Robert Gordon

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Functional Design for Effective Traffic Management

Second Edition

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Preface

Functional design, as described in this book, is the selection of ITS management strategies and the field equipment deployments required to implement them. In most cases, functional design stops short of the selection of detailed technologies. Starting with the development of detailed objectives, functional design relates management strategies to project objectives, identifies alternative strategies for further consideration, and evaluates these strategies. It then determines whether one or more strategies can cost effectively satisfy the objectives and recommends the most appropriate alternative.

Although considerable effort has been expended by the Federal Highway Administration and others to develop high-level systems engineering processes, in practice, ITS designers have often used a "bottom up" approach. Designers often select devices and device locations without a strong connection to project objectives or to methodologies that assess the feasibility of the project and the proposed design. This book provides guidance for adapting these systems engineering processes to freeway ITS project functional requirements. It provides the basis for selecting the types of ITS components and the management strategies employed. A number of handbooks and other resources are available to provide guidance for the detailed selection of field equipment and operations to manage the equipment. This book assumes that the reader is familiar with the functions of ITS devices such as dynamic message signs, highway advisory radio, traffic detectors, and CCTV applications.

This edition is essentially an updated version of *Intelligent Freeway Transportation Systems: Functional Design*. The text discusses the increased emphasis on coordination among transportation management centers and the more intensive management techniques provided by emerging active traffic management strategies. ITS evaluation techniques are described in more detail, and examples of the communication of the results of these evaluations to decision makers and to the public are described. Several types of transportation corridors are described, and examples of corridor management strategies are included. Some material was updated and obsolete material was removed.

The book emphasizes the use of fundamental transportation planning and traffic engineering principles to develop functional designs. It is assumed that the reader is somewhat familiar with this area. The book largely reflects the author's experience in adapting these principles to ITS design. For example, the book provides models to suggest appropriate locations for such ITS devices as CCTV cameras and dynamic message signs and describes methodologies for estimating the benefits of proposed functional designs. The models enable the designer to estimate the performance differences among alternatives and estimate benefits for functional design purposes. Approximations are introduced to expedite the use of these models by practitioners. While the author has found these models to be useful, readers are encouraged to modify and enhance them to better suit their needs. The web site http://www.springer.com/us/book/9783319147673 provides worksheets that facilitate the use of some of the models. The worksheets are provided in an unprotected format to enable users to modify them as required.

I give particular thanks to my wife, Norma, who provided support and encouragement to complete the effort.

Plainview, NY, USA Robert Gordon

Contents

List of Symbols, Abbreviations, and Acronyms

The following table defines the symbols, abbreviation, and acronyms that are most commonly used in the book. Parameters and variables used in the equations are defined in the discussion of the equations. Definitions for the appendices are provided in the appendix.

Acronym	Definition
AADT	Annual average daily traffic
ACCR	Accident rate
ACR	Accident rate for section
ADD	Average vehicle delay (diversion)
ADM	Active demand management
ADMS	Archived data monitoring system
ADMS	Arterial dynamic message sign
ADND	Average vehicle delay (no diversion)
ADOT	Arizona Department of Transportation
ADUS	Archived Data Use Service
AID	Automatic incident detection
ALINEA	A local ramp metering algorithm
ANPRM	Advanced notice of proposed rulemaking
APM	Active parking management
AR	Accidents reduced
ARI	Accident rate in interchange area
ARNI	Accident rate in non-interchange area
ARTEMIS	Advanced Regional Traffic Interactive Management and Information System
ATDM	Active traffic and demand management
ATM	Active traffic management
ATSMR	Average time per mile per vehicle saved by metering

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Acronym	Definition
B1	Timely detection probability for a range of scenarios for different detector spacing
B_J	Total mainline traffic in section J
BSM	Basic safety message
C	Capacity
C2C	Center-to-center
CAD	Computer aided dispatch
CALTRANS	California Department of Transportation
CCTV	Closed circuit television
CD	Capacity deficit
CDS	Total corridor delay reduction
CFA	Coordinated freeways and arterials
CFR	Code of Federal Regulations
CMS	Changeable message sign (also known as dynamic message sign)
CO	Carbon monoxide
CONOPS	Concept of operations
crf	Capital recovery factor
CS	Capacity along arterial with signal
CVF	Commercial vehicle fraction
CVRIA	Connected Vehicle Reference Implementation Architecture
DAR	Additional delay incurred by pre-diversion traffic on diversion route
DC	Delay from TC to T
DD	Delay prior to TC
DF	Public diversion fraction for no major arterial congestion
D_I	Delay from the start of the incident up to incident clearance
DIF	Delay for non-diverted freeway traffic
DOT	Department of Transportation
DMS	Dynamic message sign
D_Q	Delay from incident clearance to queue dissipation
DQC	Delay after incident clearance
DSRC	Direct short range communication
DSS	Decision support system
D_T	Total delay
DTA	Dynamic traffic assignment
E511	Emergency telephone response service provided by PSAP
ER	Emission rate
FE	Excess fuel consumption
FHWA	Federal Highway Administration
FRM	Fraction of roadway segment influenced by metering
FRR	Fraction of ramps in roadway segment that contain ramp meters
G	Gini coefficient
GE	Excess fuel consumption rate

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Acronym	Definition
GPS	Global positioning system
GS	Green split along arterial
H	Potential ability for ITS to provide incident management support
HAR	Highway advisory radio
HC	Hydrocarbons
i	Interest rate
ICM	Integrated corridor management
ICS	Incident command system
IDI	Duration of incidents and accidents in interchange areas
IDN	Duration of incidents and accidents in non-interchange areas
IDV	Time saved by non-diverting vehicles
IEEE	Institute of Electrical and Electronics Engineers
ILD	Inductive loop detector
INCOSE	International Council on Systems Engineering
INFORM	Information for motorists
ITS	Intelligent Transportation Systems
IVI	In-vehicle infotainment system
k	Density or concentration
K	Parameter
KD	Constant for utility calculation
KS	Satisfaction rating
L1	Distance in the section in the vicinity of the upstream interchange for the section. Midpoint of the interchange that encompasses most of the accidents
L2	Distance in the section in the vicinity of the downstream interchange
LCS	Lane control signal
LD	Length of detector sensing area
LOS	Level of service
LRT	Light rail transit
LS	Section length
LV	Length of vehicle
MAC	Machine access control
M(J)	Mainline AADT for Section J
MCO	Maintenance and Construction Operations Center
M_D	Mainline AADT for section with upstream DMS closest to section being analyzed
MDF	Maximum divertible freeway flow without major arterial congestion
MF	Maximum flow without major arterial congestion
MOVES	Motor vehicle emission simulator
MTF	Fraction of planned metering period that freeway is at level of service E or worse
MTTSV	Average delay reduced per assisted vehicle
MU	Multivariate utility value

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Acronym	Definition
MUTCD	Manual of uniform traffic control devices
MV	Utility for message type
MVMPY	Motor vehicle miles per year
n	Project useful life
NAIR	Non-accident incident rate
NCHRP	National Cooperative Highway Research Program
ND	Total number of diverted vehicles until incident clearance
NFA	Normal background traffic
NHTSA	National Highway Traffic Safety Administration
NIMS	National Incident Management System
NMV	Utility for other than message type
NND	Total number of vehicles served until incident clearance
NOX	Oxides of nitrogen
NT	Number of travelers
NTCIP	National Transportation Communications for ITS Protocol
NYSDOT	New York State Department of Transportation
OBU	On-board unit
OREMS	Oak ridge emergency evacuation system
P	Probability of functional capability
P(x)	Cumulative probability distribution
P10	Probability incident is managed if TMC is staffed
P21	Probability TMC staffed when incidents occur
P3	Probability motorist receives and understands message from all media
P34	Probability that motorist encounters CMS prior to reaching diversion location
P35	Probability that motorist will read and understand CMS message
P4	Probability that qualifying motorist receiving and understanding the message diverts
PC	Capital equipment cost
PD	Propensity to divert
PDF	Private component of diversion fraction
PDSL	Priced dynamic shoulder lane
PeMS	Performance measurement system
PennDOT	Pennsylvania Department of Transportation
PHV	Peak hour volume
PORTAL	Portland Oregon Regional Transportation Archive Listing
PSAP	Public service access point
q	Volume
q/C	Volume-to-capacity ratio
q_1	Volume at incident
q_2	Volume entering incident
q_3	Volume when incident is present
qA	Normal arterial volume

