerable; if we talk about 8 layers of asphalt on average each had 7 centimeters, so they had to demolish an average of 56 centimeters by 42 miles length.

To form the embankment, was used largely the result of excavation material, which when mixed with cement formed a part of the structure recycled. Later flowed fill concrete was used to form the base of pavement.

The characteristics of the concrete used for paving took into account a lifetime of 25 years, with inflows from up 23 000 to 95 000 AADT (Annual Average Daily Rate) depending on the sections, which have led to pavement thickness from 24 to 30 centimeters with a flexural strength of 45 kg_f/cm^2.

Sometimes - more through lack of information or ignorance - the concrete is usually not in the list of people who view this material as "green." For the reasons shown, there is evidence that the concrete provides a broad spectrum of benefits to the environment and the community, (Celis, 2009), which in the case of Inner Circuit did a sustainable solution.

Care of natural resources

Concrete pavements using fewer aggregates, in general, than asphalt pavements, besides obviously do not use petroleum products in its composition. (Mendoza-Delatte, 2009).

Energy Saving

Concrete pavements have a lower rolling resistance of vehicles (friction) as compared with asphalt so there is a significant reduction in vehicle fuel. (Mendoza-Delatte, 2009).

The concrete shows excellent environmental performance by saving energy during its manufacturing process, its means lower fuel consumption leads to lower carbon footprint when compared to alternative materials such as asphalt. The concrete has characteristics of thermal and reflective of sunlight, thus being less hot emits less heat on the surrounding buildings, greatly reducing power consumption for heating, cooling and lighting, with benefits savings of up to 50 percent. (CEMEX, 2009)

In terms of energy saving, the concrete pavement reduces the need for lighting of roads. (Mendoza-Delatte, 2009)

Safety

Due to the roughness of the concrete, roads become safer by requiring less stopping distance on dry or wet at 50 km/h, this distance is 10% less on the concrete surface than the asphalt (Mendoza, 2009). In concrete surface curves as less slippage, additional concrete surface is skid and improved surface drainage by decreasing the puddles on the pavement.

In terms of brightness, due to its light color, the pavement acts as a diffuser and reflector surface of the light rays incident on it, which facilitates the collection of fixed or moving obstacles that are on the road (Mendoza, 2009) , It is considered to have 2.8 times higher reflectance than asphalt, providing greater confidence to drivers.

Reduced heat island effect

The concrete, being a clear material absorbs less heat; therefore it reflects about 30% of solar radiation.

In the Inner Circuit different thermograms were taken between the surfaces of asphalt and concrete, making observed differences of up to 13 ° C between the two materials, concrete temperatures being the lowest. (See Figure 2)

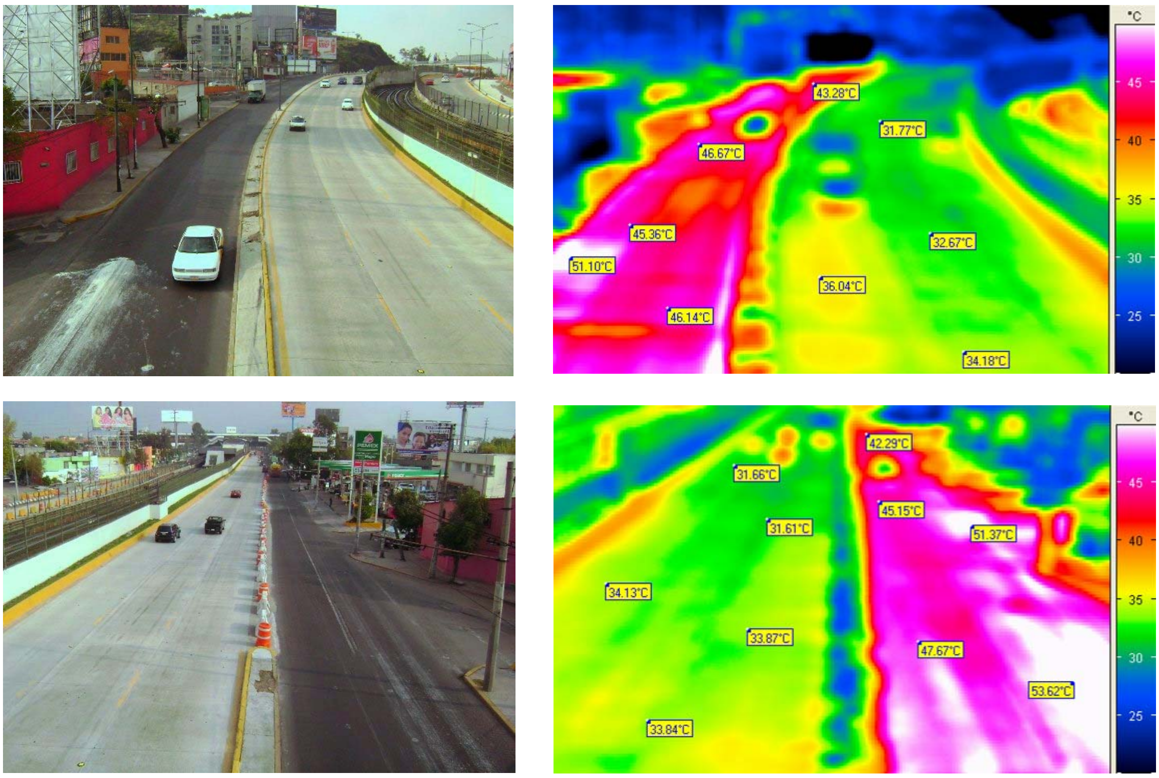

Figure 2. Thermograms between concrete and asphalt in two different sections.

Economic benefits

The ongoing maintenance items are very low when you use a rigid pavement with virtually no special care needs. Maintenance costs at the end of the life of a flexible pavement (25-30 years), they may be four or five times higher than those of a rigid. This helps the user or administrator costs remain low and should be considered more than a method of constructing a system of planning for the future of cities. The hydraulic concrete roads are built faster. There is evidence that performance of 1000 meters per day. In a matter of maintenance, minor works are limited to the care of gasket seals and cleaning them. (Mendoza, 2009)

Although the cost of paving a road with similar hydraulic concrete compared to asphalt pavement, a paved street with hydraulic concrete offers lower maintenance costs, higher quality longer life to 40 years. Specifically for drivers of vehicles bearing on concrete surfaces can say that its handling is safer and more comfortable, saves fuel and greatly reduce maintenance costs of their vehicles. A cubic meter of concrete required to manufacture half of energy demanded by a cubic meter of asphalt (CEMEX, 2009)

In the case of Inner Circuit, an economic analysis comparing the alternatives of asphalt and concrete is included.

Item	Cost
Asphalt Cost (spread, compacted and 2 irrigations)	$215/m^3 usd
An asphalt layer of 7 cm	$15/m^2 usd
8 layers of asphalt of 7 cm each	$120,6 /m^2 usd
Investment in 16 years a GDF [1]	$120,6 /m^2 usd
concrete layer of 27 cm to 20 years [1]	$ 34,5 /m^2 usd
Interior Circuit Area	882 000 m^2
Asphalt Pavement in 16 years	$106 382 769,23 usd
Concrete Pavement in 20 years	$ 30 582 846, 15 usd
Difference of materials and placement Concrete vs Asphalt	**$ 75 799 923, 08 usd**

[1] Excluding minor maintenance such as pothole repair.

Each layer of asphalt of 7 cm that put in Inner Circuit, the GMC was placed every two years.

Social benefits

In addition that we mention before, the project involved the construction of parks, rehabilitation of green areas, pedestrian bridges, vehicular bridge maintenance and rehabilitation of the fixtures. (See Figure 3)

The existing conditions and areas were abandoned, unlit and without maintenance, unused spaces were served to the accumulation of garbage, ponding of water, concentration of gangs to promote addictions, due to abandonment mention above. From planning the rehabilitation of Inner Circuit, to incorporate the social aspect was considered the rehabilitation of all these public places to address different groups and promote social welfare. In these spaces with architectural concrete was used to give better image color throughout.

Figure 3. Construction of recreation areas and green areas

3. Conclusions

Based on the analysis provides this report leads to the following conclusions.

1. The use of hydraulic concrete pavement is an alternative that contributes to the decrease in the emission of environmentally harmful like greenhouse gases.
2. The heat island effect, currently present in cities with large concentrations of population, can be mitigated with the use of hydraulic concrete pavements. There thermograms comparing temperatures asphalt concrete pavements against those made with hydraulic concrete in the internal circuit where there are temperature differentials of up to 13 °C.
3. The initial cost of use of hydraulic concrete pavements are higher compared with those obtained by the use of asphalt concrete. However, this difference was reversed over time as costs for the maintenance of asphalt concrete pavements are much higher compared with those for the use of hydraulic concrete. It is necessary to make life cycle assessments, eco-efficiency and carbon footprint to compare the environmental and economic benefits of concrete compared to asphalt.
4. The resurfacing of Inner Circuit in Mexico City is a sustainable alternative to the problems besetting the city.
5. The next step is to replicate this case to the road infrastructure projects to ensure continuity of these efforts in sustainability, adding more and more environmental specifications as a limit on emissions of CO_2 per cubic meter of concrete produced and thus modify the selection process materials and concrete production.

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Thin Whitetopping for Green Highways

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ABSTRACT

Thin Whitetopping (TWT) is the process of rehabilitating distressed asphalt concrete (AC) pavements using a concrete overlay. Thin Whitetopping has the potential to become a low maintenance, green treatment for the AC pavements needing rehabilitation in the urban area because of unique advantages offered by concrete. This study was done to develop a design procedure for the AC pavements to be overlaid with TWT using finite element (FE) analysis. The FE analysis was performed with SolidWorks, a 3-D FE software program for different TWT thickness, existing AC layer thickness and modulus, bonding condition between TWT and existing AC layer, and temperature differentials. Each model was built as a three-layer pavement system- concrete (TWT), asphalt layer and subgrade soil. The traffic load was modeled as a constant pressure with a rectangular area applied at the surface and with intensity equal to the tire inflation pressure of 100 psi. The expected lives of TWT overlays were estimated using the equations developed by the Portland Cement Association (PCA). The greener aspects of such a treatment were outlined.

Keywords: Rehabilitation, Thin Whitetopping (TWT), AC pavement, Finite Element (FE) Analysis, SolidWorks.

INTRODUCTION

The formation of heat island (HI) is a major concern in the city areas that influences energy demand, air and water quality, and global warming. Heat Islands are the areas that are hotter than neighboring rural area. Along with other factors, engineering materials such as asphalt concrete, Portland cement concrete, stone and steel that are used in urban development are responsible for HI formation. These materials have high thermal conductivities and heat storage capacities. They also prevent water from infiltrating soil reducing the amount of water available for evapo-transpiration. All these factors contribute to HI (Barnes et al. 2001). However, it is not possible to avoid the use of these construction materials but greener use of them is doable.

Ting et al. (2001) and Lowery, G. (2005) conducted life-cycle cost (LCC) analysis of asphalt and concrete overlay for pavement rehabilitation. They found that although asphalt concrete pavement (AC) has lower initial cost for rehabilitation work than that of whitetopping, the maintenance cost is much lower for whitetopping. Whitetopping is the rehabilitation process of AC pavements using a thin Portland cement concrete overlay. Field measurements have shown that Portland cement concrete (PCC) has much higher albedo value (0.35-0.4 for new concrete and 0.2-0.3 for most older concrete) than AC (0.05-0.1 for new asphalt and 0.10-0.15 for aged asphalt) (ACPA 2002). Albedo is defined as the ratio of the reflected solar radiation to incoming solar radiation on the surface. Higher albedo values decrease the absorbed heat preventing formation of HI. Moreover, whitetopping needs much less maintenance in its service life than AC pavements. Thus, whitetopping may become a greener choice for rehabilitation of AC pavements.

There are three types of whitetopping: (1) Conventional (thickness $\geq$ 8 in.), (2) Thin (thicknesses 4-8 in.) and Ultra-thin (thickness 2-4 in.) (Sheehan et al. 2004). Existing design procedures for whitetopping are: (1)AASHTO (AASHTO 1993); (2) State of Colorado procedure (Sheehan et al. 2004, Tarr et al. 1998); (3) Portland Cement Association (PCA)/ American Concrete Pavement Association (ACPA) method (Wu et al. 1998); (4) State of New Jersey method (Nenad et al. 1998); (5) Modified ACPA approach (Riley et al. 2005); (6) State of Illinois procedure (Roesler et al. 2008); and (7) State of Texas method (Chul et al. 2008).

Among these procedures of design whitetopping only AASHTO, Colorado and Texas procedures offer guidelines for thin and conventional whitetopping, where as other procedures are for ultra-thin whitetopping. All these procedures deal with the slab thickness, support characteristics, pre-overlay preparation and slab dimensions. But, no procedure considers bonding condition between whitetopping and the existing AC layer, existing AC layer modulus and AC thicknesses. The objective of this study was to asses the behavior of 5-in, 6-in and 7.5-in thin whitetoppings on existing 5-in, 7-in and 9-in AC pavements for different bonding conditions with the AC layer and existing AC moduli. The whitetopping responses for different temperature differentials were also assessed. Based on the behavior of TWT, the service lives were calculated for different truck traffic. The analysis is based on the finite element method (FEM) using the SolidWorks (SW) software.

FINITE ELEMENT MODEL

Model Geometry

The built models were for:

(1) Whitetopping thickness: 5 in., 6 in. and 7.5 in.;
(2) Existing AC pavement thickness: 5 in., 7in. and 9in.;
(3) Interface condition: fully bonded and unbonbed; and
(4) Temperature differential: 1.5^{0}F/in and 3^{0}F/in.

Each pavement with whitetopping was modeled as a three-layer pavement system: TWT, existing AC layer and subgrade layer. A thin interlayer was used between the subgrade and the existing AC layer so that variable friction between these layers can be studied (Dumitru 2006). Only one half of the loaded area was modeled as the pavement geometry and loading are symmetric. Each pavement modeled was 12 ft long and 3 ft wide. The subgrade depth was 30 inches (to limit the size of the mesh) and 6-ft joint spacing was considered in the TWT layer.

Material Properties
All layer materials were considered as isotropic and linear elastic except the interlayer between the subgrade and the AC layer. That interlayer was considered as orthotropic but linear elastic. The properties of layer materials are:

(1) TWT:
- Modulus of Elasticity = 4,000,000 psi
- Poisson's Ratio = 0.15
- Coefficient of Thermal Expansion = 5.5×10^{-6} (/^{o}F)

(2) AC layer:
- Modulus of Elasticity = 250,000 and 350,000 psi
- Poisson's Ratio = 0.4
- Coefficient of Thermal Expansion = 13×10^{-6} (/^{o}F)

(3) Subgrade:
- Modulus of Elasticity = 20,000 psi
- Poisson's Ratio = 0.45
- Coefficient of Thermal Expansion = 2×10^{-6} (/^{o}F)

Model Meshing
Mesh size and mesh quality of the models affect the accuracy of the results. In general, finer mesh gives more accurate results. But finer mesh results in larger problem size that translates into higher computational effort and increased cost. To get better accuracy and to minimize the project expenses, the mesh size should be chosen in a way that reasonably accurate results can be obtained at optimized cost. For this reason, convergence was checked to find out the optimum mesh size (Figure 1) and TWT and AC layers were refined at their periphery (Figure 3).

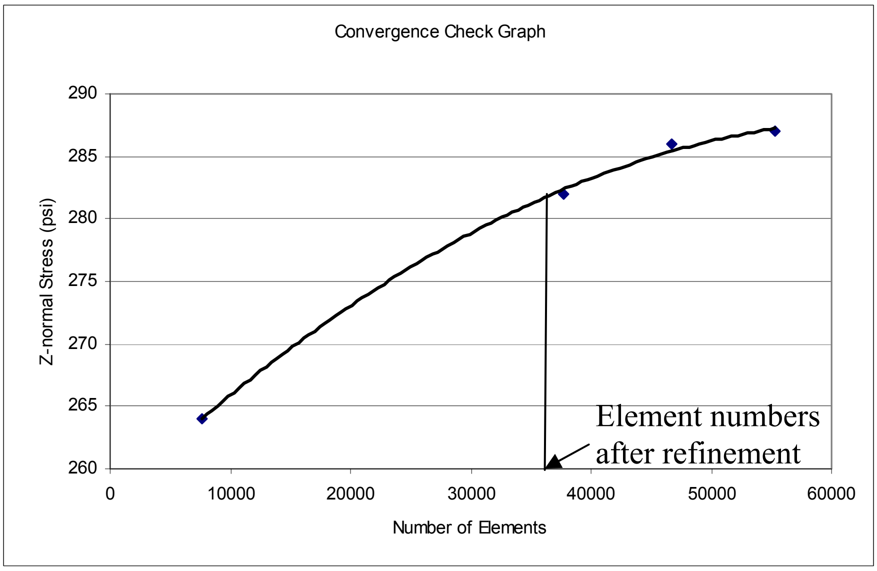


Figure 1 Convergence Check Using Z-Normal Stress as a Measure

In this analysis high quality mesh was used to get better results. There are two types of meshing available in SolidWorks (SolidWorks 2009): draft quality and high quality (Figure 2). Draft quality element has only four end nodes which provide linear (1st order) displacement field. Thus the strain field will be constant (0th order). As the stress is proportional to the strain, the stress field in a draft quality mesh is also constant (0th order). High quality element has 4 corner nodes and 6 mid-edge nodes which can model parabolic (2nd order) displacement field. Thus the stress and strain fields are linear (1st order).

Draft quality element High quality element

Figure 2 Draft Quality and High Quality Solid Element (after SolidWorks 2009)

Restraints

The symmetrical restraints were applied at all three directions of the model except on the left side (Figure 4). That side was restrained in the direction of pavement width. The bottom of the subgrade was fixed in all directions. All restraints of the model are shown in Figures 4.

Model Loading

The loaded area was rectangular, constant over the applied surface and equal to the tire inflation pressure as shown in Figure 5. The 20,000-lb load was applied on a single axle with dual tire (legal load in Kansas), as a pressure of equal to 100 psi on the element faces. Self-weight was considered for all materials**.** The length of the contact rectangle, L_x, was computed from the tire width and inflation pressure.

$$L_x = \frac{10{,}000}{2 \times 8 \times 100} = 6.25 in$$

The resulting SolidWorks model loading has been shown in Figure 6.