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Acronym	Definition
QUAL	Relative quality of information
QWS	Queue warning system
R	Annualized cost with interest
R(j)	Meter rate after time j
R(J)	Residual volume for section J after exit ramps
RC	One direction arterial capacity
RE	Residual capacity
RI	Project class
RI_A	Relative importance of attribute A
RITA	Research and Innovative Technology Administration
RSU	Roadside unit
RTV	Relative coverage of incidents
S_j	Speed of vehicle j
sppwf	Single payment present worth factor
SWARM	System wide adaptive ramp metering algorithm
T	Time from start of incident to incident clearance
TA	Total number of accidents in section
TC	Time from incident occurrence until diversion is implemented
TCIP	Transit communications interface profiles
TD	Time for queue to dissipate after incident starts
TDD	Time period after incident clearance until queue clears under diversion
TDF	Total diversion fraction
TIP	Transportation improvement plan
t_j	Occupancy period sensed by detector for vehicle j
TMC	Transportation (or traffic) management center
TNA	Test for presence of non-interchange area in section
TO	Metering hours per year
TOND	Improvement in delay on diversion route
TS	Delay reduced
TSI	Delay reduced per incident
TSDV	Time saved by diverting vehicles
TVI	Fraction of roadway visible to CCTV at interchanges
TVN	Fraction of roadway visible to CCTV away from interchanges
U	Utility value or difference in utility values
u	Mean-space-speed
u_T	Mean-time-speed
V	Volume
V2I	Vehicle to infrastructure communication
V2V	Vehicle to vehicle communications
VA	Mainline volume upstream of queue formed by incident
VA1	Entry volume downstream of DMS and upstream of incident
VD	Diversion volume

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Acronym	Definition
VDS	Vehicle detector station
V_{ED}	Exit ramp volume when diversion is implemented
V_{EW}	Exit ramp volume when diversion is not implemented
VMT	Vehicle miles traveled
VPN	Virtual private network
VSD	Vehicle system delay
VSLS	Variable speed limit sign
W_{AB}	Velocity of shock wave propagation. A is downstream boundary, B is upstream boundary
WAN	Wide area network
x	Queue discharge volume
X(J)	Sum of exit ramp AADT for Section J
Y	Fraction of incident management operation represented by timely assistance to emergency responder function
511	Telephone number for public service answering point
α	Shape parameter
β	Scale parameter
θ	Occupancy
θ_I	Filter input data
θ_M	Mainline detector occupancy
θ_O	Filter output data
θ_S	Occupancy setpoint

Chapter 1
Introduction

Abstract *Intelligent Freeway Transportation Systems: Functional Design for Effective Traffic Management* was written to provide engineers engaged in the functional design of freeway intelligent transportation systems with the background and tools to develop effective systems that are properly scaled to traffic conditions, and that use project resources efficiently. This chapter describes the migration of ITS from its initial technology constraints to its current ability to support additional functions that can be integrated into a system that better satisfies stakeholders' needs. A guide to the book's chapters is also provided.

1.1 Purpose of Book

The purpose of this book is to provide engineers engaged in the functional design of freeway ITS with the background and tools to develop effective systems that are properly scaled to traffic conditions and that use project resources efficiently. The major functions provided by freeway ITS include

- Assisting emergency service providers in detecting and clearing incidents more rapidly. Supporting rapid response reduces the queues on the freeway with corresponding reduction in motorist delay and secondary accidents.
- Providing information on incidents and other travel conditions to motorists. Benefits accrue to motorists that choose to alter their route, trip initiation time or travel mode. The resulting reduction in the queue on the freeway mainline also reduces the delay for motorists that do not alter their trip plan.
- Controlling access to the freeway mainline or controlling lane use. Ramp metering improves the capability of the mainline to service traffic and redistributes it on the network to reduce overall delay. Lane control signals and dynamic speed control signs may be used to improve traffic flow under incident conditions and improve lane allocations during normal traffic conditions. Dynamically managing lane use and use of the shoulders may improve traffic flow.

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- Managing information and controls to support a broad array of transportation needs, including transit, optimization of passenger throughput in transportation corridors and traffic management to support responses to emergencies and evacuations.
- Providing information on traffic conditions and incidents to private traffic information services.

This book provides guidance on functional design for a number of these topics.

1.2 Development of ITS Design Practices

The freeway management systems that were designed in the 1960s and 1970s were often single purpose or limited function systems. Examples include ramp metering systems, incident management in tunnels, and systems that provided limited levels of motorist information. The operational constraints on these early systems were often determined by limitations in computing and communications capability.

With improvements in computing and communications, freeway ITS were designed to provide a more comprehensive capability to manage traffic. CCTV coverage was extensively employed. Comprehensive system-wide imagery is currently often available in major metropolitan areas, and transportation management centers often operate 24 h per day, 7 days per week. In some cases, service was extended to provide priority to high occupancy vehicles through management of lanes and ramp meter by-passes for high occupancy vehicles.

During the late 1990s, greater emphasis was placed on the introduction of systems engineering principles into freeway ITS design. These principles are embodied in the National ITS Architecture [1]. Guidance is also provided by an California Department of Transportation and FHWA report [2]. Systems engineering principles include:

- A systematic life cycle process for establishing needs and objectives, developing a set of design alternatives, evaluating the alternatives, designing the system and installing it, providing the logistic services necessary to support the system, operating the system, and evaluating its performance for the purpose of improving future ITS designs and operations.
- Provision of a process to integrate the freeway system into the overall transportation system including support of transit, corridor operations, other regional traffic and transportation management systems. The process emphasizes interaction with other stakeholders.
- Employing approved standards to enable interchangeability of field equipment and to support the interchange of communication among stakeholders and communication with field equipment.

Systems engineering is discussed further in Sect. 2.1.

More recently, increased emphasis has been placed on more intensive management of freeway lane use and vehicle speeds under incident and congestion conditions. With the reduced availability of federal aid and, in some cases, state matching funds, issues such as whether it is more cost effective to cover a wider geographic area with ITS treatments or to deploy ITS devices more intensively in a smaller area are important considerations for project planning and scoping.

1.3 Summary of Contents and Organization

This book describes the application of system engineering principles and cost effective design methodologies to the selection of management strategies and placement for field equipments for commonly employed ITS techniques. The relationship of traffic conditions to project scoping and preliminary design is extensively discussed.

System engineering methodologies employ "top-down" functional design processes. Figure 1.1 illustrates the process described in the book.

The following discussion relates the book's contents to Fig. 1.1.

The first task group in the figure identifies objectives and evaluation measures. Chapter 2 describes system engineering techniques as applied to ITS and identifies goals and objectives. It relates evaluation measures to objectives, and discusses the rationale for evaluating design alternatives and project performance.

Chapter 3 prepares the groundwork for describing ITS treatments later in the book. The chapter discusses traffic conditions as they affect ITS, including traffic volume, speed, density and capacity. Congestion and diversion are also explored. A section describing performance and benefit assessment recommends certain performance measures for assessing design alternatives. Project evaluation techniques are introduced.

The second task group in Fig. 1.1 identifies management concepts, strategies, and classes of technologies that lead to functional design. Management concepts that directly provide benefits to motorists include

- Reduction of time to clear incidents (Chap. 4). Models of delay caused by incidents are presented, and a relationship for the delay reduced by lowering the incident clearance time is discussed. ITS techniques for improving emergency vehicle response time, such as the use of CCTV and traffic detectors,[1] are described. Procedures for maximizing the cost effectiveness of camera deployments and a trade-off of the effectiveness of traffic detector deployment and reduced incident detection time are provided. The role of the transportation management center in assisting incident responders and a model for evaluating the effect of incident management is presented.

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[1] The terms "*detectors* or *traffic detectors*" are used in this book for devices that provide indications of volume, speed or occupancy at a point on the roadway. These devices are also often called *sensors* or *traffic sensors.*

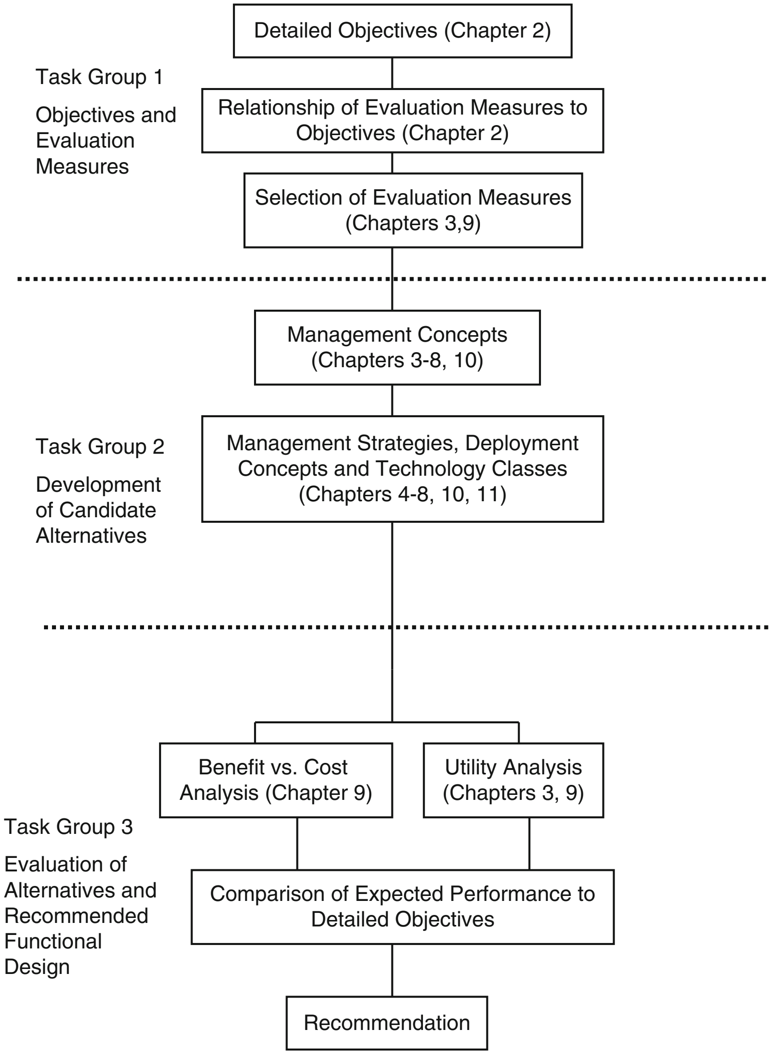

Fig. 1.1 Functional ITS design process

- Motorist information for non-recurrent congestion (Chap. 5). The role of motorist diversion and its implementation is described. The chapter discusses the capability to control the level of diversion through altering the types of messages and presents a model to assist in obtaining the desired diversion fraction. Strategies to control the diversion fraction in real time are introduced and the effect of the diverted traffic on the alternate routes is explored. The chapter covers methods for communicating incident information to the motorist and models to optimize the placement of changeable message signs. A model to estimate the quality of information provided to the motorist is described.

- Motorist information to address recurrent congestion (Chap. 6). In addition to supplying information on non-recurrent congestion, some agencies choose to provide information on recurrent congestion. In many cases, little or no additional equipment is required to support this capability. The chapter addresses the methodologies for generating this information, and discusses how it provides a modest level of benefits that result from knowledge of traffic variations during normal capacity conditions.
- Entry ramp control. Management approaches include entry ramp closure and bypass of entry ramp meters by high-occupancy vehicles. Chapter 7 covers ramp metering, the most commonly used entry ramp control strategy. Guidance is provided to determine whether ramps are suitable for metering. The ability of metering to improve merge characteristics and increase capacity is covered as it the use of metering to control access to the freeway's mainline. Basic strategies include restrictive and non-restrictive metering and their effects on ramp queues and diversion. Sub-strategies include pretimed and traffic-responsive metering as well as isolated and system-wide metering. Design issues, impacts of traffic diversion and accommodations that may be necessary to achieve motorist acceptance of ramp metering are described and a model for obtaining benefits is provided.
- Active transportation and demand management. Strategies to more intensively control lane use and vehicle speeds during incident or congested periods of operation have recently been the focus of a number of ITS projects and are discussed in Chap. 10.
- Chapter 11 discusses transportation corridor management and operations. Managed corridors better utilize all of the highway facilities and modes available, particularly under incident or weather related conditions.

Functional design alternatives may differ in the following ways:

- Different selections of the management strategies identified above and different choices of sub-strategies (e.g. type of ramp metering and ramps to be metered and motorist messaging strategies).
- Intensity of implementation (e.g. average number of CCTV cameras, detector stations and changeable message signs per mile of roadway).
- Types of services provided by the transportation management center such as hours of operation, and interaction with other agencies such as transit and emergency responders.

Chapter 8 discusses the support provided for the following functions by transportation management centers:

- Support of emergency management services.
- Provision of information to motorists.
- Operation of ramp meters.
- Operation of service patrols.
- Coordination of traffic signals with freeway and corridor operations.
- Provision of weather related information to motorists.
- Coordination of traffic management centers on a regional and statewide basis.

The chapter describes methods for establishing information pathways among stakeholders, and provides an example of how the flows that are required by a regional ITS architecture may be implemented. The functions of the INFORM Traffic Management Center, a TMC in a major metropolitan area, illustrates the application of the concepts in the chapter. Methodologies for coordinating the activities of TMCs and other management centers are described.

The third task group in Fig. 1.1 leads to a recommendation for functional design. Benefit vs. cost analysis is, in many cases, the key to recommending further continuation of the project, and the design alternative to be implemented. Chapter 9 describes the steps required by this type of evaluation. Chapter 9 also discusses how traffic detector and safety information obtained by traffic management centers may be used to estimate ITS benefits.

A website containing worksheets to support several methodologies discussed in the book is available. The use of these worksheets is described in the relevant chapters. Chapter 12 identifies these worksheets and provides a brief description of their application.

Chapter 13 discusses the relationship of ITS to connected vehicles. ITS related connected vehicle data links, services and motorist displays are described. The USDOT connected vehicle program is introduced.

References

1. National ITS Architecture V7.0. http://www.iteris.com/itsarch/ Online 3 Sept 2014
2. California Department of Transportation and Federal Highway Administration (2009) Systems engineering guidebook for ITS, version 3.0

Chapter 2
Cost Effective Design Processes

Abstract This chapter discusses the following processes in the design and life-cycle operation of a freeway ITS project:

- Systems engineering requirements for federal aid projects, and the adaptation of these requirements to the design and project development process used by many agencies.
- Objectives for freeway management systems and their relationship to project benefits.
- Methodologies for the evaluation of design alternatives, project feasibility and project life-cycle evaluation.