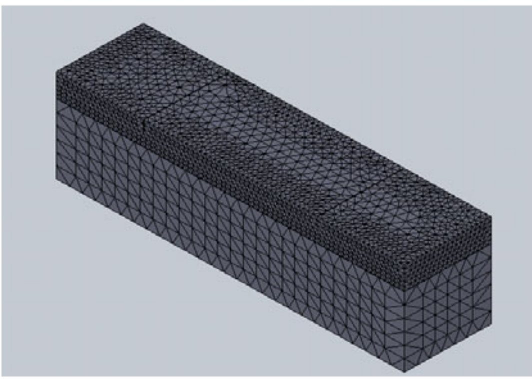


Figure 3 Meshed Model

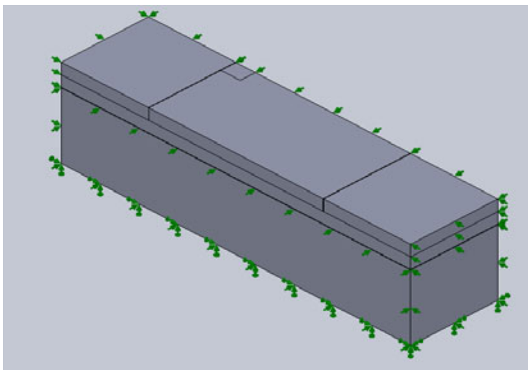


Figure 4 Restraints

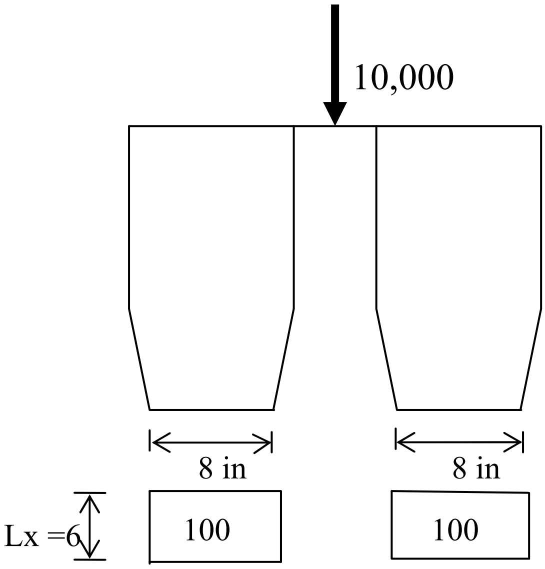


Figure 5 Load model (after Dumitru 2006)

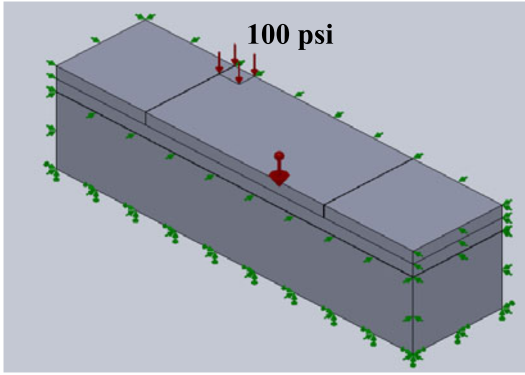
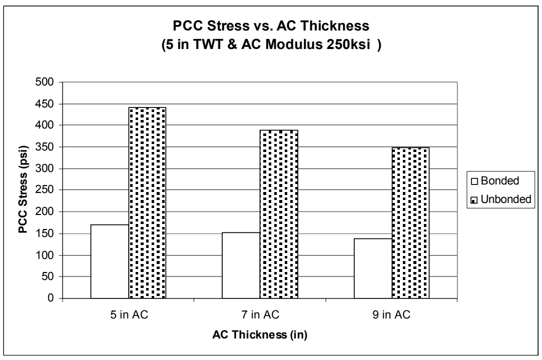


Figure 6 Model Loading

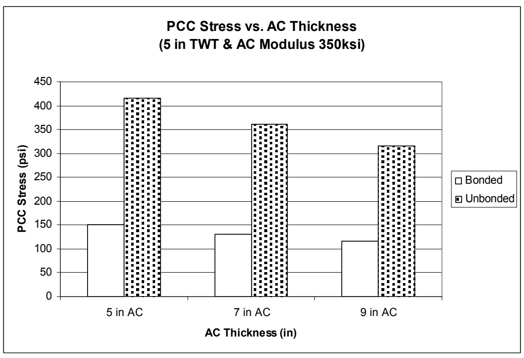
RESULTS

Load-Induced Stresses

The Portland Cement Concrete (PCC) slab tensile stress on TWT for various interface bonding condition (bonded or unbonded) have been shown in Figures 7, 8 and 9. The results show that bonding condition has a prominent effect on the PCC tensile stress. On bonded TWT, the load-induced stress is much less than that of unbonded TWT, as bonded TWT has the opportunity of transferring load to the existing AC layer. Figure 7 (a), Figure 8 (a), and Figure 9 (a) show the PCC stress vs. AC thickness graph for the AC modulus of 250 ksi while Figure 7 (b), Figure 8 (b), and Figure 9 (b) show that for AC modulus of 350 ksi. The results show that existing AC condition (modulus) does not affect TWT stress much but the existing AC thickness contributes toward lowering the tensile stress especially for unbonded condition.

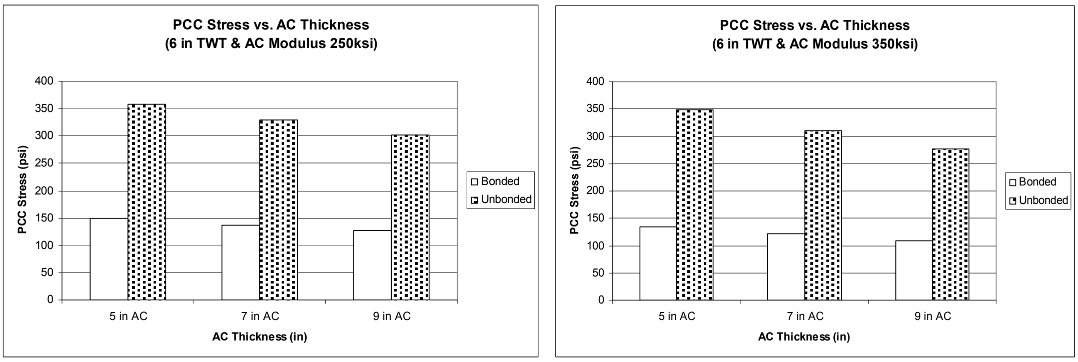


(a)



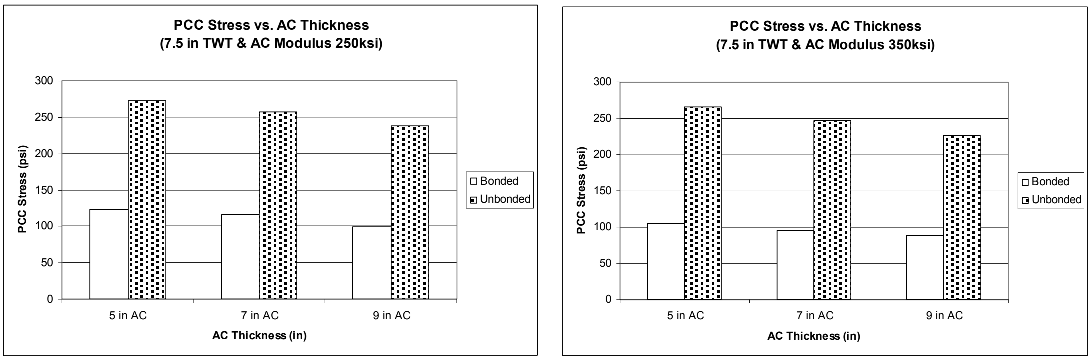
(b)

Figure 7 PCC Stress vs. AC thickness for 5 in TWT (a) AC Modulus 250 ksi and (b) AC Modulus 350 ksi



(a) (b)

Figure 8 PCC Stress vs. AC thickness for 6 in TWT (a) AC Modulus 250 ksi and (b) AC Modulus 350 ksi

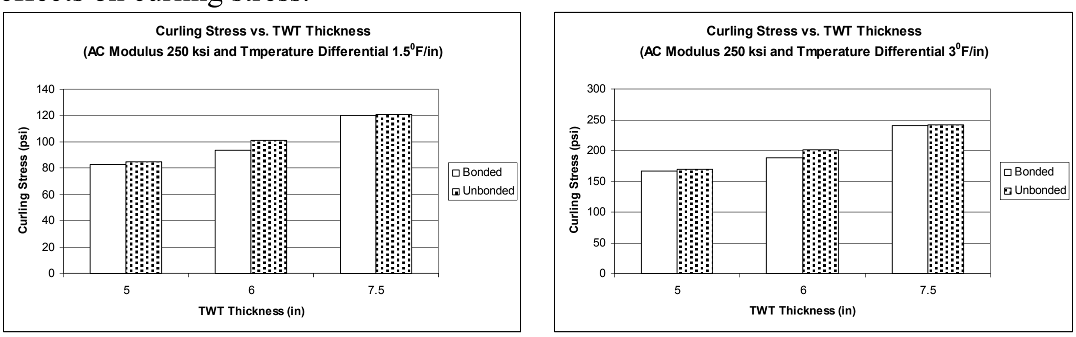


(a) (b)

Figure 9 PCC Stress vs. AC thickness for 7.5 in TWT (a) AC Modulus 250 ksi and (b) AC Modulus 350 ksi

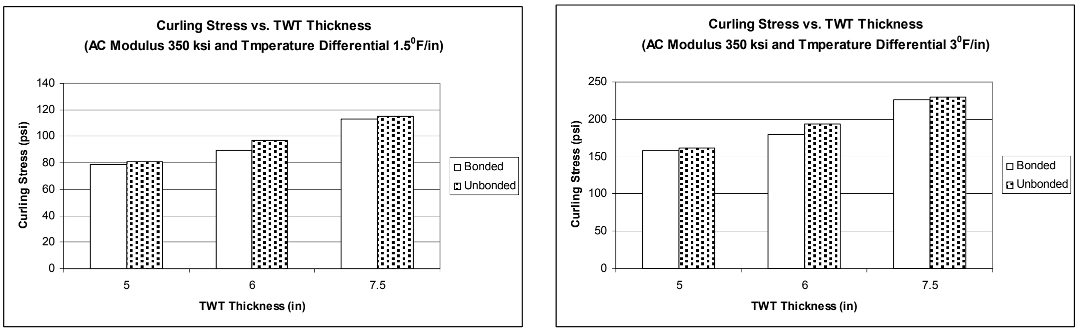
Curling Effect

The curling effect for temperature differential 1.5 ^{0}F/in and 3 ^{0}F/in on TWT were also examined. The curling stresses for different TWT thickness have been shown in Figures 10 and 11. The curling stresses did not change with the change in existing AC thicknesses. From the figures it can be seen that with the increase in TWT thickness, curling stress increases. However, the bonding condition and AC modulus have no effects on curling stress.



(a) (b)

Figure 10 PCC Stress vs. TWT thickness for AC Modulus 250 ksi (a) Temp. Diff. of 1.5 ^{0}F/in and (b) Temp. Diff. 3 ^{0}F/in



(a) **(b)**

Figure 11 PCC Stress vs. TWT thickness for AC Modulus 350 ksi (a) Temp. Diff. of 1.5 ^{0}F/in and (b) Temp. Diff. 3 ^{0}F/in

Service Lives

According to the PCA fatigue criterion (PCA 1984), the allowable load repetitions are calculated based on the stress ratio of the concrete. The stress ratio (SR) is the ratio of the concrete tensile stress to the concrete modulus of rupture. In this study, the concrete modulus of rupture was taken as 650 psi.

For SR > 0.55

$$\log_{10}(N) = \frac{0.97187 - SR}{0.0828};$$

For 0.45 ≤ SR ≤ 0.55

$$N = \left(\frac{4.2577}{SR - 0.43248}\right)^{3.268}$$

For SR < 0.45

N = Unlimited

Where, SR = flexural stress to strength (modulus of rapture of concrete) ratio, and

N = number of allowable load repetitions

From the allowable load repetitions, the design life can be estimated. The maximum service life of a whitetopping was taken as 10 years, considering durability. The estimated service lives for existing AC thickness 5 in, 7 in and 9 in have been shown in Tables 1, 2 and 3. The truck factor was assumed to be 1.5 and zero growth factor was considered. The results show that for fully bonded condition of all TWT and AC layer thickness, TWT is expected to last through 10 years assumed in design. But, unbonded TWT results in disastrous consequences when TWT and existing AC thickness are lower.

Table 1 Service Lives for 5-in. existing AC Thickness

AC Modulus (ksi)	TWT (in)	Bonded Condition	Stress (psi)	Stress Ratio (SR)	N	Service Life (yrs)			
						Daily Truck Traffic per Lane			
						≤200	300	400	500
250	5	Bonded	170	0.2615	Unlimited	10	10	10	10
	5	Unbonded	442	0.68	3350	0.06	0.04	0.03	0.02
	6	Bonded	149	0.2292	Unlimited	10	10	10	10
	6	Unbonded	359	0.5523	116,729	2.13	1.42	1.07	0.85
	7.5	Bonded	123	0.1892	Unlimited	10	10	10	10
	7.5	Unbonded	272	0.4185	Unlimited	10	10	10	10
350	5	Bonded	150	0.2308	Unlimited	10	10	10	10
	5	Unbonded	416	0.64	10,188	0.19	0.12	0.09	0.07
	6	Bonded	134	0.2062	Unlimited	10	10	10	10
	6	Unbonded	349	0.5369	182,998	3.34	2.23	1.67	1.34
	7.5	Bonded	105	0.1615	Unlimited	10	10	10	10
	7.5	Unbonded	266	0.4092	Unlimited	10	10	10	10

Table 2 Service Lives for 7-in. existing AC Thickness

AC Modulus (ksi)	TWT (in)	Bonded Condition	Stress (psi)	Stress Ratio (SR)	N	Service Life (yrs)			
						Daily Truck Traffic per Lane			
						≤200	300	400	500
250	5	Bonded	151	0.2323	Unlimited	10	10	10	10
	5	Unbonded	389	0.5985	32,342	0.6	0.4	0.3	0.2
	6	Bonded	127	0.2108	Unlimited	10	10	10	10
	6	Unbonded	329	0.5062	572,485	10	7	5.2	4.2
	7.5	Bonded	116	0.1785	Unlimited	10	10	10	10
	7.5	Unbonded	257	0.3954	Unlimited	10	10	10	10
350	5	Bonded	130	0.2308	Unlimited	10	10	10	10
	5	Unbonded	361	0.64	107,156	1.96	1.3	1	0.8
	6	Bonded	121	0.2062	Unlimited	10	10	10	10
	6	Unbonded	310	0.5369	2,986,209	10	10	10	10
	7.5	Bonded	95	0.1615	Unlimited	10	10	10	10
	7.5	Unbonded	246	0.4092	Unlimited	10	10	10	10

Table 3 Service Lives for 9-in. existing AC Thickness

AC Modulus (ksi)	TWT (in)	Bonded Condition	Stress (psi)	Stress Ratio (SR)	N	Service Life (yrs) Daily Truck Traffic per Lane			
						≤200	300	400	500
250	5	Bonded	138	0.2323	Unlimited	10	10	10	10
	5	Unbonded	348	0.5985	192,091	3.5	2.3	1.8	1.4
	6	Bonded	127	0.2108	Unlimited	10	10	10	10
	6	Unbonded	302	0.5062	8,616,324	10	10	10	10
	7.5	Bonded	99	0.1785	Unlimited	10	10	10	10
	7.5	Unbonded	238	0.3954	Unlimited	10	10	10	10
350	5	Bonded	117	0.2308	Unlimited	10	10	10	10
	5	Unbonded	316	0.64	1,611,683	10	10	10	10
	6	Bonded	109	0.2062	Unlimited	10	10	10	10
	6	Unbonded	277	0.5369	Unlimited	10	10	10	10
	7.5	Bonded	88	0.1615	Unlimited	10	10	10	10
	7.5	Unbonded	226	0.4092	Unlimited	10	10	10	10

HEAT ANALYSIS

The total heat absorbed by Whitetopping and AC pavement can be calculated from the albedo value. On a clear day earth, surface receives 1000 W/m^2 solar insolation (a measure of solar radiation energy received on a given surface area in a given time) (Sticklar, NASA). The comparison of absorbed energy between Whitetopping and AC is shown in Table 4. One mile segment of a 4-lane (12 ft wide) highway with center lane (11 ft wide) was considered to calculate absorbed energy.

Table 4 Energy Absorption

Alternative	Albedo value		Solar Insolation (W/m^2)	Area (m^2)	Energy Absorbed × 10^6 (W)	
	New	Old			New	Old
Whitetopping	0.4	0.3	1000	28,956	17.36	20.27
AC	0.1	0.15	1000	28,956	26.06	24.61

From Table 4 it is found that the amount of AC heat absorption is much higher than Whitetopping which results in higher potential for heat island from AC pavement.

COST ANALYSIS

The Life-Cycle Cost (LCC) analysis of TWT and AC overlays were conducted by Lowery (2005). The SH-4 project (Sheehan et al. 2004) in Colorado was considered for the analysis period of 40 years. From the analysis the initial cost of TWT (6-in. thick) and AC overlay (2-in. thick) were found as \$2,737,474 and \$922,136, respectively. Thus, considering only initial cost, TWT is three times more expensive than AC overlay. When maintenance and future rehabilitation costs are considered asphalt overlay cost (\$3,019,643 in 2005 value) was only one percent lower than TWT (\$3,061,266 in 2005 value). If the user cost is included in the LCC analysis, the

TWT was found to be 11 percent cheaper than the asphalt overlay. The present (2005) value with user cost of TWT and AC overlay were found as $3,589,625 and $4,022,295, respectively.

CONCLUSIONS

Based on the exhaustive literature review and this study, the following conclusions can be drawn:

1. Whitetopping (TWT) has higher albedo value than asphalt concrete (AC) that can turn TWT into a green rehabilitation strategy.
2. Thin Whitetopping (TWT) needs much less maintenance than conventional AC overlay and considering the user cost, TWT is a cost-effective rehabilitation strategy.
3. The curling stress increases with as increase in TWT thickness. Existing AC thickness, existing AC modulus and bonding condition do not influence curling stress.
4. The service life of thin whitetopping is mostly affected by the interface bonding condition between TWT and AC layer especially for smaller TWT thickness. Bonded TWT results in much higher service life than unbonded ones.
5. The thickness of existing AC pavement significantly affects TWT life whereas existing AC condition does not have much effect.
6. For unbonded condition, thicker TWT is recommended.

ACKNOWLEDGEMENTS

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STUDIES ON A CEMENT KILN DUST (CKD)-STABILIZED LOW-STRENGTH SOIL FOR ROAD PAVEMENT CONSTRUCTION IN EASTERN NIGERIA

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ABSTRACT
Soils in the eastern part of Nigeria are known for high erosivity and collapse, and as a result, roads and infrastructural developments of the area have been a difficult and expensive venture. The constructed road infrastructures are found not to be durable due to weakening effect of subgrade by erosion during rain. There have been serious investigations on ways of improving these soils to enhance their performance in pavement construction but a number of stabilizers used such as cement and lime have resulted in high cost of construction. This problem forms the basis of an extensive investigations currently being conducted on economic and sustainable methods of improving the engineering qualities of the soil and thus enhance their performance under pavement traffic load. This paper presents results of on-going laboratory studies on the effects of cement kiln dust, a waste product from cement manufacture, in stabilizing the problem soil of Amatutu/Agulu in Anambra State, Eastern Nigeria, and thus finds an economic use of the waste in civil engineering construction in Nigeria. The results of engineering properties of the soil tested i.e. Atterberg Limits, Dry-Density, California Bearing Ratio (CBR), and Unconfined Compression Strength (UCS), when CKD was added at varying percentages showed an improvement over the "as-is" soil engineering properties, thus giving hope of improved pavement performance in the area with CKD. Also, the result showed that CKD, a waste material from cement manufacture, can be profitably utilized in civil engineering construction and therefore contribute to environment sustainability and green development in Nigeria.

1.0 INTRODUCTION

The construction of road pavements in Nigeria, as well as in other countries, is an expensive venture and therefore demands that the pavement constructed should be able to withstand the intended traffic without undue stresses. This is more so, especially with the peculiar traffic loads to which Nigerian roads are subjected. There is no compliance to maximum axle loads on pavements in the country due to lack of, or dysfunctional weighbridges, across major roads in Nigeria.