2.1 Systems Engineering

2.1.1 Systems Engineering Requirements for Federal Aid Projects

Part 940 of Title 23 of the Code of Federal Regulations (23CFR940) describes the requirements for receiving federal aid. Key provisions include the availability of a Regional ITS Architecture and a project-based systems engineering analysis. The regulation states that the regional ITS architecture comprises a regional framework for insuring institutional agreement and technical integration for the implementation of ITS projects or groups of projects. To qualify for federal aid, ITS projects must conform to the National ITS Architecture [1], a framework on which the Regional ITS Architecture is based. The Regional ITS Architecture includes:

- Development of operational concepts and agreements among the participating regional agencies and stakeholders.
- System functional requirements.
- Interface requirements and information exchanges with planned and existing systems.
- Identification of ITS standards.
- Sequence of projects required for implementation.

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A project-level ITS architecture that is coordinated with the Regional ITS Architecture is also required by 23CFR940. The systems engineering analysis for the project level architecture includes as a minimum:

- Identification of the portions of the Regional ITS architecture being implemented, and identification of cognizant agencies and responsibilities.
- Definition of requirements.
- Analysis of alternative system configurations and technologies.
- Procurement options.
- Identification of applicable ITS standards and testing procedures.
- Procedures and resources necessary for operation and management of the system.

2.1.2 Systems Engineering as a Life-Cycle Process

The concept of systems engineering developed significantly in the 1960s with the advent of large military and space systems. It represents the amalgamation of a number of engineering disciplines together with economics, human factors, goal setting and evaluation techniques [2].

The International Council on Systems Engineering (INCOSE) defines Systems Engineering as follows [3]:

> Systems Engineering is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem.

Systems engineering practices differ considerably depending on the application. Advanced military systems, for example emphasize development of technology, while ITS design decisions principally utilize existing components and adaptations of existing software. The Systems Engineering Guidebook for ITS [4] provides project guidance for implementation by applying the Vee technical development model (Fig. 2.1). The Guidebook indicates that the items in the Vee diagram ranging from Concept Exploration through System Requirements are influenced by the Regional ITS Architecture.

A key element in the Vee diagram is the Concept of Operations (CONOPS). The objectives of the CONOPS are to document the total environment and use of the system from the point of view of the stakeholders. The Guidebook provides the template shown in Table 2.1 to assist in CONOPS development.

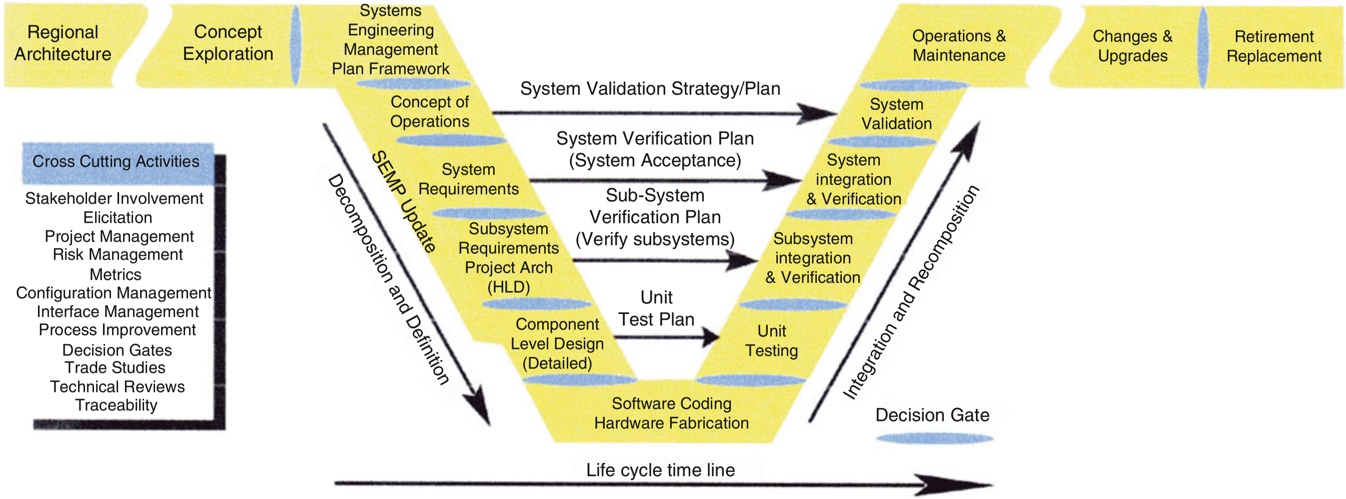

Fig. 2.1 Vee technical development model

Table 2.1 Template for concept of operations

Section	Contents
Title page	The title page should follow the Transportation Agency procedures or style guide At a minimum, it should contain the following information: • CONCEPT OF OPERATIONS FOR THE [insert name of project] AND [insert name of transportation agency] • Contract number • Date that the document was formally approved • The organization responsible for preparing the document • Internal document control number, if available • Revision version and date issued
1.0 Purpose of document	This section is a brief statement of the purpose of this document. It is a description and rationale of the expected operations of the system under development. It is a vehicle for stakeholder discussion and consensus to ensure that the system that is built is operationally feasible. This will briefly describe contents, intention, and audience. One or two paragraphs will suffice
2.0 Scope of project	This short section gives a brief overview of the system to be built. It includes its purpose and a high-level description. It describes what area will be covered and which agencies will be involved, either directly or through interfaces. One or two paragraphs will suffice
3.0 Referenced documents	This optional section is a place to list any supporting documentation used and other resources that are useful in understanding the operations of the system. This could include any documentation of current operations and any strategic plans that drive the goals of the system under development
4.0 Background	Here is a brief description of the current system or situation, how it is used currently, and its drawbacks and limitations. This leads into the reasons for the proposed development and the general approach to improving the system. This is followed by a discussion of the nature of the planned changes and a justification for them
5.0 Concept for the proposed system	This section describes the concept exploration. It starts with a list and description of the alternative concepts examined. The evaluation and assessment of each alternative follows. This leads into the justification for the selected approach. The operational concept for that selected approach is described here. This is not a design, but a high-level, conceptual, operational description. It uses only as much detail as needed to be able to develop meaningful scenarios. In particular, if alternative approaches differ in terms of which agency does what, that will need to be resolved and described. An example would be the question of whether or not a regional signal system will have centralized control
6.0 User-oriented operational description	This section focuses on how the goals and objectives are accomplished currently. Specifically, it describes strategies, tactics, policies, and constraints. This is where the stakeholders are described. It includes who users are and what the users do. Specifically, it covers when, and in what order, operations take place, personnel capabilities, organizational structures, personnel and inter-agency interactions, and types of activities. This may also include operational process models in terms of sequence and interrelationships
7.0 Operational needs	Here is a description of the vision, goals and objectives, and personnel needs that drive the requirements for the system. Specifically, this describes what the system needs to do that it is not currently doing

(continued)

Table 2.1 (continued)