This lack of load restrictions result in early pavement damages and its ultimate failure due to uncontrolled axle loads. This effect has led to several losses to government, who is the major investor on roads, as well as the road-users who have to suffer vehicular damages, higher operating costs, and sometimes accidents due to poor pavement conditions.

Aside from the uncontrolled axle loads, other factors that have been found to be affecting the performance of pavements are poor construction and use of poor quality soil materials for embankment and pavement construction. The construction of roads is usually a costly venture in most countries of the world particularly the developing countries and this gulp substantial portion of budget. And this therefore demands that the pavement constructed should be durable and to have little maintenance cost. However, in Nigeria this is not the case because the road pavements with design life of 20 years hardly survive one or two years after construction before distresses such as rutting, furrowing, cracking, undulations and other types of pavement deformations are noticed. This therefore demands extra maintenance budgets to put the roads back into good shape.

These problems as well as the need to improve the transportation infrastructures in the country form the basis of these research programs currently being conducted at the Materials Laboratory, Department of Civil & Environmental Engineering, University of Lagos, Nigeria. Also, the study is aimed at finding a way of using the cement kiln dust produced in the manufacture of cement in civil engineering construction to reduce their environmental hazard in many areas particularly the pollution of surface and groundwater. The studies are aimed at finding an economic and durable solutions to pavement problems affecting transportation infrastructures in Nigeria, particularly in the eastern Nigeria where soil materials in the area makes roads to be susceptible to early failure, and thus alleviate the suffering of the road-users.

This paper therefore presents the results of laboratory studies conducted on the application of CKD (a cement production waste) in stabilizing a marginal strength soil from Amatutu/Agulu, Anambra State, Nigeria where there have been previous occurrences of soil failures leading into disruption to road pavement infrastructures for an improved performance under heavy and low traffic loads, thereby, contribute to the current knowledge on effective soil stabilization in road and airfield pavement construction.

2.0 CEMENT KILN DUST IN PAVEMENT CONSTRUCTION: REVIEW OF PREVIOUS RESEARCHES

In the recent times, there have been tremendous investigations into the application of wastes in civil engineering construction in many parts of the world. Several wastes such as cement kiln dust, lime kiln dusts, waste tyres, foundry sand, sludge wastes, etc., have been studied experimentally as well as in field application in pavement construction (Button, 2003; Parsons and Kneebone, 2004; Miller and Azad, 2000; Miller *et al,* 1999). These wastes have constituted serious hazards to the environment, particularly surface and underground water sources thereby limiting their potential potable use in many parts of the world.

A detailed review of these research data is currently being conducted by the author and the results of this shall be published later. However, a brief review of researches on the application of CKD in stabilizing fine-grained soils from different parts of the world and of course, in stabilizing dune sands commonly found in the Middle East is presented.

2.1 CKD-STABILIZED SOFT CLAY SOILS

Baghdadi (1990) studied the effect of CKD in stabilizing kaolinite and bentonite clay soil materials for pavement construction and found that the use of CKD as stabilizing agent resulted in improved engineering properties of the soils. The unconfined compressive strength of the CKD stabilized clays showed a marked improvement over the unstabilized soil and that the plasticity indices of the soils reduced thus reducing the swelling and shrinkage character of the soils. Bhatty *et al* (1996) showed that CKD when used to stabilize clay soils gave satisfactory performances as the unconfined compressive strength of the soils increased. Miller and Azad (2000) have shown that the strength of CKD stabilized clay soil were inversely proportional to the plasticity index of the untreated clay soil especially when the plasticity index (PI) of the clay soil is high.

Cement kiln dust have been found to be useful in the stabilization of slopes and for erosion control in soils (Button, 2003).

Peethamparan and Olek (2008) reported results of studies conducted on the effectiveness of CKD in stabilizing Na-Montmorillonite clays. It was found that the PI of the Na-Montmorillonite clay reduced and that the pH of the CKD-soil mixtures were found to increase indicating that further chemical reaction leading to further pozzolanic reaction can be achieved, and thus lead to improved strength properties of the clay soil. The unconfined compressive strength and stiffness properties of the soil were also increased, and these increased properties were related to the chemical composition of the particular CKD especially its free-lime content.

However, the effectiveness of CKD in soil stabilization has been noted to be influenced by its physical and chemical compositions (Bhatty *et al,* 1996) because CKD is a waste product from cement production processes. Therefore its physical and chemical constituents are variable depending on factors such as the sources of raw materials fed into the kiln, the type of kiln operation used, the type of dust collection facility and fuel used (Button, 2003). Also, the mineralogical composition of the soil and of the CKD plays significant roles in the effectiveness of CKD as a stabilizing agent in soils (Oduola, 2009).

2.2 CKD-STABILIZED DUNE SANDS

The application of CKD to stabilize dune sands in parts of the Middle East has been studied by many researchers (Baghdadi and Rahman, 1990; Baghdadi et al, 1995). Dune sands are abundantly available in the Middle East countries (Baghdadi and Rahman, 1990) and this constitute threat to durable and economic pavement construction and the use of CKD as a sustainable method in producing pavement construction materials was conducted. The dune sand was classified as A-3 and SP according to AASHTO and USCS methods of soil classification respectively. The application of CKD showed that there was a remarkable improvement in the CBR of the dune sand and the CKD-stabilized dune sand when about 13% of CKD was added although better improvement were recorded with higher percentages of CKD.

The use of CKD in pavement construction in Nigeria is not yet known and this research is aimed at the sustainable use of the cement kiln waste products generated from several cement factories in the country, particularly with the current drive world-wide on environment sustainability and green development. The CKD generated from the Lafarge Cement plants is about 25% of the raw materials fed into the kiln and so substantial quantities of these materials are generated and quite sufficient for pavement engineering use (Oduola, 2009).

3.0 MATERIALS AND EXPERIMENTAL PROCEDURES

3. MATERIAL SAMPLING AND MATERIAL USED IN THE EXPERIMENT

The soil materials used in these investigations were obtained from Amatutu/Agulu area of Anambra State in the eastern part of Nigeria. The soil sample is reddish-brown in colour and fine in texture. This area has been found to be highly susceptible to erosion and development of gullies in the area has created serious environmental and ecological problems affecting the life of the people. The author has been involved in the design of drainage and erosion control facilities in the area as one of the intervention of government to save infrastructures such as roads and buildings in the Amatutu-Agulu area. Figure 1 shows the failed embankment and a retaining wall in the area.

Figure 1: Eroded Roadside Retaining Wall and Roadside Embankment at Amatutu, Anambra State

Disturbed samples of the soil were taken at two selected points, placed in polythene bags and transported to the Materials Laboratory of the Department of Civil Engineering, University of Lagos. Cement Kiln Dust (CKD) used for the stabilization of the soil samples was obtained from Lafarge/West African Portland Cement, Shagamu Plant, Ogun State, Nigeria.

4. EXPERIMENTAL PROCEDURES

The laboratory tests conducted on the samples of soils were the particle size sieve analysis, specific gravity, soil classification, Atterberg limits, compaction test, CBR and UCS. The experimental procedures adopted were as specified in BS 1377 (1990) and BS 1924 (1990). The chemical components of the CKD were analyzed using AARL 900 cement Analyzer shown in Figure 2 at the Quality Control Laboratory of the Lafarge/WAPCO Portland Cement Plant Shagamu, Ogun State.

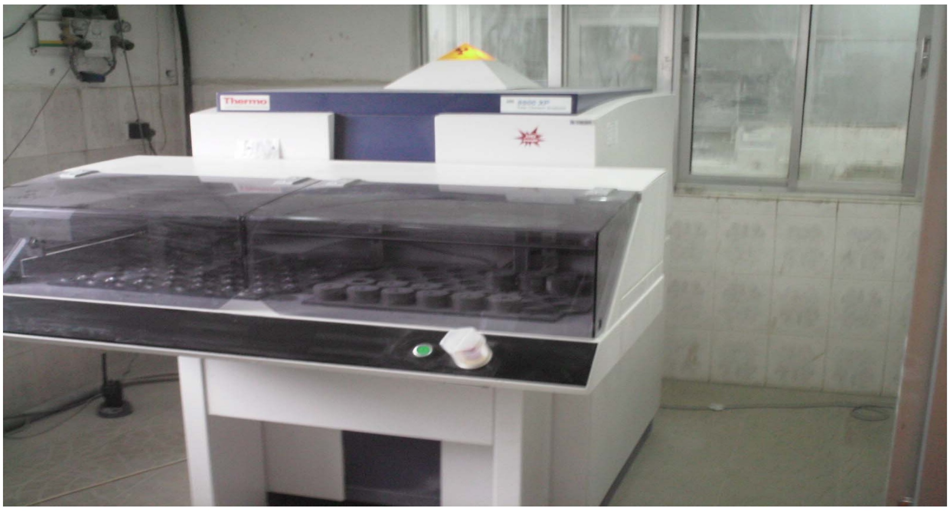

Figure 2: AARL 900 Cement Analyzer used for Chemical Analysis of Cement Kiln Dust Samples

5. RESULTS, ANALYSIS AND DISCUSSIONS

5.1 RESULTS OF TESTS CONDUCTED

Figure 3 shows the geological map of the study area which is located on Anambra basin indicated as No. 5 on the legend of the geological map. The results of the Grain size sieve analysis conducted using the procedure in BS 1377 (1990) is shown in Figure 4. Three grain size analyses were carried out and they are as shown.

The results of Atterberg Limits conducted on the ‘as-is’ soil sample and the addition of cement in the range of 0 to 10% shown in Table 1 and the variation of the PI index with percentage cement kiln dust added is shown in Figure 4. The results of the chemical analysis of the CKD used in the experiment conducted using the AARL 900 Cement Analyzer is shown in Table 1.

Similarly, the results of maximum dry densities obtained with percent addition of cement are shown in Figure 5. The CBR and UCS results are shown in Figure 7, 8 and 9 respectively. All the results shown are the mean of three test results obtained for each

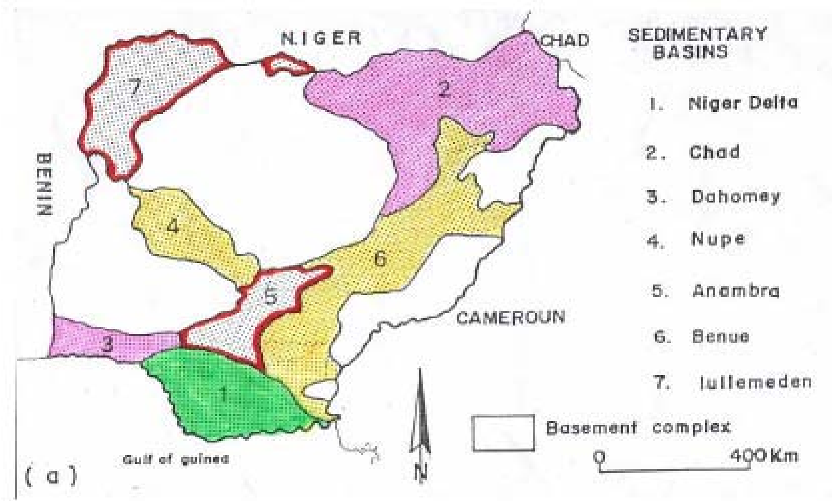

Figure 3: Geological Map of the Study Area (Federal Surveys, 1969)

investigation conducted on samples prepared according to the standard test procedures in BS 1377 (1990) for the 'as-is' soil engineering properties and according to BS 1924 (1990) for the cement-soil mixtures.

TABLE 1: RESULTS OF CHEMICAL ANALYSIS OF 5 SAMPLES OF CEMENT KILN DUST

Parameters Tested							
SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	F/CaO
16.150	4.720	2.840	57.470	1.640	1.260	1.010	6.330
15.760	4.800	2.830	58.250	1.620	1.440	0.970	5.150
15.840	4.760	2.860	58.170	1.600	1.370	1.000	5.900
16.250	4.570	2.900	57.530	1.600	1.240	1.030	6.400
16.490	4.640	2.900	56.830	1.600	1.210	1.020	5.900

5.2 DISCUSSION OF RESULTS

The specific gravity of the soil sample was found to be 2.65 while the Atterberg limits of the soil conducted according to BS 1377 (1990) was conducted from which the variations of the plasticity index and percent increase of CKD with the two samples of soil A and B are shown in Figure 5. The liquid limit of the soil was found to decrease and the plasticity limit was found to increase as the percentage content of the cement additive increased leading to reduced plasticity index of the soil.

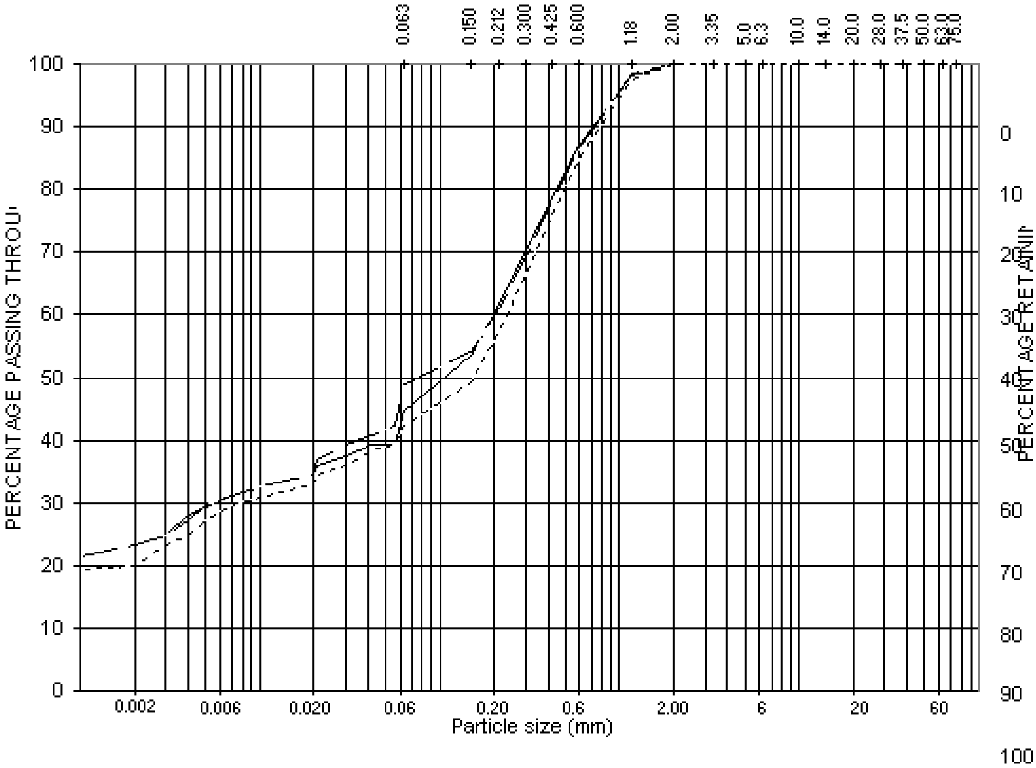

Figure 4: Grain Size Curve for the Soil Sample

The results of chemical analysis of 5 samples of CKD taken over a period of 24 hours showed that lime (CaO) is the predominating chemical component of CKD with a value of about 57%. The presence of this free-lime in CKD accounts for its pozzolanic reaction with the soil material tested, particularly on the plasticity index (PI).

As noted in Peethamparan and Olek (2008), the presence of free-lime (CaO) indicate that the pH of the CKD-soil mixtures is increased as the percentage of addition of CKD in the soil samples is increased. This means that the propensity of the reactions in the soil will result in increased engineering properties of the stabilized mixture. The maximum dry density of the samples decreased while the optimum moisture content increased as the percentage of CKD increased from 0 to 10% by weight in both samples A and B as shown in Figures 7.

The soaked California Bearing Ratio (CBR) of the CKD-stabilized soil sample A increased at 2% addition of CKD and later decreased while the unsoaked CBR of the CKD-stabilized sample A showed a gradual decrease as the percentage addition of CKD increased from 0 to 10% as shown in Figures 8 and 9. This behaviour is being further investigated to confirm this behaviour and the factors responsible.

However, there was a gradual increase in the unconfined compressive strength (UCS) as the percentage of CKD decreased from 0 to 10% as shown in Figure 10. Also, there was a reduced strength of sample B as the percentage addition of CKD increased as shown in Figures 10.

This reduced strength as shown by the soaked CBR, and the UCS may be attributed to the reactions of the lime (CaO) with some constituents of the soil, and of course, due to experimental errors. However, investigations are still on-going to unraffle this trend in the results.

CONCLUSIONS

The results of the on-going investigations on the effect of CKD in stabilizing a low-strength soil in Amatutu/Agulu area of Anambra State, Nigeria for pavement construction are presented and discussed above. The followings are the specific conclusions made therefrom.

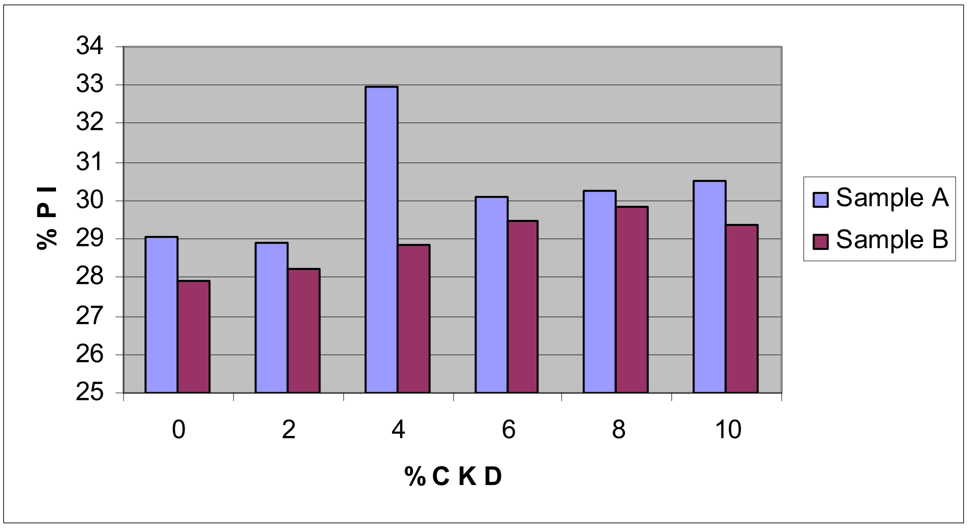

Figure 5: Plasticity Index vs. Percent CKD for Samples A and B

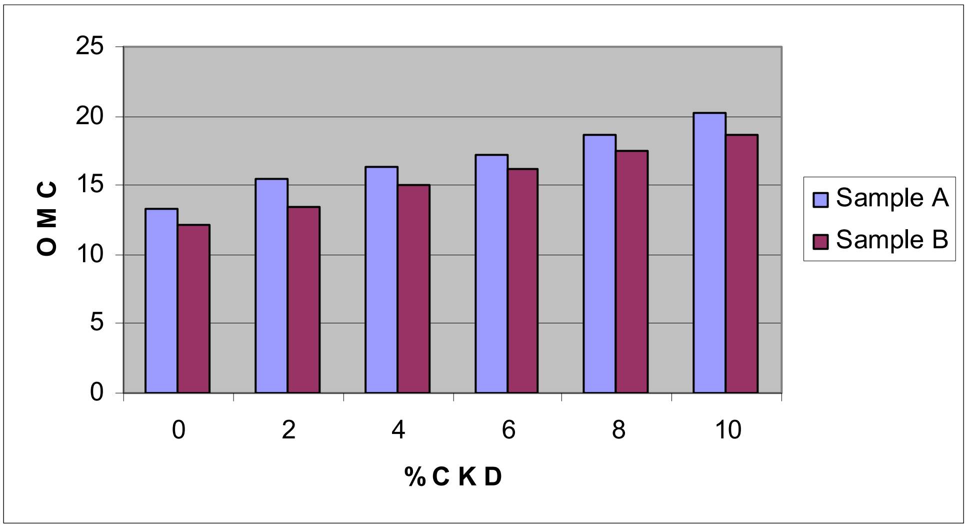

Figure 6: Optimum Moisture Content vs. Percent CKD of Sample A and B

1. The addition of cement kiln dust decreased the LL and PI of the soil material as the percentage additions increased from 0% to 10% and showed an improvement in the engineering properties of the soil.
2. Large increases in compressive strength of soil sample A were observed while the density were observed to reduce as the percentage of CKD increased for the cement kiln dust-stabilized soil sample A, which means that the engineering properties of the soil improved.

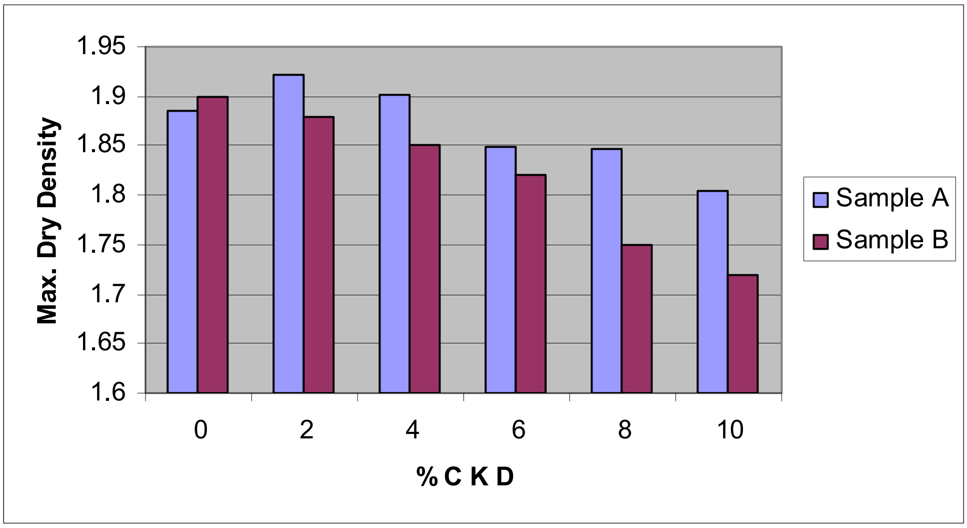

Figure 7: Maximum Dry Density vs. Percent CKD of Sample A and B

3. The results of this study confirm the effectiveness of cement kiln dust as a potential stabilizer in improving the engineering qualities of marginal soils in pavement construction, and the results reported therefore show that there is hope for the use of this soil in road pavement construction and of course in the road network development in Amatutu/Agulu area and its environs.

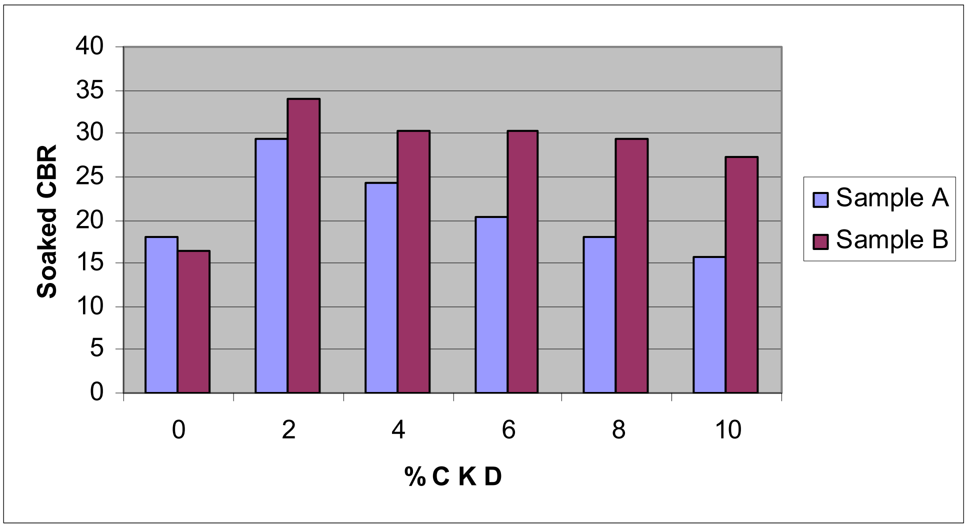

Figure 8: Soaked CBR vs. Percent CKD of Sample A

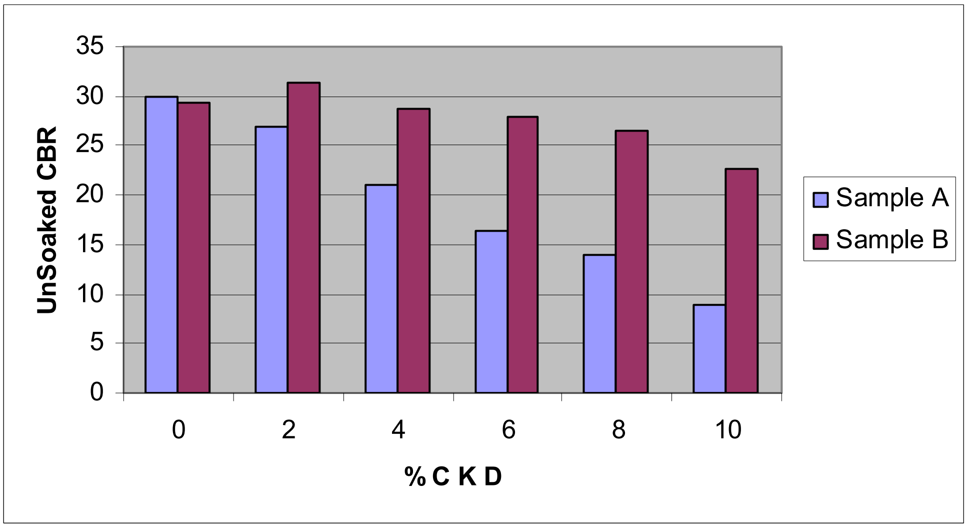

Figure 9: Unsoaked CBR vs. Percent CKD of Samples A and B

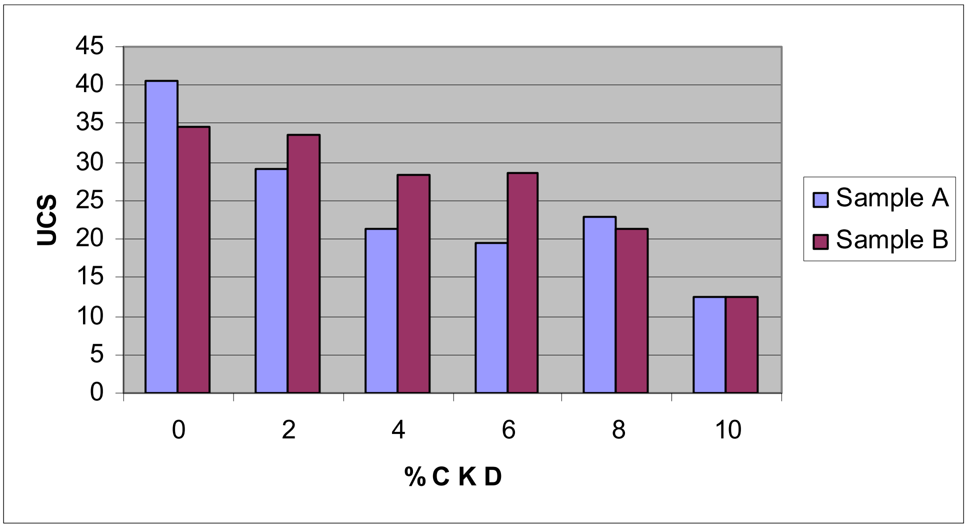

Figure 10: Unconfined Compressive Strength vs. Percent CKD of Samples A and B

4. The results further show that CKD, a waste material from cement manufacture, is cost-effective especially when compared to other stabilizers, is environmentally sustainable, and can be gainfully used in pavement engineering construction. Therefore reduce its environmental impact and damage to the environment if employed as part of green growth development strategy in achieving economic growth and industrialization.
5. Further investigations are currently being conducted on the effect of the chemical reactions and mineralogical contents of the CKD on the engineering behaviour of the soil-CKD mixtures.

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Moving Towards Sustainability:
New York State Department of Transportation's GreenLITES Story

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ABSTRACT
Transportation is an essential component of a sustainable society, and its benefits and costs are well studied at the project level (FHWA 2001; Green Highways Partnership[1] 2010). However, while methodologies for assessing environmental impacts are well developed, commensurate tools for assessing how transportation investments contribute to a sustainable society and what the mechanisms are for adjusting transportation programs to support a sustainable society are lacking. Under the current construct, transportation agencies avoid impacts but find it difficult to quantify benefits and align transportation programs with the greater needs of a sustainable society.

The New York State Department of Transportation's (NYSDOT's) GreenLITES (Green Leadership In Transportation and Environmental Sustainability) program is a tool to advance the Department's efforts to better align sustainability efforts in planning, design, construction, and maintenance operations with long term needs. Though the Department has been incorporating sustainable elements into its transportation projects for years, GreenLITES promotes increased awareness and best practices across program areas to enhance sustainability. GreenLITES also gives the Department a way to measure our performance, recognize best practices, and identify needed partnerships.

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[1] www.greenhighwayspartnership.org

GreenLITES was initially designed to assess capital project environmental sustainability elements. However, as GreenLITES was put into use, its potential to address transportation investments across a range of program areas became apparent, and a more holistic approach to the "triple bottom line" of economy, society, and environment has been adopted. As a result, the GreenLITES program expanded to include a growing collection of tools (rating systems, spreadsheets, and other metrics) to assess projects, plans, operations and maintenance programs, and regional programs.

This paper describes NYSDOT's GreenLITES program evolution from its environmentally based beginnings to a more comprehensive approach in support of a more sustainable society. The paper covers program vision, goals, benefits, management, and evolving next steps.

THE EVOLUTION OF THE PRINCIPLES OF SUSTAINABILITY

Sustainability is not a new concept. The Ancient Greeks recognized that "a society grows great when old men plant trees in whose shade they know they shall not sit." Similarly, the Native Americans noted that "we do not inherit the earth from our ancestors; we borrow it from our children." The Great Law of the Iroquois states "in every deliberation, we must consider the impact on the seventh generation..." This recognition to ensure that decision-making is guided by consideration of the welfare and well-being of the future generations provides strong guiding principles.

The principles of sustainability are rooted in the National Environmental Policy Act (NEPA), passed in 1969, in which Congress declared a national environmental policy: "*The Congress, recognizing the profound impact of man's activity on the interrelations of all components of the natural environment, particularly the profound influences of population growth, high-density urbanization, industrial expansion, resource exploitation, and new and expanding technological advances and recognizing further the critical importance of restoring and maintaining environmental quality to the overall welfare and development of man, declares that it is the continuing policy of the Federal Government, in cooperation with State and local governments, and other concerned public and private organizations, to use all practicable means and measures, including financial and technical assistance, in a manner calculated to foster and promote the general welfare, to create and maintain conditions under which man and nature can exist in productive harmony, and fulfill the social, economic, and other requirements of present and future generations of Americans*." (NEPA, Section 101 [42 USC § 4331] 1969)

In 1987, the United Nations' Brundtland Commission Report identified sustainability as: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." As stated in various United Nation documents, sustainable development, at its simplest, is development based on patterns of production and consumption that can be pursued into the distant future without degrading the human or natural environment. It requires, within each nation's technological and social capabilities, the prudent management of resources and the equitable sharing of the economic benefits (World Commission on Environment and Development 1987).

TRANSPORTATION AND SUSTAINABILITY

The concept of sustainability is a foundation for a good society and is easy to embrace in principle. However, it is difficult to exercise in practice, and even more difficult to measure. Also, the role of transportation and sustainability is widely debated, whether it is about sustainable transportation, transportation sustainability, or transportation in support of a sustainable society.

In 1999, FHWA sponsored an international scanning review to examine how other developed countries are addressing sustainable transportation issues. The team visited Sweden, Germany, the Netherlands, and the United Kingdom as these countries had been actively addressing sustainable transportation issues for several years. Findings from that scan indicated that sustainable development is viewed as "development that improves service quality, the standard of living, and quality of life, while at the same time protecting and enhancing the natural environment and honoring local culture and history." (FHWA 2001)

Each host country recognized that transportation is an important tool to help meet overall sustainability objectives. Attributes of sustainable transportation follow from the expanded definition of sustainable development: "Sustainable transportation is safe, high quality, and accessible to all; ecologically sound; economical; and a positive contributor to regional development." Specific goals for sustainable transportation include improved service quality and quality of access to goods and services, safety, improved air quality, noise reduction, improved water quality, protection of habitat and open space, historic preservation, reduced carbon emissions, increased social equity, economic development, and a satisfying quality of life, plus local goals consistent with the overall objective (FHWA 2001).

The topic of addressing sustainability in transportation systems is explored in Jeon and Amekudzi (2005). They found that there is no standard way in which sustainable transportation is considered. However, the three-dimensional framework of economic development, environmental preservation, and social development is the substance of several definitions of sustainable transportation and other infrastructure systems (Jeon and Amekudzi 2005). Deakin's (2001) working paper on sustainable development and sustainable transportation notes that, increasingly, the idea of sustainability has come to be understood as a collective process for considered decision-making and action, and not simply a particular end-state or outcome (Deakin 2001).

NYSDOT SUSTAINABILITY POLICY

NYSDOT recognizes it has a role in supporting a sustainable society. Consistent with the Brundtland Commission definition, NYSDOT understands that a sustainable society manages resources in a way that fulfills the community/social, economic, and environmental needs of the present without compromising future generations' needs and opportunities. Accordingly, a transportation system that supports a sustainable society is one that:

- Allows individual and societal transportation needs to be met in a manner consistent with human and ecosystem health with equity within and between generations.
- Is safe, affordable, accessible, operates efficiently, offers choice of transport mode, and supports a vibrant economy.
- Protects and preserves the environment by limiting transportation emissions and wastes, minimizes the consumption of resources, and enhances the existing environment as practicable.

Considering these concepts and applying them to NYSDOT's mission, the Department can advance sustainability by:

- Advocating and promoting the above vision to appropriate stakeholders and communities in the transportation decision making process.
- Incorporating sustainability concepts into the Department's procedures, investments, policies, manuals, specifications, programs, projects, and best practices.
- Evaluating the costs and benefits (societal, environmental, and economic) of transportation investments over life-cycles as well as fiscal cycles.
- Recognizing the transportation system's significant contribution as an integral part of a sustainable society.

Practically, this means, as NYSDOT improves safety and mobility in New York State, the Department's decisions and actions will strive to:

- Protect and enhance the environment.
- Conserve energy and natural resources.
- Preserve or enhance the historic, scenic, and aesthetic project setting characteristics.
- Encourage public involvement in the transportation planning process.
- Integrate Smart Growth and other sound land-use practices.
- Encourage new and innovative approaches to sustainable design, and how we operate and maintain our facilities.

NYSDOT'S PATH TO SUSTAINABILITY

Even back in 1949, the New York Department of Transportation's predecessor, the Department of Public Works, recognized the importance of sustainable transportation and the need to plan for tomorrow. In the Highway Needs Study, "A Look at the New York State Highway System," compiled by the New York State Department of Public Works (NYS DPW 1949), it is noted "This generation has seen many so-called roads of tomorrow reduced to ineffectual bottlenecks. It is therefore incumbent upon us to give full consideration of tomorrow's needs as we plan and build for today."

In 1949, it appears that the primary factors were economics and the need to meet the demands of safety, condition, and service. Societal influences included support for agriculture, industry, commerce, and recreation. The environmental influence was not yet as evident but would become instrumental nearly half a century later.

NYSDOT's environmental ethic evolved over the last decade (McVoy, et al. 2000; Nelson, et al. 2002). NYSDOT has received recognition for its proactive environmental stewardship efforts, including multiple American Association of State Highway and Transportation Officials (AASHTO) and Federal Highway Administration (FHWA) national awards, thus gaining endorsement for delivery of environmentally sound transportation services.

Moving from stewardship to sustainability is a logical progression. Considering that there are approximately 113,000 centerline miles of state and local highways in New York State, there is a tremendous opportunity for ensuring that transportation planning and spending is done in a manner that supports a sustainable society in New York State.

In March 2008 the Department submitted to the New York State Legislature the *NYSDOT Multimodal Transportation Program Submission: 2009-2014*. This capital program plan/report acknowledged that NYSDOT needs to support the State's priorities of economic development, energy efficiency, and promoting a sustainable society. To achieve this, NYSDOT set these goals:

- Promote economic development, supported by cost-effective investments in existing and new transportation infrastructure.
- Promote energy efficiency in support of lower costs, and reductions in energy usage and greenhouse gas emissions.
- Encourage smart growth statewide through State support for improved land use planning. (NYSDOT 2008a)

Consistent with these goals and to develop a more holistic approach to sustainability, NYSDOT developed GreenLITES, a transportation sustainability rating program and the more comprehensive sustainability policy summarized in the above **NYSDOT SUSTAINABILITY POLICY** section.

The GreenLITES sustainability rating program builds on NYSDOT's past successes in several established programs and initiatives that are consistent with and incorporate the principles of sustainability, including the Environmental Initiative, Context Sensitive Solutions (CSS), Green and Blue Highways, Environmental Research, Integrating Land Use and Transportation Planning, and the Climate Change/Energy Efficiency Team.

Environmental Initiative

In 1998, the NYSDOT Environmental Initiative was launched. In its Environmental Initiative Statement, NYSDOT outlined its purpose and goals to advance state environmental policies and objectives; promote an environmental ethic throughout the Department; and strengthen relationships with environmental agencies and groups. As a public works agency, NYSDOT recognized that it "can most effectively attain these goals by doing dedicated environmental work in support of its corporate environmental ethic. This, in turn, will advance a shift in attitudes. This will provide real environmental protection, assure staff that the agency has a strong environmental ethic and provide opportunities to engage the environmental community in positive joint undertakings that will demonstrate the Department's commitment." (NYSDOT 1999) Since that time, NYSDOT has undertaken deliberate actions and adopted a proactive approach to addressing environmental matters.

In 1999, NYSDOT received AASHTO's Best Practices in Environmental Stewardship for its Environmental Initiative.

Context Sensitive Solutions/Public Involvement
Context Sensitive Solutions was adopted as NYSDOT policy in 1999 to ensure that safe and efficient transportation projects are designed and developed in harmony with New York's communities. Through CSS, NYSDOT staff work together with members of the public, elected officials, other state agencies and interest groups to design projects that balance mobility and safety needs with community preservation and quality of life interests.

CSS strives to balance environmental, scenic, aesthetic, cultural, natural resources, community, and transportation service needs (NYSDOT 2001). Project designs that are advanced under this philosophy recognize community goals and are designed, built, and maintained to be safe and sustainable while minimizing disruption to the community and the environment. CSS incorporates flexible, innovative solutions that result in the appropriate application of design details and criteria for the site.