Section	Contents
8.0 System overview	This is an overview of the system to be developed. This describes its scope, the users of the system, what it interfaces with, its states and modes, the planned capabilities, its goals and objectives, and the system architecture. Note that the system architecture is not a design [that will be done later]. It provides a structure for describing the operations, in terms of where the operations will be carried out, and what the lines of communication will be
9.0 Operational environment	This section describes the physical operational environment in terms of facilities, equipment, computing hardware, software, personnel, operational procedures and support necessary to operate the deployed system. For example, it will describe the personnel in terms of their expected experience, skills and training, typical work hours, and other activities [e.g., driving] that must be or may be performed concurrently
10.0 Support environment	This describes the current and planned physical support environment. This includes facilities, utilities, equipment, computing hardware, software, personnel, operational procedures, maintenance, and disposal. This includes expected support from outside agencies
11.0 Operational scenarios	This is the heart of the document. Each scenario describes a sequence of events, activities carried out by the user, the system, and the environment. It specifies what triggers the sequence, who or what performs each step, when communications occur and to whom or what [e.g., a log file], and what information is being communicated. The scenarios will need to cover all normal conditions, stress conditions, failure events, maintenance, and anomalies and exceptions. There are many ways for presenting scenarios, but the important thing is that each stakeholder can clearly see what his expected role is to be
12.0 Summary of impacts	This is an analysis of the proposed system and the impacts on each of the stakeholders. It is presented from the viewpoint of each, so that they can readily understand and validate how the proposed system will impact their operations. Here is where any constraints on system development are documented. Metrics for assessing system performance are also included here
13.0 Appendices	This is a place to put a glossary, notes, and backup or background material for any of the sections. For example, it might include analysis results in support of the concept exploration

Relevant standards are the ANSI/AIAA G-043-1992 standard and IEEE Standard 1362

2.1.3 ITS Project Development

While the Vee model provides a basis for project development, many of the agencies that acquire and operate ITS traditionally use procedures that are largely based on those used for highway construction. For example, the New York State Department of Transportation (NYSDOT) develops projects, including ITS projects through a process described in the New York State Department of Transportation Project Development Manual [5]. This manual describes the following stages of project development:

- Initial Project Proposal—A preliminary description of the problem, project objectives, schedule and cost estimate. For ITS projects this is usually a brief document.

- Project Scoping Stage—Identifies conditions, needs, objectives, design criteria, feasible alternatives and cost. For ITS projects the stage usually results in a functional design for a recommended alternative and a plan for general deployment of major devices such as DMS.
- Design Stage—This stage is broken into a number of phases. A design document is prepared to summarize the results of the preliminary design phases, and the final design phases result in a set of plans, specifications and estimates (PS&E) for the project.

In order to adapt the NYSDOT project development process to ITS needs and facilitate the incorporation of federal system engineering requirements, Appendix 6 (Intelligent Transportation Systems Scoping Guidance) was incorporated into the Project Development Manual. Figure 2.2 shows an overview of the scoping guidance provided in that appendix.

Table 2.2 shows the relationship of the major NYSDOT project stages and operations functions to the Vee diagram. The identification numbers in the scoping column correspond to the processes in Fig. 2.2.

2.2 Goals, Objectives and Requirements

Systems for various technical fields are often developed to satisfy a specific set of objectives or requirements. For example, the acceptance of a newly designed airplane by an airline is often based on its performance to a set of previously agreed on specifications such as the attainment of a speed vs. altitude envelope.

ITS objectives or requirements are usually formulated from a more general set of goals established by stakeholders. The National ITS Architecture [1] defines goals in a broad manner for all ITS applications. These goals are:

- Improve the safety of the nation's surface transportation system.
- Increase the operational efficiency and capacity of the surface transportation system.
- Reduce energy consumption and environmental costs.
- Enhance present and future economic productivity of individuals, organizations and the economy as a whole.
- Enhance the personal mobility and the convenience and comfort of the surface transportation system.
- Create an environment in which the development and deployment of ITS can flourish.

For the purpose of scoping advanced traffic management systems, these general goals may be focused into general objectives for a project. An example of a candidate set of general objectives for both freeway and surface street systems is shown in Table 2.3 [5]. The objectives for a project should be selected by the stakeholders, and related to the Regional ITS Architecture. To be effectively employed, objectives should be measurable. Thus the table includes a set of possible evaluation measures. A freeway management project will typically employ a subset of these objectives.

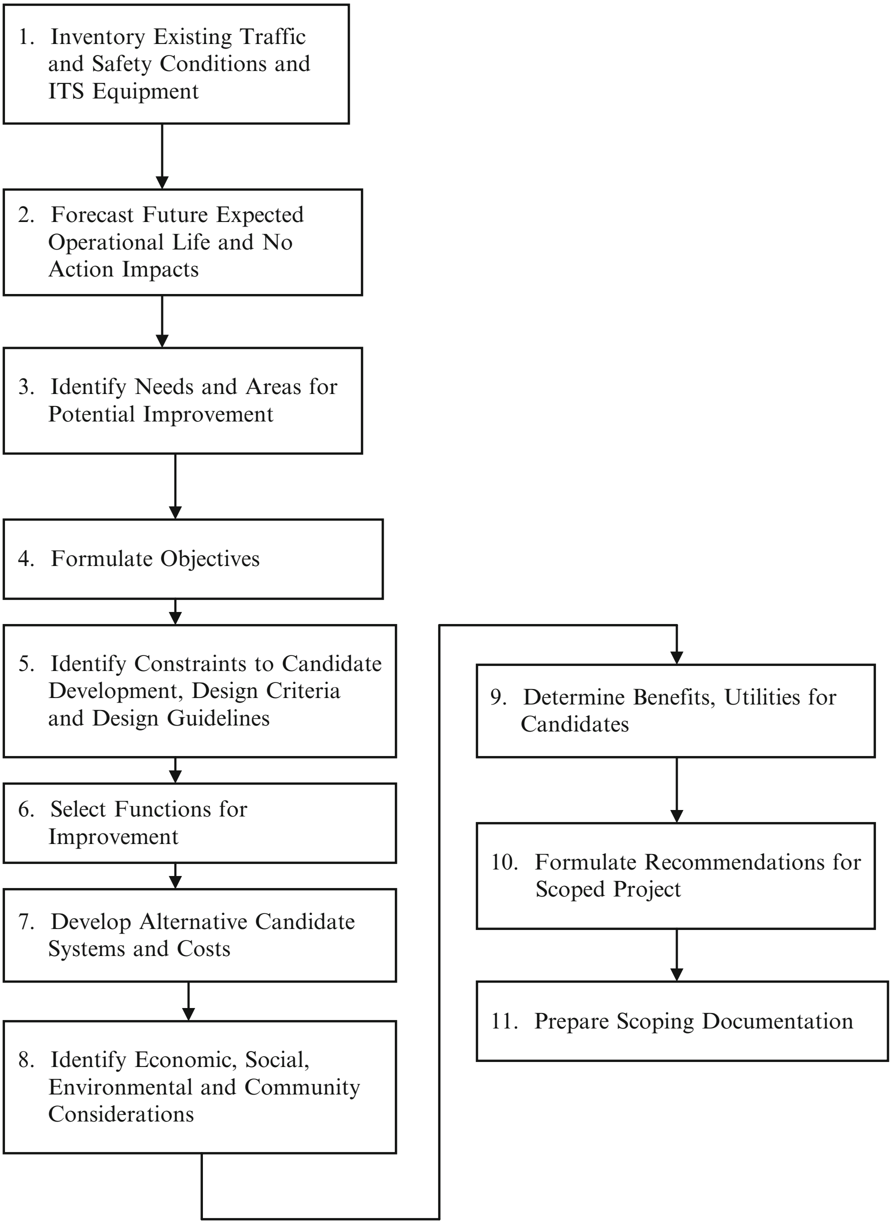

Fig. 2.2 ITS project scoping process overview [5]

Table 2.2 Relationship of NYSDOT project development and operation to systems engineering life cycle [5]

FHWA VEE diagram process	NYSDOT engineering project development and operations functions				
	Scoping	Preliminary design	Detailed design	Construction	Operations and maintenance
Concept of operations	Traffic conditions and safety inventory (1)				
	Stakeholders, participating agencies (3)				
	Objectives (4)				
	Measures of effectiveness (4)				
High level requirements	Future service life (2)				
	Constraints (5)				
	Selection of functions for improvement (6)				
	Development of alternatives (7)				
	Other considerations (8)				
	Benefits (9) Recommendations for project development (10)				
Detailed requirements		√			
High level design		√			
Detailed design			√		
Implementation				√	
Integration and test				√	
Subsystem verification				√	
System verification				√	
Operations and maintenance					√
Assessment					Performance measures from step 4