In 2005, AASHTO awarded NYSDOT with its Best Practices in Context Sensitive Solutions Award for the Best Institutionalization of CSS program.

Green and Blue Highways
The Green and Blue Highways Program was launched in 2005 as a way to encourage implementation of various low or no-cost maintenance and operation activities across the State that protect and enhance the environment. Utilizing best practices and suggestions from highway maintenance staff, program initiatives have included using over-the-rail mowers to improve vegetation management, using evergreen trees as living snow-fences at drift-prone locations, upgrading parking areas and improving drainage on State routes to reduce sedimentation of wetlands (NYSDOT 2008b; NCHRP 2005).

In 2007, NYSDOT's Green and Blue Highways Program was recognized by FHWA through its Exemplary Ecosystem program.

Environmental and Transportation Research
NYSDOT develops and funds many research projects that explore the complex interaction between the built, natural, and human environments. Environmentally-motivated research assists NYSDOT in defining and attending to environmental challenges and integrating environmental decisions into all our activities using the best information available. Environmental research allows for many non-traditional aspects of NYSDOT's mission to be investigated with the objective of maximizing the effectiveness of our programs, designs, and operations.

Through existing and new research projects[2], NYSDOT's research program is helping the Department with environmental stewardship, to protect and enhance communities and natural ecosystems, and to reach for the vision of sustainable transportation and transportation that supports a sustainable society.

Integrating Land Use and Transportation Planning
NYSDOT is taking a more active role in land use and transportation planning. The expected results could significantly enrich the State's communities by making more effective transportation investments, enhancing sustainable economic development, and improving the quality of life in its communities.

The Department has developed a smart planning[3] web site that provides direct links to NYSDOT activities and programs relating to transportation and land use in our communities; to planning tools and information provided by the Department and other organizations; and to potential sources of funding.

Climate Change/Energy Efficiency Team
The related issues of climate change and energy efficiency are expected to have profound effects on all sectors of the economy, including the transportation sector. To help New York's transportation sector understand and address these issues and to provide leadership for other transportation agencies in the State, the Department has formed a Climate Change/Energy Efficiency[4] Team in 2008. The team is addressing both greenhouse gas emission reduction and adaptation to effects of climate change.

GREENLITES – A TRANSPORTATION AND ENVIRONMENTAL SUSTAINABILITY RATING PROGRAM
NYSDOT is committed to improving the quality of our transportation infrastructure in ways that minimize impacts to the environment, including the depletion of irreplaceable resources. To this end, NYSDOT developed the GreenLITES certification program to help integrate sustainability principles into transportation. The program is used on a continuous basis and formally ranks capital projects,

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[2] https://www.nysdot.gov/divisions/engineering/environmental-analysis/research-and-training/environmental-research
[3] www.nysdot.gov/smartplanning
[4] https://www.nysdot.gov/programs/climate-change

operations/maintenance work on a sub-regional basis, and all region-wide investments made (and not made) on an annual cycle for internal review and comparison.

GreenLITES[5] is modeled after the building industry's Leadership in Energy and Environmental Design (LEED[6]) certification program for green building practices as well as University of Washington's Greenroads[7] program. GreenLITES applies a similar approach to recognize and encourage environmentally sustainable practices in transportation (BNA 2009).

GreenLITES is a transparent, metrics based, self-assessment program to institutionalize triple bottom-line thinking by evaluating performance on the basis of social, economic, and environmental impacts; to continuously measure performance; and to foster best practices throughout NYSDOT. It also provides an impetus for partnering with others and helps relate transportation investments to jobs, quality of life, and environmental stewardship.

The program is a continuing work in progress and has been implemented in stages. GreenLITES started in September 2008 with the GreenLITES Project Design Program, which uses the scorecard rating system. This was followed by the April 2009 GreenLITES Maintenance/Operations Plan Spreadsheet, the ongoing March 2010 Regional Pilot Sustainability Assessment Program, and, most recently, GreenLITES Planning, drafted in April 2010, which uses the Project Solicitation Tool.

All programs provide a baseline list of practices for which GreenLITES credits may be obtained. In addition, they allow extra credits to be assigned for additional sustainability innovations or actions, subject to approval by a review committee. As the program advances, additional practices that were once innovations are added to the baseline list, creating ever-expanding opportunities to reach sustainability.

GreenLITES Project Design

GreenLITES Project Design is a self-certification program that distinguishes transportation projects based on the extent to which they incorporate sustainable choices. This is primarily an internal management tool for NYSDOT to measure our performance, recognize good practices, and identify where we need to improve. It also provides the Department a way to demonstrate to the public and elected officials how we are advancing sustainable practices. Program development started in February 2008. NYSDOT began to use the program to evaluate projects in June 2008, and the Department's Commissioner publicly announced the program in September 2008. The GreenLITES Project Design certification program distinguishes itself in that it is a mandatory rather than voluntary program.

5 https://www.nysdot.gov/programs/greenlites
6 http://www.usgbc.org/DisplayPage.aspx?CMSPageID=222
7 http://www.greenroads.us/

GreenLITES Design identifies more than 175 sustainable items in five categories (Sustainable Sites, Water Quality, Materials & Resources, Energy & Atmosphere, and Innovation/Unlisted) and lists these in a GreenLITES scorecard (Figure 1). The complete GreenLITES scorecard is located on NYSDOT's GreenLITES project design web page[8].

GreenLITES Project Environmental Sustainability Rating System Scorecard v 2.0.1

Please fill in all *yellow highlighted cells* *and follow all instructions in* *red text.*

Project: *PIN:* *Type:* *Contact Name:* *Ph #:* *Element Specific?*

	CATEGORY	ID	DESCRIPTION	POINTS Available	POINTS Scored	INSTRUCTIONS	EXPLANATION OR COMMENTS *(optional)*
Sustainable Sites (S)	S-1 *Alignment Selection*	S-1a	Avoidance of previously undeveloped lands (open spaces or "greenfields").	2		<= Please enter 0 or 2	
		S-1b	Selecting an alignment that establishes a minimum 100-foot buffer zone between the edge of pavement and a natural watercourse or significantly sized natural wetland to serve the purpose of stormwater filtration.	2		<= Please enter 0 or 2	
		S-1c	Alignments which minimize overall construction "footprint." Examples: use of retaining walls, selecting design option with minimal footprint.	2		<= Please enter 0 or 2	
		S-1d	Design vertical alignments which minimize total earthwork.	1		<= Please enter 0 or 1	
		S-1e	Adjust alignment to avoid or minimize impacts to social/environmental resources (avoidance of parklands, wetlands, historic sites, farmlands, residential and commercial buildings, etc.).	1		<= Please enter 0 or 1	
		S-1f	Alignments that optimize benefits among competing constraints (the goal is not always the minimum-length alignment, but the one with the best benefit overall).	1		<= Please enter 0 or 1	
		S-1g	Micro-adjustments that do not compromise safety or operation but that might make the difference in providing sufficient clear area for tree planting.	1		<= Please enter 0 or 1	
		S-1h	Clear zones seeded with seed mixtures that help to reduce maintenance needs and increase carbon sequestration.	1		<= Please enter 0 or 1	
		S-1i	Provide a depressed roadway alignment.	1		<= Please enter 0 or 1	
		S-1j	Use of launched soil nails as a more cost effective option to stabilize a slope rather than, for example, closing a road to construct a retaining wall which may negatively affect traffic flow and neighboring properties.	1		<= Please enter 0 or 1	
	S-2 *Context Sensitive Solutions*	S-2a	Adjust or incorporate highway features to respond to the unique character or sense of place (both natural and built) of the area ("Unique character" means whatever identifiable elements make a place distinctive, memorable, important to the community, etc. - landmarks, views, historic bridges & buildings, parkways, characteristic use of materials, a notable stand of trees, etc.).	2		<= Please enter 0 or 2	
		S-2b	Incorporate local or natural materials for substantial visual elements (e.g., bridge fascia, retaining walls).	2		<= Please enter 0 or 2	
		S-2c	Visual enhancements (screening objectionable views, strategic placement of vegetation, enhancing scenic views, burying utilities, etc.).	2		<= Please enter 0 or 2	
		S-2d	Period street furniture/lighting/appurtenances.	1		<= Please enter 0 or 1	
		S-2e	Inclusion of visually-contrasting (colored and/or textured) pedestrian crosswalk treatments.	1		<= Please enter 0 or 1	
		S-2g	Follows the NYS Bridge Manual, Section 23 - Aesthetics.	1		<= Please enter 0 or 1	
		S-2h	Site materials selection & detailing to reduce overall urban "heat island" effect.	1		<= Please enter 0 or 1	
		S-2i	Permanently protect viewsheds via environmental or conservation easements.	1		<= Please enter 0 or 1	

Figure 1: GreenLITES Project Design Scorecard

Early in the project's development, the Project Design Team, appropriate local community groups, and various government stakeholders review the GreenLITES scorecard for sustainable items and practices to incorporate into the project. Throughout the project's development, the design team continues to work with these groups to develop a design that meets the project's transportation goals and objectives while achieving desired sustainable outcomes. When Plans, Specifications & Estimates (PS&E) are complete, the project may receive one of four GreenLITES certification levels: Certified, Silver, Gold, or Evergreen. Annually, special awards are given to the projects that attain the highest levels of sustainability - Gold and Evergreen (Figure 2).

[8] https://www.nysdot.gov/programs/greenlites/project-design-cert

Level:	Certified	Silver	Gold	Evergreen
Symbol:				
Points:	15-29	30-44	45-59	60 & up

Figure 2: GreenLITES Project Design Points Chart

A common criticism is that sometimes a sustainable approach costs more money. NYSDOT understands that sustainability is about balancing what is beneficial to people, while considering what is economically feasible and environmentally compatible. This may or may not necessarily increase project costs, but where project costs are increased, they may be warranted, especially when all external and life cycle costs are considered. Generally this extra cost is offset by longer infrastructure durability and difficult-to-quantify social benefits.

GreenLITES Operations

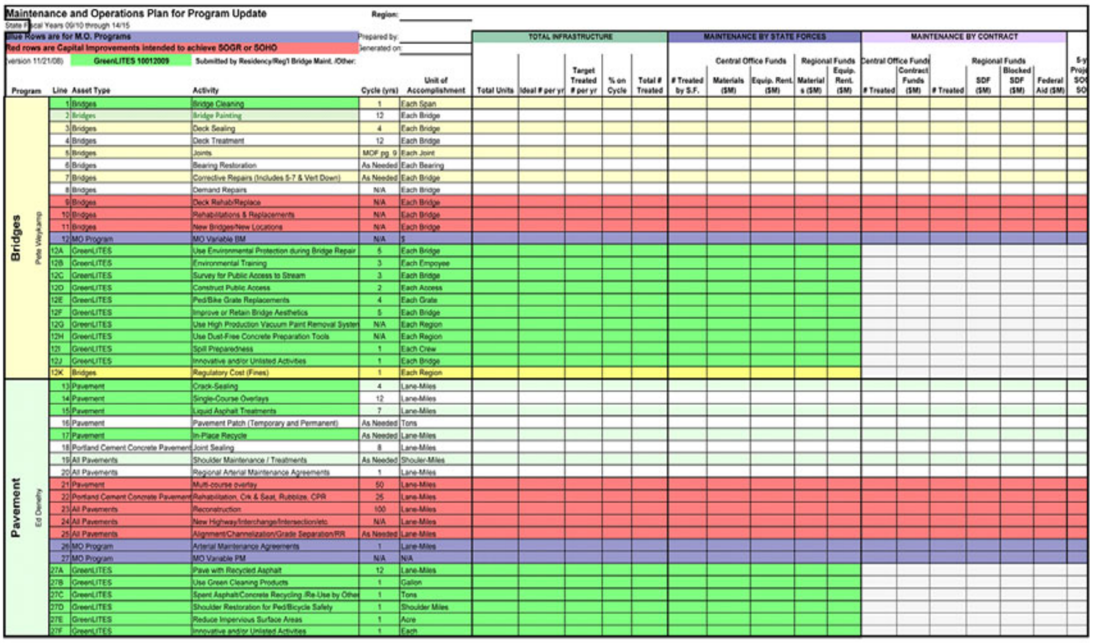
Between 1995 and 2007, New York State added 0.06% per year of new lane miles to its extensive (38,000 lane mile) highway system. Over the same time period, Vehicle Miles Traveled (VMT) on the system increased by 1.3% per year. Clearly, the system is essentially built, while use increases. A case can be made that any serious sustainability effort must address the operation and maintenance of the existing system. If issues such as highway runoff or greenhouse gas emissions are of concern, the emphasis of the solution should focus on better existing system maintenance and operation rather than on new capital projects.

Recognizing this need to move beyond new capital projects, the GreenLITES Operations program was developed in 2009 as a tool for Transportation Maintenance, Fleet Administration, Traffic, Safety & Mobility, and Modal Safety and Security to advance sustainability principles in all aspects of their work and help them track their performance. Residency Managers and others are required to plan and report on broad-ranging environmental/sustainability activities related to bridge, road, and roadside maintenance, and facility management.

The goal is to operate and maintain our transportation system in support of a sustainable society, specifically in a manner that does not deplete and, if possible, enhances resources for future generations, supports the economy, and enhances quality of life for everyone. To accomplish this, the NYSDOT Operations Division added and/or highlighted approximately 100 separate tasks into its planning spreadsheet so that sustainability tradeoffs can be quantified and performance tracked. This tool might be categorized as an activity-based framework, as described by Jeon and Amekudzi (2005) which focuses on the benefits and impacts of various actions on the sustainability of the particular system under consideration (Jeon and Amekudzi 2005). Residencies and Bridge Maintenance Groups are certified as

Evergreen, Gold, Silver, or Certified based on work accomplished from "green" points scored.

The uniqueness of GreenLITES Operations lies in its integration into the annual Maintenance and Operations Plan[9] (MOP) (Figure 3), which is a required planning tool for all NYSDOT Operations Managers. Through this integration, sustainability principles are addressed as part of the normal work flow rather than through separate ancillary initiatives. Residency Managers weigh in on broad ranging activities related to bridge, road and roadside maintenance, and facility management with environmental components.


Maintenance and Operations Plan for Program Update
State Fiscal Years 09/10 through 14/15
Blue Rows are for M.O. Programs
Red rows are Capital Improvements intended to achieve SOGR or SOHO
version 11/21/08) GreenLITES 10012009 Submitted by Residency/Reg'l Bridge Maint. /Other:
Region:
Prepared by:
Generated on:

Program	Line	Asset Type	Activity	Cycle (yrs)	Unit of Accomplishment	TOTAL INFRASTRUCTURE: Total Units	Ideal # per yr	Target Treated # per yr	% on Cycle	Total # Treated	MAINTENANCE BY STATE FORCES: # Treated by S.F.	Central Office Funds: Materials ($M)	Equip. Rent. ($M)	Regional Funds: Materials ($M)	Equip. Rent. ($M)	MAINTENANCE BY CONTRACT: # Treated	Central Office Funds: Contract Funds ($M)	# Treated	Regional Funds: SDF ($M)	Blocked SDF ($M)	Federal Aid ($M)	5-y Proj SO SO
Bridges (Pete Weykamp)	1	Bridges	Bridge Cleaning	1	Each Span																	
	2	Bridges	Bridge Painting	12	Each Bridge																	
	3	Bridges	Deck Sealing	4	Each Bridge																	
	4	Bridges	Deck Treatment	12	Each Bridge																	
	5	Bridges	Joints	MOF pg. 9	Each Joint																	
	6	Bridges	Bearing Restoration	As Needed	Each Bearing																	
	7	Bridges	Corrective Repairs (Includes 5-7 & Vert Down)	As Needed	Each Bridge																	
	8	Bridges	Demand Repairs	N/A	Each Bridge																	
	9	Bridges	Deck Rehab/Replace	N/A	Each Bridge																	
	10	Bridges	Rehabilitations & Replacements	N/A	Each Bridge																	
	11	Bridges	New Bridges/New Locations	N/A	Each Bridge																	
	12	MO Program	MO Variable BM	N/A	$																	
	12A	GreenLITES	Use Environmental Protection during Bridge Repair	5	Each Bridge																	
	12B	GreenLITES	Environmental Training	3	Each Empoyee																	
	12C	GreenLITES	Survey for Public Access to Stream	3	Each Bridge																	
	12D	GreenLITES	Construct Public Access	2	Each Access																	
	12E	GreenLITES	Ped/Bike Grate Replacements	4	Each Grate																	
	12F	GreenLITES	Improve or Retain Bridge Aesthetics	5	Each Bridge																	
	12G	GreenLITES	Use High Production Vacuum Paint Removal System	N/A	Each Region																	
	12H	GreenLITES	Use Dust-Free Concrete Preparation Tools	N/A	Each Region																	
	12I	GreenLITES	Spill Preparedness	1	Each Crew																	
	12J	GreenLITES	Innovative and/or Unlisted Activities	1	Each Bridge																	
	12K	Bridges	Regulatory Cost (Fines)	1	Each Region																	
Pavement (Ed Denehy)	13	Pavement	Crack-Sealing	4	Lane-Miles																	
	14	Pavement	Single-Course Overlays	12	Lane-Miles																	
	15	Pavement	Liquid Asphalt Treatments	7	Lane-Miles																	
	16	Pavement	Pavement Patch (Temporary and Permanent)	As Needed	Tons																	
	17	Pavement	In-Place Recycle	As Needed	Lane-Miles																	
	18	Portland Cement Concrete Pavement	Joint Sealing	8	Lane-Miles																	
	19	All Pavements	Shoulder Maintenance / Treatments	As Needed	Shouler-Miles																	
	20	All Pavements	Regional Arterial Maintenance Agreements	1	Lane-Miles																	
	21	Pavement	Multi-course overlay	50	Lane-Miles																	
	22	Portland Cement Concrete Pavement	Rehabilitation, Crk & Seat, Rubblize, CPR	25	Lane-Miles																	
	23	All Pavements	Reconstruction	100	Lane-Miles																	
	24	All Pavements	New Highway/Interchange/Intersection/etc	N/A	Lane-Miles																	
	25	All Pavements	Alignment/Channelization/Grade Separation/RR	As Needed	Lane-Miles																	
	26	MO Program	Arterial Maintenance Agreements	1	Lane-Miles																	
	27	MO Program	MO Variable PM	N/A	N/A																	
	27A	GreenLITES	Pave with Recycled Asphalt	12	Lane-Miles																	
	27B	GreenLITES	Use Green Cleaning Products	1	Gallon																	
	27C	GreenLITES	Spent Asphalt/Concrete Recycling /Re-Use by Other	1	Tons																	
	27D	GreenLITES	Shoulder Restoration for Ped/Bicycle Safety	1	Shoulder Miles																	
	27E	GreenLITES	Reduce Impervious Surface Areas	1	Acre																	
	27F	GreenLITES	Innovative and/or Unlisted Activities	1	Each																	

Figure 3: Sample of Operation's GreenLITES "MOP"

The new green lines have been integrated into the annual MOP where activities are tracked and accomplishments recorded at the end of each fiscal year. Some added lines include:

- Spill Preparedness
- Pavement Recycling
- Aquatic Connectivity
- Hybrid Vehicles/Alternative Fleet
- Transit Signal Priority Systems
- Using Salt Brine/Alternative Deicers
- Installing Energy Efficient Upgrades
- Road Kill Deer Composting
- Installing Living Snow Fences
- Re-use and Recycle

[9] https://www.nysdot.gov/programs/greenlites/operations-cert

- Reduce Mowing
- Innovative Practices

Activities with relatively low start-up cost, such as surveying for public access to streams, increasing adopt-a-highway agreements, installing setback thermostats, and inventorying chemical storage, are most likely to be accomplished in many locations. Some green practices, such as reducing idling or mowing with no initial start-up cost, are expected to be instituted in all locations. GreenLITES Operations offers opportunities and incentives to share innovative green practices and have these practices recognized and evaluated for statewide use. Results for all locations (typically a county) are published, and outstanding efforts are recognized as Evergreen, Gold, Silver, or Certified.

GreenLITES Planning

The integration of GreenLITES into the transportation planning and programming process will help ensure a more balanced approach in making transportation decisions. By incorporating sustainable practices in the planning phase, communities will begin the process of securing a more sustainable, vibrant and healthy environment. An example, a major, high profile, sensitive, complex, and until recently a much debated project, in the New York metropolitan area (Route 347 in Suffolk County, NY) is now being progressed more readily. This is because the stakeholders, the affected communities and NYSDOT used GreenLITES as a tool to find common ground in the development of project objectives. Ultimately, NYSDOT and the public agreed that if this project obtains the Evergreen certification level, along with other transportation objectives, all would support it. NYSDOT accepted this, modified the project accordingly, and the project is progressing more smoothly. Such a process-based approach, as described in Jeon and Amekudzi (2005), acknowledges that sustainability must be done through a planning process that effectively engages stakeholders in creating their vision of sustainability.

Although the preservation of our existing transportation infrastructure is vitally important, finding new solutions that enhance our communities is also important. This is accomplished by incorporating planning practices that promote more livable, vibrant communities and, at the same time, preserve the environment.

Federal planning factors already address sustainability considerations in many ways. However, to further and more systematically emphasize these considerations, NYSDOT has examined various ways of addressing GreenLITES in the planning process, including incorporating sustainable goals in long-range plans and in the development of the Department's capital program. Another option involves promoting GreenLITES in planning at the local level, which led to the development of the project solicitation tool. The tool provides a mechanism for project sponsors to review and rate the sustainability of a proposed transportation project.

The Draft GreenLITES project solicitation tool[10] (figure 4), developed by NYSDOT in collaboration with several New York State Metropolitan Planning Organizations[11] (MPOs), will assist municipalities in identifying and developing sustainable transportation projects.

Emphasis is placed on projects that support sustainability by improving the community's transportation infrastructure and quality of life, contributing to a vibrant economy, and minimizing impacts to the environment.

The tool is envisioned for use when the 13 New York State MPOs periodically reach out to the local municipalities to identify projects for inclusion in the State's transportation program. The tool's purpose is to ensure a more balanced approach in selecting projects and making sustainable transportation decisions. This helps municipalities assess how closely projects are aligned with transportation planning practices that support a sustainable society.

[10] https://www.nysdot.gov/programs/greenlites/GreenLITES%20Planning
[11] http://www.nysmpos.org/

How to Use This DRAFT Tool

This rating tool will provide a mechanism to determine how closely your project is consistent with these sustainability goals. Points are awarded for each criterion that supports these goals, with each "yes" answer receiving one point. If the criterion is not applicable to the project, the "no" box can be checked or "NA" written in the comment box. The comment box is an opportunity to briefly explain how the project addresses the specific criteria.

The criteria below are preceded by a question which provides context to the criteria. For example, the first question focuses on the comprehensive plan and all the subsequent questions relate to the plan.

1. Is the project consistent with current local comprehensive plan (developed within last 10 years), and does that Plan address sustainable practices (see below)?

		YES	NO	Comments
1a.	Does the Plan provide a clear vision of community objectives and priorities?	☐	☐	
1b.	Is the Plan consistent with regional plans?	☐	☐	
1c.	Does the zoning map and zoning ordinances reflect the intent of the Plan?	☐	☐	
1d.	Does the Plan incorporate "walkable communities" and /or "complete streets" concepts?	☐	☐	
1e.	Has the Plan been developed through an enhanced public outreach effort? This would involve reaching out to all members of the community, including minority and low income and Limited English Proficiency populations.	☐	☐	
1f.	Does the Plan promote population and development densities that are sufficient to warrant public transit?	☐	☐	

Total Points (Maximum points= 6) ___________

Figure 4: GreenLITES Planning, Project Solicitation Tool

Municipalities may use the Draft GreenLITES project solicitation tool posted on NYSDOT's website to self-rate their proposed projects. The rated projects would then be submitted as appropriate to the respective MPO and reviewed for completeness and accuracy, and verification of information.

Rated projects would be considered by the MPOs for inclusion in the transportation program, known as the Transportation Improvement Program (TIP). Additional screening of projects will take place at the MPO through their project selection process.

GreenLITES Regions

To truly measure and enhance transportation's role in supporting a sustainable society, we must move beyond projects and activities. The GreenLITES program currently looks at individual projects, planning, operations and NYSDOT county residencies. However, sustainability, with its "triple bottom line" of economy, environment, and social equity, is more a function of all transportation modes and activities on a larger county/regional scale.

Without a framework for addressing how transportation investments contribute to the sustainability of society, it is difficult to make good investment choices. To extend the use of this valuable tool over the larger scope and scale needed to truly address sustainability on a landscape scale; NYSDOT has begun to assess all projects, all residencies, and all activities as they influence sustainability across our regions.

To expand GreenLITES to include more multimodal aspects (transit, pedestrian, bicycle, rail), NYSDOT conducted an initial consciousness-raising exercise in March 2010 in each of eleven regions. The Pilot GreenLITES Regional Assessment Tool (Figure 5) was developed and applied to assess "existing" and "desired" states for a full range of sustainability factors, mostly gleaned from the Bipartisan Policy Project (National Transportation Policy Project 2009). The GreenLITES Regional Assessment rubric includes a Design Component (normalized average regional GreenLITES project scores), an Operations (Residency) Component (normalized average regional Operations score), and a Regional Component (determined by completing the Draft Regional Assessment Table) that includes ratings for the elements of the triple bottom line: economy, environment, and social equity - including livability and safety.

Region "X" GreenLITES Sustainability Assessment Table
June 2010

Economy Assessment Items	Current State (Base Line year – 2010)	Desired State *(Place target year here)*	Action Plans Getting from Current to Desired State (Include target completion date, may yellow highlight items with no direct control)	Accomplishments/Status Year *(Insert Year)*	Next Steps/Comments
Access to jobs and labor					
Access to non-work activities (Quality of Life: recreation, schools, etc.)					
System Connectivity					
Transportation Preservation (Maintenance backlog)					
Competitiveness (All modes):					
Reliability					
Timeliness					
Predictability					
Attractiveness to business					
Transit passenger miles					
Other:					
Environment **Assessment Items**					
Petroleum consumption reduction					
Air Quality - CO2 emissions					
Water Quality:					
Groundwater					
Surface water					
Habitat:					
Terrestrial					
Aquatic					
Visual / Aesthetics					
Electrical energy reduction					
Noise reduction					
Other:					
Social Equity **(Includes Livability & Safety)** **Assessment Items**					
Fatality and injury reductions per VMT					
Improved mobility for all including the disadvantaged and disabled					
Improved mobility options & choices					
Generational Equity					
Access to affordable transportation					
Incorporate community cohesion, long range land use plans and smart growth principles					
Progress Environmental Justice & ADA					
Other:					

Figure 5: GreenLITES Regions, Regional Sustainability Assessment Table

MEASURING THE TRIPLE BOTTOM LINE

As noted on the AASHTO Center for Environmental Excellence website[12], current and future transportation growth patterns and the way that we develop transportation systems are important factors in sustaining the world's limited economic, environmental, and social resources and capacity. According to AASHTO, "America's transportation system has served us well, but now faces the challenges of congestion, energy supply, environmental impacts, climate change, and sprawl that threaten to undermine the economic, social, and environmental future of the nation." (AASHTO 2009)

NYSDOT is taking steps to apply the AASHTO triple bottom line (Figure 6) to assess projects, programs, and policies. The adage "What gets measured gets done" is being embraced by NYSDOT in its application and expansion of its GreenLITES program. As GreenLITES was put into use, its potential to address transportation investments across a range of program areas became apparent and a more holistic approach to the "triple bottom line" of economy, society and environment has been adopted. As a result, the GreenLITES program has expanded to include a growing collection of tools (rating systems, spreadsheets, and other metrics) to assess projects, operations and maintenance programs, and regional programs.

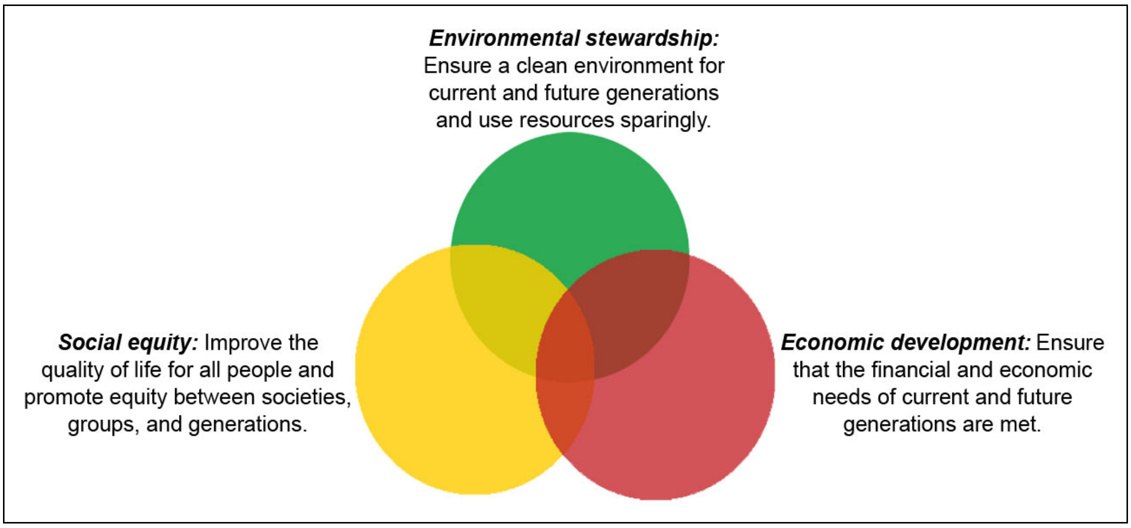


Figure 6: AASHTO Triple Bottom Line Diagram

CONCLUSION

As discussed, NYSDOT has adopted a triple bottom line approach to sustainability and is working to better align transportation with the needs of a sustainable society. We are learning by doing and welcome constructive critique. The various GreenLITES frameworks and tools are undergoing continuous development as we

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12 http://environment.transportation.org/

strive to incorporate sustainability principles into our corporate processes. Consistent with NEPA Section 102, NYSDOT is going beyond the permit/projects/activities-driven focus, and seeking to measure how we, as a public works agency, are taking steps to insure the integrated use of the natural and social sciences and the environmental design arts in planning and in decision-making which may have an impact on the environment (NEPA, Section 102 [42 USC § 4332] 1969). Advice, assistance, and collaboration are most welcome.

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USE OF BE^{2}ST IN-HIGHWAYS FOR GREEN HIGHWAY CONSTRUCTION RATING IN WISCONSIN

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ABSTRACT

This paper describes a green highway construction rating system named Building Environmentally and Economically Sustainable Transportation Infrastructure-Highways (BE^{2}ST in-Highways). BE^{2}ST in-Highways employs life cycle analysis techniques to provide a quantitative assessment of the impacts associated with a highway construction project. Energy and water consumption, greenhouse gas emissions, service life, and life cycle cost are evaluated in a quantitative framework that can be used to compare alternative construction strategies from a holistic perspective. The methodology is grounded in quantitative metrics rather than an arbitrary point system so that a transparent linkage exists between the project rating and the sustainable practices employed in design and construction. This transparency reduces the potential for 'gaming' of the rating system. Application of the BE^{2}ST in-Highways system to a project in Wisconsin is described. Results of the application indicate that using recycled materials in a pavement can result in reductions in global warming potential (32%), energy consumption (28%), water consumption (29%), and hazardous waste generation (25%) as compared to the reference design using conventional materials, while also extending the service life of the pavement. In addition, using recycled materials in a pavement can result in a life cycle cost savings of 23%. Because of this environmental and economical outperformance of the alternative design using recycled materials compared to the reference design using conventional materials, the maximum total credit (i.e., 12 points) is granted to the project.

INTRODUCTION

There is considerable research showing that construction projects are directly or indirectly causing adverse environmental impact [Gambatese 2005, Kibert 2002]. For example, the built environment accounts for 30% of all primary energy use in the U.S. [Gambatese 2005]. Approximately 7.0×10^6 MJ of energy are required to construct a 1-km length of a typical two-lane road with asphalt concrete pavement [AASHTO 2008]. Additionally, 6% of the total U.S. industrial greenhouse gas (GHG) emissions was produced by the construction sector in 2002, and 13.4% of that was produced by highway, street, and bridge construction [Kibert 2002]. The U.S. national highway system continuously requires new construction of highways and their periodic improvement to meet growing traffic demand. However, the conventional project value used in the construction industry has primarily emphasized three aspects: cost, schedule, and quality. Using these relatively short-term strategies limits the ability of construction projects to avoid the conflicts between satisfying human demands and abatement of environmental and social responsibility risks. Therefore, availability of procedures to quantify the benefits of sustainable construction practices is a key factor influencing growth in sustainable construction of public infrastructure. For example, the Leadership in Energy and Environmental Design (LEED) evaluation system has resulted in considerable interest and investment in sustainable building construction. Established evaluation systems similar to LEED are not yet available for highway construction projects, but are currently being developed in the U.S. and elsewhere. However, the majority of criteria and their evaluation procedure for such systems are a result of benchmarking the LEED program. Likewise, those rating systems do not consider the logical connection between their purpose and the surrounding factors. In other words, they lack transparency and objectiveness in the criteria selection and weighting process. At the same time, these rating procedures are not based on a standardized method of performance measurement. For this reason, they may lead to improvements, but the quantitative impact on meeting environmental targets is not known. Consequently, such a point system may lead to point mongering regardless of whether the choices add environmental value [Schendler and Udall 2005]. In this study, a rating system that primarily addresses sustainable highway construction, namely Building Environmentally and Economically Sustainable Transportation Infrastructure-Highways (BE^2ST in-Highways), is described. The system encompasses a rating tool to score the performance of an alternative design compared to the reference design (conventional design concept) of the pavement structure using standardized measurement methods. Rehabilitation activities are explicitly included in the life cycle analysis using the international roughness index (IRI) as a metric to define when rehabilitation would be required, as suggested by FHWA [1998].

The proposed rating system was applied to a pilot project to check the system's actual functionality and the degree of difficulty in obtaining the target value in each criterion. In the pilot project evaluation, the proposed rating system was used to quantify the environmental and economic benefits that could be accrued by using recycled materials when constructing a 4.7-km-long section of the Burlington Bypass in southeastern Wisconsin. The rating system, based on quantitatively measured environmental and economic benefits, is expected to encourage wider adoption of recycled materials in roadway construction and rehabilitation.

PRINCIPLES OF BE^{2}ST IN-HIGHWAYS

The first step of designing a sustainable highway construction rating system is constructing a broad view of sustainable highway construction consisting of two general components: the criteria and the target value of each criterion. Gambatese [2005] pointed out that sustainable road construction could be accomplished by several factors including use of recycled material and use of the principles of the 4R's (Reduce, Recover, Reuse, and Recycle). Gambatese [2005] claimed that several other factors such as noise levels, GHG emissions, hazardous waste, and workers' safety should also be incorporated into the planning and design process of a project to generate sustainable road construction. Others [e.g., Kibert 2002, Toleman 2008] also suggested similar criteria. The fifth clause of the Bellagio Principles to gauge sustainable development emphasizes that a limited number of criteria should be used [Bell and Morse 1999]. Bellagio Principles are the result of a conference held by the International Institute for Sustainable Development in November 1996 to discuss action plans for sustainable development. Hence, criteria selection should be based on whether or not standardized measurement is available.

Once the criteria selection is accomplished, the next step is to make decisions about the target value of each criterion. Target values are projected numbers, which the system is ultimately trying to achieve. For example, the target value for global warming potential (GWP) or GHG emissions reduction could be acquired though a series of calculations based on related theories and information. The 2002 Census results show that road construction is roughly 6.8% of the entire construction industry [U.S. Census Bureau 2005]. Thus, if the construction industry is allocated one wedge of the CO_2 stabilization triangle (i.e., 22.7 billion Mg) [Socolow and Pacala 2006], 1.54 billion Mg-CO_2e will be allocated to the road construction industry over a period of 50 years from the overall allocation to the construction industry. According to Carpenter et al. [2007], the U.S. alone is projected to construct 6 million km of roadway over the next 40 years. At the same time, construction of 1 km of a typical four-lane road and related rehabilitation activities for 50 years releases roughly 865 Mg of CO_2. This results in about 6.5 billion Mg-CO_2e. Therefore, 24% CO_2 (i.e., 1.54 billion Mg-CO_2e) should be mitigated during highway construction and rehabilitation to accomplish the reduction goal of the global warming potential.

According to Bell and Morse [1999], as stated earlier, the first task of building a rating system itself is "to identify and bring together the stakeholders in the project and to gain a clear vision of the sustainability system which is expected to emerge from the project process." For this purpose, a series of committee meetings was held at the Wisconsin Department of Transportation with stakeholders to move towards consensus on the criteria and the target values. Figure 1 depicts a summary of the developed criteria and their target values in this rating system being developed with the participation of the Wisconsin Department of Transportation.

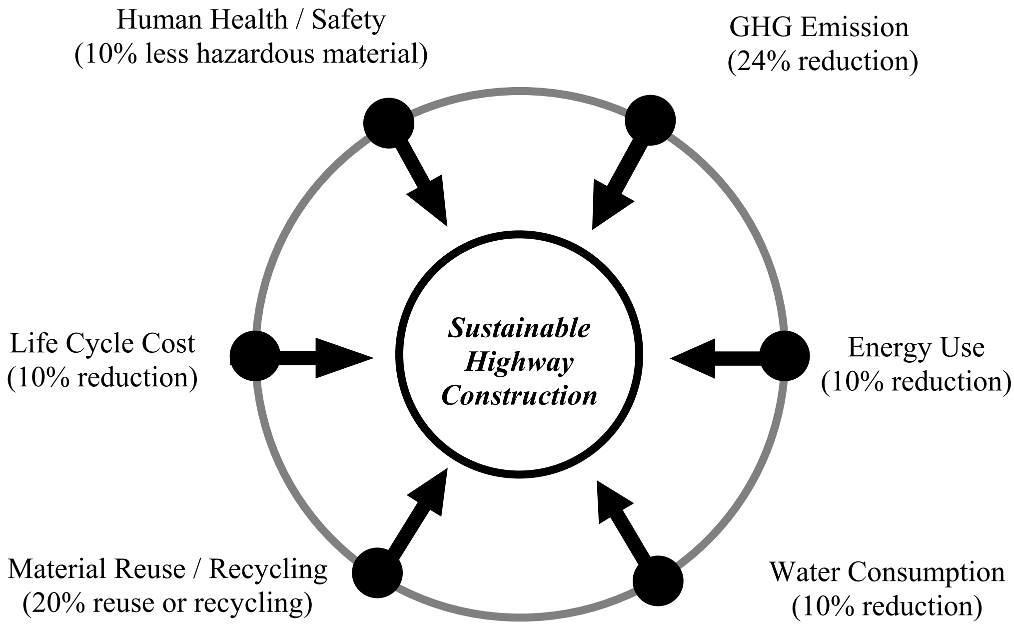

Figure 1. General Components of the BE^{2}ST in-Highways System.