Table 2.3 General candidate objectives [5]

Objective	Possible evaluation measure
1. Reduce congestion and improve travel time	
(a) Recurrent congestion/travel time—significant section	Vehicle hours per year saved, person hours per year saved
(b) Recurrent congestion—spot	Vehicle hours per year saved, person hours per year saved
(c) Non-recurrent congestion—significant section	Vehicle hours per year saved, person hours per year saved
(d) Non-recurrent congestion—spot	Vehicle hours per year saved, person hours per year saved
2. Reduce accident rate	
(a) Over significant section	Reduction in accidents per year
(b) Spot	Reduction in accidents per year
3. Reduce emissions and fuel consumption	Reduction in grams of HC, NOX, CO per year
4. Serve as a corridor link in a wider area highway system	Provide capability for this roadway to offer meaningful diversion opportunity for incidents on another freeway that carries interregional traffic
5. Serve as a diversion route in local corridor	Provide capability for this roadway to offer meaningful diversion opportunity for incidents on another freeway or surface street that carries local or intraregional traffic
6. Special traffic management functions	
(a) Traffic monitoring for major roadway reconstruction	Provision of capability to assist in management of traffic during construction
(b) Traffic monitoring for minor roadway construction	Provision of capability to assist in management of traffic during construction
(c) High occupancy vehicles	Provision of ITS support for HOV operations
(d) Signal preemption for railroad or emergency vehicles	Reduction in accidents per year
(e) Priority for transit	Reduction in total traveler hours per year. Reduction in total grams of HC, NOX, CO per year
(f) Traffic information on roadway construction	Increase in motorists notified
(g) Motorist information on travel conditions, parking, special events, roadway weather	Increase in motorists notified
(h) Pedestrian and bicycle movement	Reduction in total traveler hours per year. Reduction in accidents per year
(i) Mobility and safety for the disabled	Annual volume of trips for the disabled. Average travel time for trip for disabled. Number of accidents per year for disabled
(j) Traffic management for future major roadway reconstruction	Provision of capability to assist in management of traffic during construction
(k) Motorist information about detour routes	Increase in motorists notified

(continued)

Table 2.3 (continued)

Objective	Possible evaluation measure
7. Interoperability of ITS	
(a) Operating efficiency	Regional vehicle hours per year saved, person hours per year saved. Regional reduction in accidents per year
(b) Stakeholder involvement	Regional vehicle hours per year saved, person hours per year saved. Regional reduction in accidents per year
8. Improvement of NYSDOT operations	
(a) Planning and/or evaluation data collection	Annual dollar savings by elimination of other forms of data collection. Provision of data not previously available
(b) ITS equipment monitoring	Vehicle hours per year saved, person hours per year saved, reduction in accidents per year as a result of faster maintenance. Cost savings to operating agency
(c) Efficiency of operations	Annual cost reduction to operating agency in dollars
(d) Reduction of maintenance cost	Annual cost reduction to operating agency in dollars
(e) Ability to operate signals during power outages	Vehicle hours per year saved, person hours per year saved, reduction in accidents per year as a result of reduced signal outage time
(f) Operational availability of ITS	% of time TMC available, % of field devices available, monitorable and controllable
9. Provide assistance to disabled motorists	Vehicle hours per year saved, person hours per year saved, reduction in accidents per year
10. Provide travel information related to tourism	Increase in motorists notified
11. Security	
(a) Transportation system security	Reduction in cost of vandalized equipment
(b) Emergency operation	Vehicle hours per year saved, person hours per year saved, reduction in accidents per year as a result of increased number of operating hours per year
(c) Information system security	Reduction in number of unauthorized operations per year, amount of data lost per year
12. Commercial vehicle operations	Annual cost savings to industry Annual cost savings to operating authority

In establishing general project objectives, stakeholders should be aware of the relative levels of benefits that ITS treatments are likely to provide. For example, Fig. 2.3 shows the relative benefits achieved by several ITS treatments for a typical freeway whose peak period volume-to-capacity ratio is generally between 0.93 and 0.96. It is seen that objectives that result in the in the reduction of non-recurrent congestion through improvement of incident clearance time are likely to provide the greatest benefits.

To assist in evaluating design alternatives, after selection of the subset of general objectives used for the project, it is useful to further tailor this subset to the project,

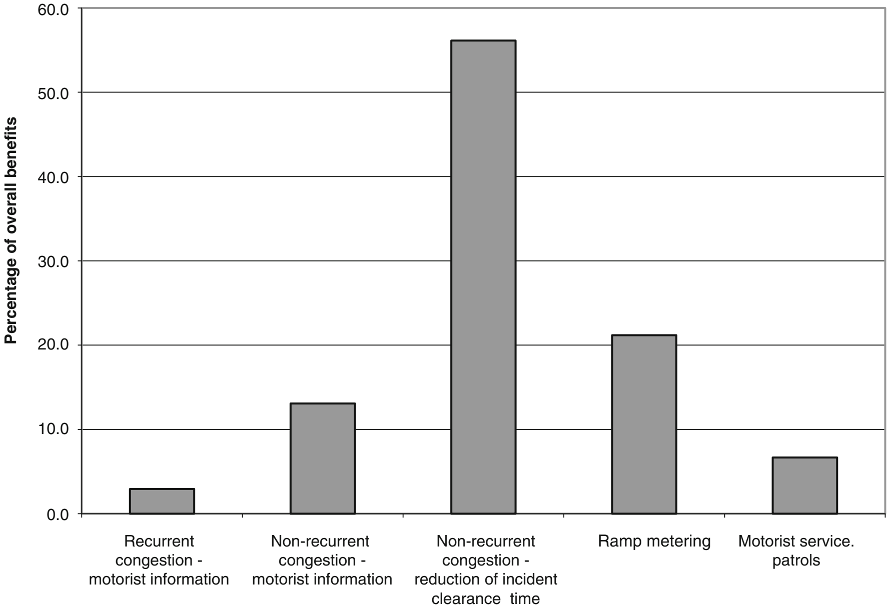

Fig. 2.3 Typical relative improvement for several ITS measures

and to provide additional detail. Accordingly specific evaluation measures are selected and objectives are quantified to the extent possible. Exploiting quantitative benefit values to express objectives is important because it provides both system designers as well as decision makers with a means to identify expectations, estimate the scale and scope of the project and determine its utility relative to other candidate projects. It also provides a basis for assessing the effectiveness of the design. The values should be sufficiently high to make a meaningful impact, but must also be achievable by technologies and resources available for the project. Many of the models described in this book and the RITA ITS benefits data base [6] provide guidance for the selection of values for objectives. We use the term *detailed project objectives* instead of *requirements* in order to provide some flexibility for stakeholder review and reassessment based on project evaluation. Other features of detailed objectives include the following [7]:

- Detailed objective should stand alone, i.e. it should not require the reader to look at additional text.
- Detailed objective should be open to only one interpretation.
- Detailed objective should be verifiable through inspection, analysis or test.

2.3 Evaluation Methodologies

Evaluation methodologies may be employed for the following major functions in the life cycle process:

- Design evaluations to select the most appropriate design alternatives and to estimate the expected performance of these alternatives relative to the detailed objectives. These *prospective* evaluations (Sect. 3.2) may be performed using the models discussed in this book and by ITS evaluation models.
- Project performance evaluations are *retrospective* evaluations (Sect. 3.2) performed to determine actual system performance and cost relative to expectations. They may be executed by field measurements, measurements made by system detectors, accident statistics and actual cost information. In some cases simulation is used. These evaluations not only evaluate the system design and operation but also provide feedback for improving the operation of the current project and provide guidance for the functional design of future projects.