Once the big picture (Figure 1) of criteria and their target values is drawn, a weighting value should be assigned to each criterion followed with the credit levels of criteria. An equally weighted system consisting of 2 points for each criterion, resulting in 12 total points, was adopted in the BE^{2}ST in-Highways system.

The performance of a construction project should be measured based on standardized measurement methods to have wide acceptance. Availability of a standardized measurement is thus necessary in the criteria selection phase. To satisfy this requirement, standard measurement methods was chosen from the currently available methods or developed if no method was available to measure the performance of a criterion.

Figure 2 shows the design procedure of the BE^{2}ST in-Highways system, a comparative quantitative assessment method. This proposed rating system can be used during the process of planning and designing highway construction projects to implement the sustainability goal of the projects (Figure 1).

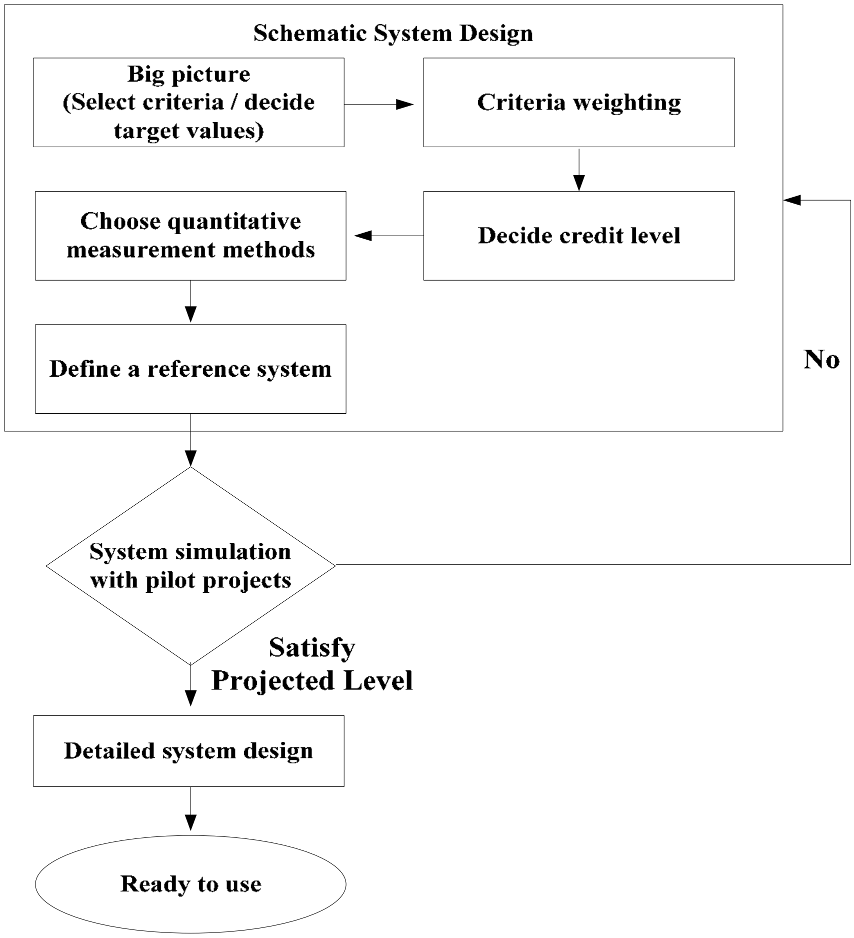

Figure 2. The Design Flow Chart of the BE^{2}ST in-Highways System.

A CASE STUDY: THE BURLINGTON BYPASS PROJECT

A case study was conducted to verify the actual functionality of the BE^{2}ST in-Highways system and to check the degree of difficulty in obtaining a score in each criterion. The case study consists of a comparative assessment and rating based on a life cycle assessment (LCA) and a life cycle cost analysis (LCCA) for construction of a section of Wisconsin State Highway (WIS) 36/83 near Burlington, Wisconsin (the Burlington Bypass) for the pavement structure constructed with conventional or recycled materials. The Burlington Bypass consists of 17.7 km of highway that routes traffic on WIS 11 and WIS 36/83 around the City of Burlington, Wisconsin. The bypass is intended to improve safety, reduce delays, and to provide an efficient travel pattern that reduces truck traffic in the downtown area of the City of Burlington [Wisconsin DOT 2009]. The western portion of the bypass was constructed between Spring 2008 to Fall 2010. A 4.7-km-long section of the western portion of the bypass was analyzed in this study.

A flowchart for the system simulation is shown in Figure 3. The steps include creating pavement designs using conventional and recycled materials, predicting the service life of both designs, identifying rehabilitation strategies, and conducting LCA and LCCA. The environmental analysis of the conventional and alternative pavements was conducted using LCA. Four environmental criteria were considered in the assessment: energy consumption, GHG emissions, water consumption, and generation of hazardous wastes, as defined by the U.S. Resource Conservation and Recovery Act (RCRA).

LCCA is a financially based decision-making tool for long-term assessment of construction projects that can be used to systematically determine costs attributable to each alternative course of action over a life cycle period and to make economic comparisons between competing designs [Bull 1993, Kirk and Dell'isola 1995].

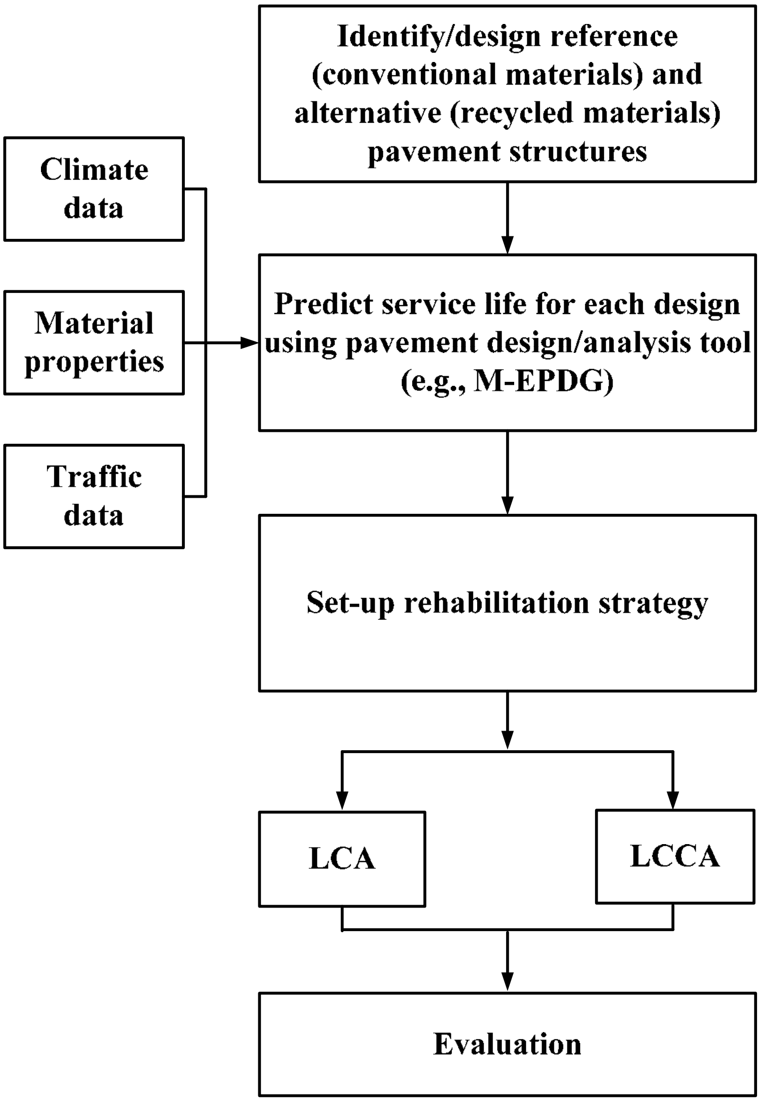

Figure 3. Flow Chart for the System Simulation Phase of Figure 2 (After Lee et al. 2010).

Two potential pavement designs considered in the assessment are shown in Figure 4, a conventional pavement design proposed by the Wisconsin Department of Transportation (WisDOT) and an alternative pavement design employing hot mix asphalt (HMA) using 15% recycled asphalt pavement (RAP) and 5% reclaimed asphalt shingles (RAS) for surface course, recycled pavement material (RPM) stabilized with fly ash as the base course, and foundry sand as the subbase. Recycled materials can also be used in other elements in the right-of-way (e.g., pipes, guide rails, barriers, etc.); however, in this study, recycled materials were considered only in the surface, base, and subbase layers of the pavement structure.

The same layer thicknesses (i.e., volume of materials) were used in the conventional and the alternative designs and the structural capacity of both pavements was determined using the same procedure. However, the recycled materials have different engineering properties than the conventional materials, which resulted in differences in the calculated service life. Design parameters for the recycled materials were obtained from the recommendations made by Geo Engineering Consulting [2009], which are based on research findings reported by Li et al. [2008] and Tanyu et al. [2005].

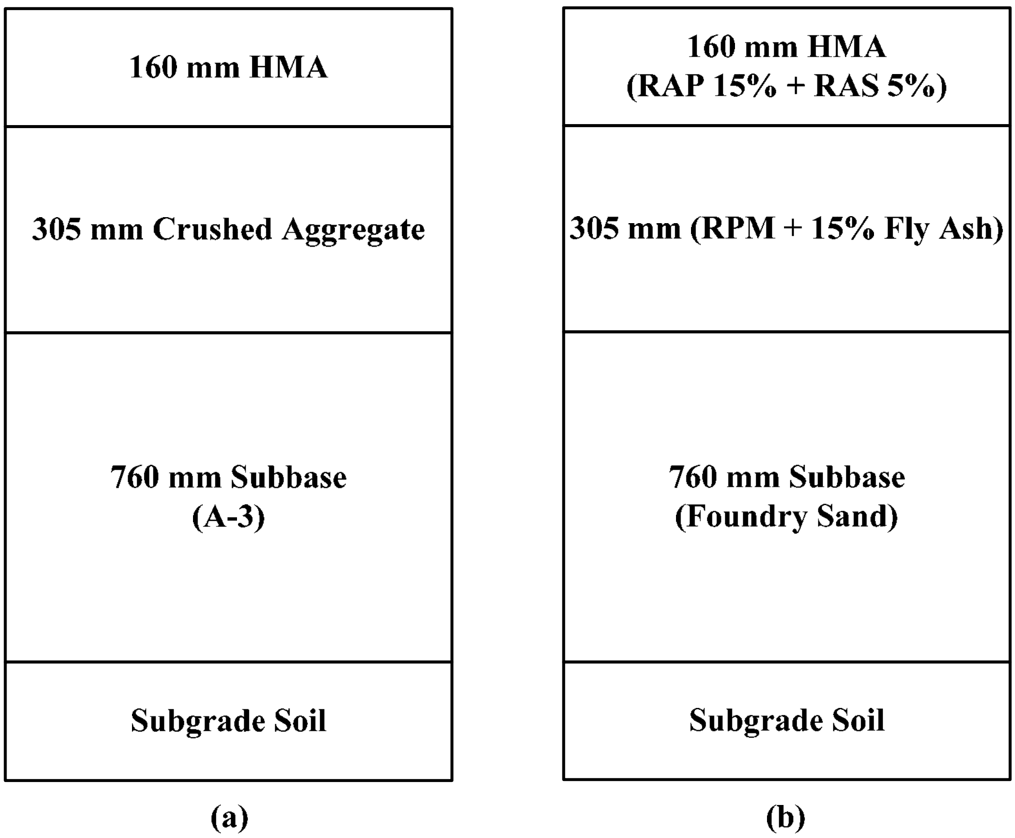

Figure 4. Schematic of Two Pavement Designs: (a) Reference-Conventional Materials vs. (b) Alternative-Recycled Materials.

Pavement systems are assumed to be serviceable until the international roughness index (IRI) reaches 2.7 m/km, as recommended in FHWA [1998]. Once this IRI is reached, the pavement is assumed to require rehabilitation. The IRI was predicted using the *Mechanistic-Empirical Pavement Design Guide (M-EPDG) Version 1.0* [NCHRP 2009]. *M-EPDG* primarily uses three key variables in the analysis: (1) traffic data, (2) climate conditions, and (3) material properties.

Predictions of the IRI for the conventional and recycled designs are shown in Figure 5. The conventional and recycled material designs reach their terminal serviceability at 29 and 32 yr, respectively. The service life for the pavement using recycled materials is 3 yr longer because of the superior properties of the recycled materials relative to the conventional materials.

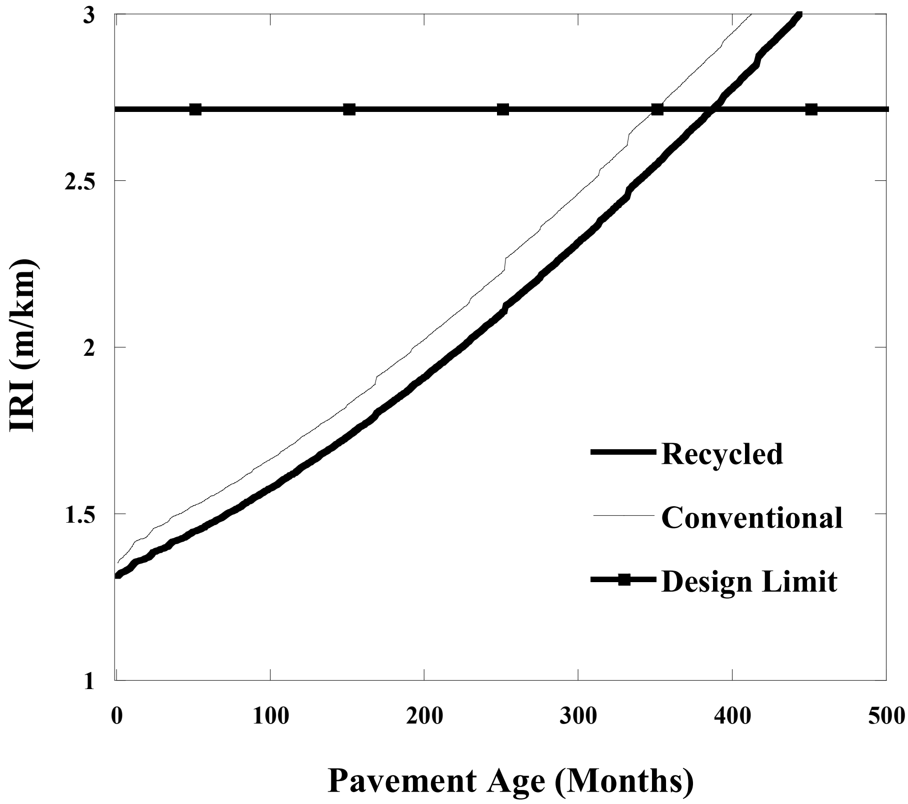

Figure 5. IRI as a Function of Pavement Age for Pavements Constructed with Conventional and Recycled Materials as Predicted Using M-EPDG.

PERFORMANCE MEASUREMENT

The LCA was conducted using the spreadsheet program, *PaLATE Version 2.0* [RMRC 2009]. *PaLATE* was used because it includes information on a variety of recycled materials, including the fly ash and foundry sand used in the base and subbase in this study. *PaLATE* employs reference factors to calculate environmental impacts for a project. For example, *PaLATE* uses CO_2 emission factors for construction equipment from the US Environmental Protection Agency inventory data [U.S. EPA 1996] to compute emissions from construction for a project. Total effects are computed as the product of unit reference factors and the quantity of an activity or material in the project.

PaLATE employs economic input-output (EIO) LCA, which permits an assessment of environmental impacts of the entire supply chain associated with conventional and recycled construction materials. EIO-LCA uses economic input-output data (e.g., data from the US Department of Commerce) as well as resource input data and environmental output data to analyze both the direct impact and supply chain effects [Horvath 2003]. Additional detail on the LCA approach used in *PaLATE* can be found in [Horvath 2003].

The LCA was conducted for a 50-yr period, which is the standard practice employed by the WisDOT. This analysis included one-time rehabilitation of the pavement at 29 or 32 yr, as noted previously. Energy use and global warming potential (reported in carbon dioxide equivalents, CO_2e) reported by *PaLATE* were used for comparing the environmental attributes of the pavements constructed with the conventional and the recycled materials. Generation of RCRA hazardous waste and water consumption during construction was also considered in the environmental assessment.

The LCCA was conducted using the spreadsheet program *RealCost version 2.5* [FHWA 2009]. As with the LCA, the LCCA was conducted for a 50-yr period. Agency costs and work zone user costs were included in the LCCA. The user costs include delay costs (cost of delay time spent in work zones) and crash costs associated with construction and rehabilitation.

RESULTS AND ANALYSIS

Results of the LCA are shown in Table 1 in terms of material production, transportation, and construction (placement of the materials in the roadway). The column labeled "difference" corresponds to the total percent change in the environmental metric by using the recycled materials in lieu of the conventional materials. Using recycled materials in other elements of the right of way (e.g., pipes, guide rails, barriers, signage) in the alternative design would further enhance the environmental benefits. However, using recycled materials just in the surface, base, and subbase layers results in significant environmental and economic benefits as illustrated subsequently.

Table 2 provides a comparison of the benefits accrued from the surface asphalt layer versus the unbound layers below due to the use of recycled materials. Considering that relatively small amount of recycled materials were incorporated in the surface layer, environmental benefits of using recycled materials in the surface layer are significant. In the case of water savings and RMRC hazardous waste reduction

TABLE 1: LCA Predictions for Pavements using Conventional and Recycled Materials

Environ-mental Metric	Conventional Materials			Recycled Materials			Diffe-rence
	Material Production	Trans-portation	Const-ruction	Material Production	Trans-portation	Const-ruction	
CO_2e (Mg)	3,630	323	111	2,551	163	54	-32%
Energy (GJ)	66,680	4,318	1,476	49,630	2,178	723	-28%
RCRA Hazardous Waste (Mg)	629	31	9	480	16	4	-25%
Water (L)	17,185	735	144	12,398	371	70	-29%

Note: GJ = gigajoules = 0.001 terajoules (TJ), Mg = megagrams.

replacing virgin asphalt concrete with concrete that includes RAP and RAS result in even higher percent changes than the base and subbase together. This is a result of higher rates of hazardous wastes production and water use during the asphalt production process than the aggregate production process. Therefore, use of recycled materials in the HMA (or an alternative asphalt construction processes) would enhance the environmental and economic benefits significantly and efficiently.

TABLE 2: Comparison of LCA Results of HMA and Other Layers

	Surface (HMA)	Base and Subbase	Total
CO_2e (Mg)	477 (-12%)	819 (-20%)	1,296 (-32%)
Energy (GJ)	8,401 (-12%)	11,542 (-16%)	19,943 (-28%)
RCRA Hazardous Waste (Mg)	131 (-19%)	38 (-6%)	169 (-25%)
Water (L)	3,241 (-18%)	1,984 (-11%)	5,225 (-29%)

Greenhouse Gas Emissions

The quantities in Table 1 indicate that a 32% reduction in GWP (CO_2e) can be achieved in this case study using recycled materials. Most of the reduction in CO_2e (83%) is from reduced emissions during material production. Heavy equipment operation is the main source of CO_2e emissions during material production. Most recycled materials are available as a byproduct from another operation (e.g., fly ash is a byproduct of electric power production) and therefore do not require mining, crushing, etc. Consequently, production of recycled materials requires less usage of heavy equipment relative to conventional materials, which results in a reduction in CO_2e emissions. Similarly, the asphalt content of RAP and RAS in the HMA does not require production of new asphalt.