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Chapter 3
Functional ITS Design Issues

Abstract This chapter discusses a number of topics that form the conceptual framework and the building blocks for developing ITS designs as described in the chapters that follow. Topics include:

- *Relationship of ITS design approaches to general transportation planning principles*. The impacts of volume, speed, density, capacity issues, recurrent and non-recurrent congestion are introduced and discussed. Insights into the decisions that influence how motorists make diversion choices to alternate routes are presented. The effect of message strength on diversion probability is described.
- *Performance and benefit assessment*. Performance measures for evaluation of ITS design alternatives are needed. Marginal analysis and multi-attribute utility analysis are described and illustrated as examples of alternatives to the use of traditional cost benefit analysis.
- *Alternatives for functional analysis*. The need for an alternatives analysis is presented along with constraints on the selection of alternatives is described. A matrix identifying the relationship of ITS management concepts to project objectives is presented in order to facilitate consideration of the appropriate ITS treatment to achieve these objectives.

3.1 Relationship of ITS Design to General Transportation Planning Principles

ITS functions and designs must be consistent with general traffic engineering and transportation planning principles. The following sections describe a number of these principles that affect ITS concept design.

3.1.1 General Traffic Flow Relationships

3.1.1.1 Relationship of Volume, Speed and Traffic Density

This relationship is provided in various texts (for example see May [1]) as

$$q = k \cdot u \tag{3.1}$$

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where

q = volume (vehicles per hour per lane)
k = density or concentration (vehicles per mile per lane)
u = space-mean-speed (miles per hour)

Space-mean-speed-is the average speed of vehicles measured over a short distance, for example by converting the travel times of the vehicles measured over the distance. Probe traffic detection techniques (see Sect. 4.5.1.3) measure space-mean-speed. Time-mean-speed (u_T) is the average speed of vehicles measured at a point, and may be measured by point detectors (Sect. 4.5.1.3). These quantities are statistically related [2]. An empirical relationship is [3]:

$$u = 1.026 \cdot u_T - 1.89 \tag{3.2}$$

where u and u_T are in miles per hour. Time-mean-speed exceeds space-mean-speed with the largest divergence at low speeds.

3.1.1.2 Capacity

Capacity is defined as "the maximum sustained 15-min flow rate, expressed in passenger cars per hour per lane, that can be accommodated by a uniform freeway segment under prevailing traffic and roadway conditions in one direction of flow [4]." HCM 2000 [4] presents the suggested speed-flow relationship shown in Fig. 3.1.

The figure shows three flow regimes for basic freeway segments. In the undersaturated regime, as traffic volume increases, speed decreases slightly until the capacity is reached (2,250–2,400 passenger vehicles per hour per lane (pc/h/ln) depending on the free flow speed). Chapter 7 discusses the possibility of increasing this capacity by smoothing ramp entry flows. The queue discharge regime represents

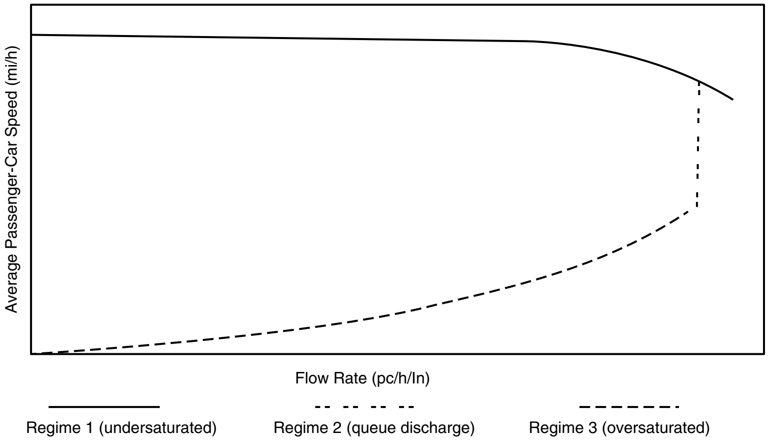

Fig. 3.1 Speed vs. flow rate [4]

the flow resulting from a bottleneck (when freeway demand exceeds capacity). Flow rates of from 2,000 to 2,300 pc/h/ln are usually experienced in this regime for basic freeway sections.

Oversaturated flow is influenced by the effects of a downstream bottleneck (i.e. by flow into existing congested conditions). Low speeds and high values of density characterize the congestion in this regime.

3.1.2 Shock Waves

Shock waves are defined as boundary conditions in the time-space domain that demark a discontinuity in flow-density conditions [1]. The propagation speeds of shock waves often determine the time it takes to detect an incident with ITS devices. Section 4.5.1.3 discusses these issues.

3.1.3 Classification of Congestion

Congestion is travel time or delay in excess of that normally incurred under light or free-flow travel conditions. Unacceptable congestion is travel time or delay in excess of an agreed-upon norm. The agreed-upon norm may vary by type of transportation facility, travel mode, geographic location, and time of day, and should be derived taking into account the expectations for each portion of the transportation system as influenced by community input and technical considerations [5]. Many transportation agencies use a “D” level of service during peak hours in urban areas as the basis for acceptable operation and therefore as the baseline for defining delay.

Congestion is often classified as either recurrent or non-recurrent. The type of congestion depends on whether the capacity or the demand factor is out of balance.

- **Recurrent** congestion occurs when demand increases beyond the normally available capacity. It usually is associated with the morning and afternoon work commutes, when demand reaches a level that overwhelms the freeway and traffic flow deteriorates to unstable stop-and-go conditions [5]. The role of ITS in reducing recurrent congestion is discussed in Sect. 3.1.5 and in Chap. 6.
- **Non-recurrent** congestion results from a temporary decrease in capacity while the demand remains unchanged. This kind of congestion usually results when the freeway capacity becomes temporarily restricted. A stopped vehicle, for example, can take a lane out of service, however the same number of vehicles require passage. Speed and volume drop until the lane is reopened, and then they return to full capacity. Capacity can also be decreased by weather events and events near the travel way (i.e., “rubber necking”), leading to non-recurrent congestion and reduced reliability of the entire transportation system [1]. ITS techniques to reduce the effect of non-recurrent information include reducing the time to clear an incident (Chap. 4) and motorist diversion (Sect. 3.1.4 and Chap. 5).

3.1.4 Diversion for Non-Recurrent Congestion

3.1.4.1 Diversion Decisions by Motorists

The motorist normally selects a route based on the comparative utility (travel time and other factors) of alternative route choices. Traffic assignment models estimate the choices by user class. Other factors being equal, the freeway route is selected by most users under normal conditions.

When an incident has happened on the freeway and motorists are aware of a problem, some percentage of motorists using the freeway will choose to divert to an alternate route.

Individual diversion decisions are made on the basis of perceived time saved or other factors such as trip reliability based on information available to the motorists from various sources, along with their perception of the traffic environment. Studies show that the propensity for a motorist to divert depends on the "strength" of the message. Table 3.1 shows an example of increasing message strength [6].

Operating agencies may consider the degree of diversion desired in formulating message displays (see Chap. 5).

Estimates and models have been developed that show the probability of diversion based on the perception of time saved. An early example of an assignment curve is shown in Fig. 3.2.

Using data from Ullman et al. [8], Fig. 3.3 depicts the diversion percentage from a freeway to a surface street for motorists receiving a message of strength 8 in Table 3.1 for a particular set of circumstances. The slope of the curve for time savings for less than 20 min is approximately 6 % diversion increase per minute of time saved.