To stabilize greenhouse gas emissions at current levels, the highway construction industry must reduce emissions by 1.54 billion Mg-CO_2e over 50 yr as indicated above. The LCA for this case study indicates that a reduction of 1,296 Mg-CO_2e could be achieved using recycled materials in the 4.7-km portion of the Burlington Bypass considered in this study, or 276 Mg-CO_2e/km. The U.S. alone is projected to construct 6 million km of roadway over the next 40 yr [Carpenter et al. 2007]. Based on this construction rate and the emissions reductions computed in this study, using recycled materials in roadway construction could achieve an emissions reduction of 2.07 billion Mg-CO_2e over 50 yr using the relatively modest changes in pavement design illustrated in this example. Thus, with other modest changes to pavement design, reducing emissions by 1.54 billion Mg-CO_2e over 50 yr in roadway construction appears achievable.

Energy Savings

The quantities in Table 1 indicate that approximately 85% of the total energy savings obtained using recycled materials is associated with material production. These energy savings are analogous to the reductions in emissions associated with material production and are associated with the heavy equipment used to mine and process conventional construction materials. Use of recycled pavement materials *in situ* such as RPM also reduces the energy associated with transportation (e.g., transport to a landfill for disposal and transport of new materials to the construction site).

The total energy savings (28%) using recycled materials for the 4.7-km section is 17 terajoules (TJ), or 3.6 TJ/km, which corresponds to the annual energy consumed by 170 average households in the U.S. (based on the 2005 energy use statistics, EIA 2009). Similar application of recycled materials on a nationwide basis (assuming 150,000 km of construction annually based on Carpenter et al. 2007) corresponds to an energy savings of 540,000 TJ in the U.S. annually, which is equal to the annual energy consumed by 5.4 million average homes (e.g., a state the size of Illinois or Pennsylvania). Thus, substantial energy savings can be accrued on a nationwide basis using recycled materials in roadway construction assuming that recycled materials are readily available.

Other Environmental Impacts

Using recycled materials in the pavement design also reduced the amount of hazardous waste produced and the amount of water consumed. The reduction in hazardous wastes results in lower management costs [U.S. EPA 2009]. Using recycled materials results in a savings of 5,225 L of water (29% or 1,112 L/km) for the 4.7-km section considered in the analysis. Similar application of recycled materials on a nationwide basis (assuming 150,000 km of construction annually based on Carpenter et al. 2007) could potentially result in a savings of 166.8 million L of water nationwide (approximately 10,410 persons' annual water use for shower) and an annual reduction of 5.4 million Mg of hazardous waste.

Life Cycle Cost

The life cycle costs and the cost savings using recycled materials are summarized in Table 3. These costs savings also include avoidance of landfill disposal of the recycled materials based on an average landfill tipping fee of $40/Mg [Wisconsin Department of Natural Resources 2009]. As shown in Table 3, total life cycle costs can be reduced 23% by using recycled materials in lieu of conventional materials.

TABLE 3: Life Cycle Costs for Pavement Designs Using Conventional and Recycled Materials

Categories	Reference	Alternative	Saving
Agency Cost ($)	9,044,570	7,006,830	2,037,740 (-23%)
User Cost ($)	10,570	8,380	2,190 (-21%)
Total ($)	9,055,140	7,115,610	2,039,930 (-23%)

Based on the performance of a project in each criterion compared to the reference design (i.e., 50% or 100% satisfaction of the target value of a criterion), 1 point or 2 points will be awarded to the project respectively. Because of the superior performance of the alternative design of the Burlington Bypass project (see Table 4) compared to its reference design, the maximum total credit (i.e., 12 points) can be granted to the project. The project outperformed the target values by a wide margin in some criteria. For example, 32% reduction of global warming potential passed its target value (24%) and the recycling ratio (92%) largely exceeded its goal (20%). Therefore, the target values of the criteria can be adjusted so the rating system is more challenging. If a rating system is too easy, the power of discrimination cannot be achieved.

TABLE 4: Rating Results

Criteria	Target Value	Performance	Score
Global Warming Potential	-24%	-32%	2
Energy Consumption	-10%	-28%	2
RCRA Hazardous Material	-10%	-25%	2
Water Consumption	-10%	-29%	2
Life Cycle Cost	-10%	-23%	2
Reuse / Recycling	20%	92%	2
Total			12/12

SUMMARY and CONCLUSIONS

The potential benefits of using recycled materials and industrial by-products instead of conventional materials in a highway construction project in Wisconsin have been described using a rating system named Building Environmentally and Economically Sustainable Transportation Infrastructure-Highways (BE^2ST in-Highways). Life cycle analysis and life cycle cost analysis were used in the rating system to evaluate the environmental and economic benefits. The analyses indicate that using recycled materials in the surface, base and subbase layers of a highway pavement can result in reductions in global warming potential (32%), energy consumption (28%), water consumption (29%), and hazardous waste generation (25%). Overall, 92% use of recycled materials in the surface, base and subbase layers has a potential life cycle cost savings of 23% while providing a longer service life. For the environmental and economic benefits of using recycled materials, the case study obtained the maximum total score (12 points), thus the best label of sustainable highway construction can be awarded to the project.

When extrapolated to a nationwide scale, using recycled materials in roadway construction has the potential to provide the reductions in greenhouse gas emissions needed to maintain the emissions by the highway construction industry at the current levels using the suggested strategies. In addition, energy savings commensurate with the annual energy consumption of households in a state comparable in size to Illinois or Pennsylvania can be achieved by using recycled materials in roadway construction on a nationwide basis.

As illustrated in the case study, BE^2ST in-Highways employs life cycle analysis techniques to provide an overall assessment of the environmental impacts associated with a highway construction project. Energy and water consumption, greenhouse gas emissions, service life, and life cycle cost are evaluated in a quantitative framework that can be used to compare alternative construction strategies from a holistic perspective. The methodology is grounded in quantitative metrics rather than an arbitrary point system so that a transparent linkage exists between the project rating and the sustainable practices employed in design and construction. This transparency reduces the potential for 'gaming' of the rating system.

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The Development of I-LAST ™ Illinois - Livable and Sustainable Transportation

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In January 2010, the Illinois Department of Transportation, the American Consulting Engineers Council – Illinois Chapter, and the Illinois Road and Transportation Builders Association released a sustainability guide and rating system entitled I-LAST, Illinois - Livable and Sustainable Transportation. The document was developed by volunteers from these organizations over a two-year period. This paper reviews the reasons for undertaking this project, the contents of the resulting document, and the decisions made during its development.

Background

Though recent decades have brought marked interest in sustainable design practices and development of a number of guides and project rating systems, the previous work was primarily centered on buildings. The most famous result, LEED, established an approach and format that many other systems have emulated and adopted. More recently, other systems have been developed that address different aspects of constructed projects and use different rating approaches.

In Illinois, a group of engineers from the American Consulting Engineers Council and the Department of Transportation formed the Illinois Joint Sustainability Group (IJSG)) to evaluate ways to support more systematic use of sustainable elements in the design of highways. As the project progressed, this initial team was joined by members of the Illinois Road and Transportation Builders Association.

The Illinois Department of transportation (IDOT) has been a leader in the adoption of sustainable practices dating back to the installation of the Chicago Traffic System Center in the 1960's and the on-site recycling of existing pavement during reconstruction of the Edens Expressway in the 1970's.

This leadership role continued through the years. With the publication of I-LAST in 2010, the State of Illinois was among the first states to develop a guide for sustainable construction practices for highways.

Need for Action

The Illinois Joint Sustainability Group that developed the I-LAST document believed the action was necessary for several reasons:

1. While sustainable design elements were becoming more common in highway design, there was no organized approach or applicable references for incorporating sustainability in the design process. Too often, such elements were addressed in response to insistence from public officials. Existence of a standard guide and reference would encourage engineers to consider potentially relevant issues earlier in the design process, both improving the sustainability of projects and lowering costs by reducing late design changes.

2. Existing sustainable practices were little known outside the industry. Capturing these in a document would allow IDOT to convey this information to the public more easily, improving the image of IDOT.

3. The IJSG believed that sustainability requirements would likely become formalized in the near future by legislation or regulation at the state or federal level. Therefore it would benefit the state to start planning in advance.

Expectations for the Guide

After considerable discussion, the IJSG agreed that a comprehensive guide was required to increase awareness of sustainable practices relevant to highway projects, and it should include resources to assist with incorporation of those practices. It was also determined that a rating system should be included to provide an objective measure of success.

The IJSG then decided on the intended audience and the specifics to be covered in the document. The IJSG reviewed existing systems including LEED, NYDOT's GreenLITES, and a draft of the University of Washington's Green Highways.

Audience

The audience for the document was a crucial decision. The IJSG agreed that the document would be most beneficial at the project level. The target audience should be those with key input on development of the project: project managers and engineers at both IDOT and its partner consulting firms. The document should focus on issues and decisions where the design teams have primary responsibility for analysis, recommendations and decisions. This also meant that the associated rating system should directly reflect the decisions and recommendations made by the design team.

There are clearly other decisions on livability and sustainability that are made at the policy level of IDOT. Since the design team does not make these decisions, they are not included in the I-LAST document. The result is a "bottom up" approach that focuses on design team decisions rather than attempting higher-level policy changes. The IJSG believed that this approach could be implemented with tangible results much quicker than policy changes.

Scope

An early decision was needed concerning whether one document and rating system should cover all types of highway projects, or whether different documents were needed for new construction, modifications, and resurfacing. This was quickly complicated by discussions of the differences between rural, suburban and urban projects.

The IJSG discussed producing several different documents for different types of projects in a manner similar to LEED, however it was decided that approach was too cumbersome for the resources available to produce and maintain the system, as well as for users of the document.

After evaluation, the IJSG decided that one guide and rating system would be developed to cover all highway projects regardless of the complexity and size. It was clear at that point that the metrics of the rating system would need to accommodate the project variables in a way that yielded a fair evaluation of all project types and sizes.

Content Considerations

Compared to existing systems such as LEED, a number of content areas are substantially different for a project with a highway infrastructure focus:

- Range of Sustainable Measures – Buildings generally have many categories of items in common. Any one particular highway project will have a number of sustainable measures that do not apply.
- Energy Consumption – Buildings are themselves consumers of energy and the energy consuming systems are a large portion of the building design and construction. Most energy consumption related to highways comes from the vehicles that use them. The decisions available to designers related to energy consumption are therefore limited.
- Surrounding Environment - Projects in areas from the most rural to the most urban needed to be covered. Designs for different types of terrain require very different practices.
- Range of Project Types – A goal was to cover all highway projects ranging from resurfacing to new construction. A rating system needed to fairly evaluate the entire range of project types and sizes.

- o Project Site – During modifications to existing highways, location decisions are limited compared to new construction, so total avoidance is often infeasible.

I-LAST Contents

The resulting I-LAST guide consists of over 150 possible sustainable or livable practices that may be included in highway projects. These practices are grouped into 17 sections and 8 general categories. They include design phase activities, such as using Context Sensitive Solutions practices; design decisions, such as alignments to avoid environmentally sensitive areas or inclusion of transit facilities; and construction specifications, such as allowing the reuse of reclaimed materials.

Category	Section	Description	Items
Planning	Context Sensitive Solutions	Identify and address stakeholder concerns and engage public participation.	4
	Land Use / Community Planning	Balance community goals and transportation needs.	6
Design	Alignment Selection	Avoid ecologically sensitive areas and minimize impacts to the environment.	7
	Context Sensitive Design	Consider design flexibility that responds to the project area's character.	6
Environmental	Protect, Enhance or Restore Wildlife Communities	Design to protect, enhance, or restore natural habitats.	11
	Protect, Enhance, Restore Native Plant Communities	Avoid damage to ecologically sensitive vegetation, promote native plant material, revegetate areas and remove invasive species.	10
	Noise Abatement	Reduce noise associated with vehicles.	13
Water Quality	Reduce Impervious Area	Reduce stormwater volumes and pollution by returning water to natural pathways that recharge groundwater.	11
	Stormwater Treatment	Use design features that remove pollutants.	10
	Construction Practices to Protect Water Quality	Provide protection to streams during and after construction and improve stormwater quality	13

Category	Section	Description	Items
Transportation	Traffic Operations	Increase traffic efficiency on roadways to reduce delay and fuel consumption.	6
	Transit	Promote increased transit use through facilities on or adjacent to highways.	10
	Improve Bicycle and Pedestrian Facilities	Improve conditions for bicycle and pedestrian travel.	13
Lighting	Reduce Electrical Consumption	Incorporate new technology to reduce power consumption and minimize the impact of providing power.	7
	Stray Light Reduction	Reduce adverse effects of artificial light including sky glow, glare, light trespass, and clutter.	2
Materials	Materials	Give contractors the flexibility to reduce waste generation, and reuse and recycle materials in beneficial ways.	13
Innovation	Innovation	Use features which have not yet been sufficiently tested to merit acceptance without reservations.	1

Scoring

Importance of scoring

The document has two functions: provide a guide for design and rating system for scoring. The importance of a scoring system was much debated. The goal was to improve the sustainability of projects, but some IJSG members suggested that scoring was not significant in accomplishing that. The contention was that scoring a project after the completion of the design phase did not change the design. But it was clear that scoring would be important for several reasons:

- The competitive nature of design teams would lead designers to take a closer look at possible measures in order to improve their score.
- Scoring can provide feedback to the design teams.
- Scores provide IDOT with information on the sustainability of designs that can be used to communicate with the public.

It was agreed that a scoring system was needed. The question became: what kind of scoring?

Scoring System Evaluations

The IJSG's review of existing systems revealed two basic approaches to scoring, with several systems that use a combination of the two.

1. Evaluate impacts. For this approach, a measure of impact on the environment is calculated. These include:
    - Greenhouse gas reduction
    - Water pollution reduction
    - Air pollution reduction
    - Waste reduction
    - Community livability measures
    - Mode shifts generated (and potential greenhouse gas reduction?)

    Defining a common scoring system that would put all of these measures in a common unit would be complicated and probably beyond the current state of knowledge. This approach would also require the designers to complete significant calculations to generate the results, placing it beyond the cost limitations of the program.

2. Prescriptive measures. For this approach, a range of actions is given and a point system is developed to score each action. This can be a simple "Yes / No" approach or measures of effectiveness can be developed for each action. The disadvantage of this system is that it does not produce a score that represents the results of the action. The advantages include a potential to greatly reduce the cost of the scoring process and a direct relationship of the scoring to the decisions made by the design team.

After discussions it was clear that the only feasible option was to use a prescriptive scoring system.

Scoring Process

The IJSG reviewed several scoring processes. In the LEED system projects are certified by a third party, USGBC. This approach, where substantial proof and documentation are required for certification, was found to be too expensive and cumbersome for IDOT. The state does not have the substantial funds required for design teams to prepare complicated submittals or to administer the process. IDOT also trusted its design teams to do fair and reasonable self-scoring of projects.

The GreenLITES approach, of an agency person reviewing and scoring every project, was also found to be infeasible. IDOT has seen considerable staff reductions and would be unable to devote the staff time required to have a person unfamiliar with the projects do the investigation required for an independent scoring.

Within the financial constraints of current funding, it was clear that self-scoring was the only practical approach. But even self-scoring has a cost, and it became a priority to keep that cost as low as possible. If implementation of the process would create additional costs, they must be related to improvements in project quality, not simply to scoring and record keeping.

⇒ *A simple, low cost scoring system was clearly a requirement.*

Scoring Various Project Types

Project Size and Complexity

The range of project types from resurfacing to reconstruction, roadway widening, and construction of new roadways presents a problem for scoring. The more complex projects offer more opportunities for making sustainable decisions and increasing the scoring point total. The range of project sizes, from small projects of only a few blocks, to mega-projects of many miles creates a similar disparity.

By simply totaling points the system would reward larger, more complex projects, and discourage design teams on smaller projects from paying any attention to I-LAST, since there may be few opportunities to score points.

The IJSG believed that it is important to have design teams of all IDOT projects embrace the system and look for opportunities to improve their projects regardless of size or complexity.

Project Phases

While building projects are usually completed by one team from inception through construction services, for many agencies, including IDOT, roadway design is completed in at least two distinct phases: (1) Preliminary Engineering and NEPA environmental documentation, and (2) Final Design and preparation of contract documents. It is normal at IDOT and some other agencies, for these phases to be completed by different design teams, usually from different consulting firms. It is common for the design phase to take two or more years to complete, and construction can take several years. If funding issues arise and the design or construction is delayed, or the project is large and built in sections, then these periods can be years longer.

If the scoring of the project is only completed at the end of construction, then the scoring would occur three to ten years after the completion of the initial team's work. That is too distant from the completion of the work to provide a useful measure of the team's success. This disconnect also means that the design teams are not involved during construction and are not aware of construction information about the project.

The IJSG believed that for the scoring to serve as a source of feedback to the design teams, it had to be done at the time the team was completing the work. While a scoring system that only measures the complete project provides information to the agency and possibly to the public, it is not an effective tool for the designer.

Proportional Scoring

The question then became how to accommodate all the variables of project size, type, location and phase.

An example used in discussion was avoidance of wetlands. On projects in dense urban areas, there are usually no wetlands in the vicinity. In that case, are points awarded for avoiding wetlands, or are no points awarded since there are no wetlands to avoid? Either alternative seemed to skew the results with no thought or effort required by the designers.

An alternative was to simply remove the wetlands items from the scoring of that project. If only applicable items are evaluated in the scoring, then the scoring better reflects the effectiveness of the design team in improving the sustainability of the project. For instance, this approach would allow the preliminary engineering team to be scored only on the issues applicable to that phase of the design, leaving out construction material specifications, etc.

The IJSG felt that this was a process that would put all projects on an equal footing and truly focus the designers on the issues that were appropriate for the project and the phase of the process.

Based on this it was decided that there would be a two step scoring process:

1. Review all I-LAST items to determine if they are applicable to the project. For instance, if there is no transit service provided along the roadway, and none is planned, then adding bus stops, shelters, and similar appurtenances would not be applicable. The fact that it is not in the program or the budget does not mean that it is not applicable. Total the maximum points for the applicable items. This can be done as early as initial project scoping.

2. Evaluate the number of items that were achieved, and total the points for those.

The score is then the percentage of available points that were achieved. By eliminating the total number of points and using a percentage of the available points, the differences between the project scopes are removed and projects can be compared on an equal basis.

Ranking

While the IJSG scored a few projects in the process of developing the guide there were not sufficient scores available to determine what the various scores would mean.

Instead of spending considerable time developing a scoring curve before releasing the guide, it was decided to release it to the local engineering community and enlist their assistance in developing a scoring curve. Both IDOT staff and engineering firms were asked to use the guide for a year and provide scores and self assessments to the IJSG.

The IJSG will develop a grading curve to be included in the update of the guide in early 2011.

Status

I-LAST version 1.0 was jointly released by IDOT, ACEC and IRTBA in January 2010. It was agreed that the guide would remain an ACEC document for the remainder of 2010. At the end of the year the Illinois Joint Sustainability Group would reconvene to gather comments and input received, update the guide, revise the scoring as needed and complete a grading curve. The document would also be prepared to become an internal IDOT document at that point.

References

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