Another example of the use of message strength to result in diversion is provided by Jindahra and Choocharukul [9]. Their survey considered the following types of message combinations:

- Quantitative delay (e.g. 15 min)
- Cause
- Suggested route
- Quantitative delay plus suggested route

Table 3.1 Example of increasing message strength [6]

Message type	Message content
1	Occurrence of accident only
2	Location of the accident only
3	Expected delay only
4	The best detour strategy only
5	Location of the accident and the best detour strategy
6	Location of the accident and the expected delay
7	Expected delay and the best detour strategy
8	Location of the accident, expected delay and the best detour strategy

Source: Ref. [6]. Reproduced with permission of the Transportation Research Board

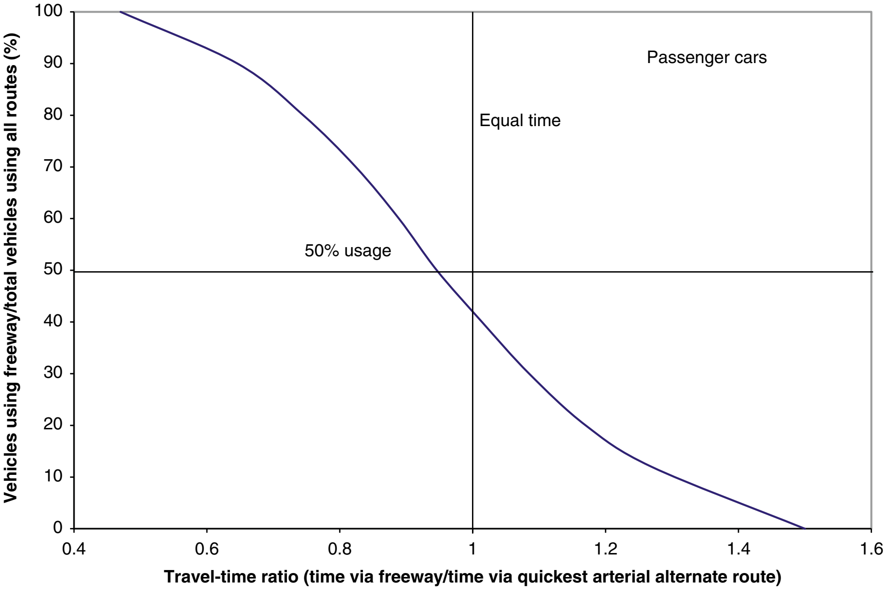

Fig. 3.2 Bureau of Public Roads diversion curve [7]

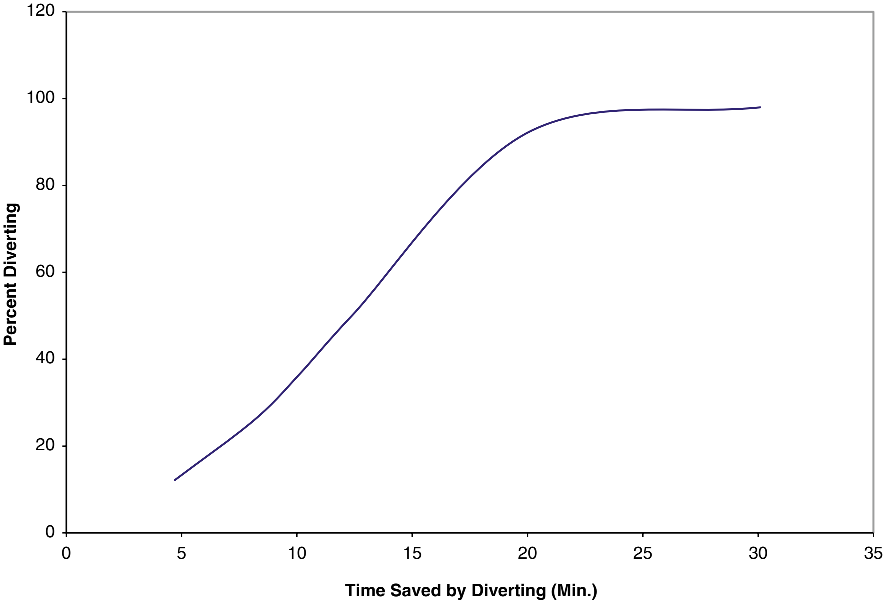

Fig. 3.3 Diversion from freeway to surface street [8] (redrawn)

- Qualitative delay (e.g. expected long delay)
- Cause plus quantitative delay
- Quantitative delay plus suggested route
- Cause plus qualitative delay
- Cause plus suggested route

The responses were placed into three categories:

- Motorist likely to stay on current route
- Motorist is indecisive
- Motorist likely to divert

Figure 3.4 shows a re-plotting of the data in the reference and indicates the substantial effect of message content on diversion.

Schroeder and Demetsky [10] correlated the effects of message strength with diversion fraction by using traffic detector stations to measure diversion fraction. Table 3.2 shows an example of their results.

Deeter [11] reports on surveys that examined the effect of posted travel times longer than normal as the basis for diversion. An example of the results of a survey in the Seattle area is shown in Table 3.3.

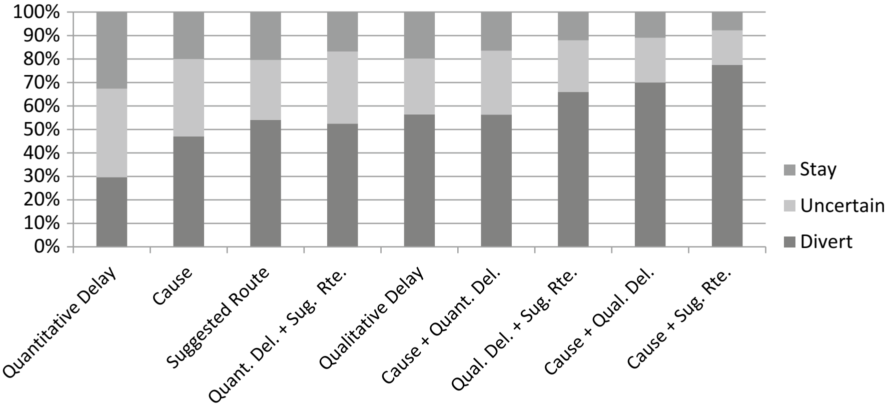

Fig. 3.4 Effect of message strength on diversion probability

Table 3.2 Percent diversion for message types

Message type	Example of message	% diversion
0: No incident		
1: No guidance provided	"ACCIDENT AT EXIT 73, EXPECT DELAYS"	5.0
2: Alternate route recommended	"ACCIDENT AT EXIT 75, EXPECT DELAYS, USE ALT ROUTE"	9.3
3: Specific major alternate route recommended	"ACCIDENT AT EXIT 75, THRU TRAFFIC USE I-295 SOUTH"	11.3

Table 3.3 Minutes over the typical travel time that drivers divert

Minutes over the typical travel time	Percent of survey respondents that described each threshold (%)
5	16
10	37
15	26
20	11
30	11

Different results may be obtained depending on the spacing of the dynamic message signs used to convey this information. Diversion fraction DF at an exit ramp may be defined as follows:

$$\mathrm{DF} = \left(\mathrm{V}_{\mathrm{ED}} - \mathrm{V}_{\mathrm{EW}}\right) / \mathrm{V}_{\mathrm{A}} \tag{3.3}$$

where

V_A is the volume upstream of the exit ramp when
V_{ED} is the exit ramp volume when diversion is implemented at this ramp
V_{EW} is the exit ramp volume when diversion is not implemented at this ramp

Diversion is discussed further in Chap. 5. Although the research indicates that the diversion fraction increases with increasing message strength, the diversion fractions for a particular message strength appear to vary among installations. They also vary with time of day and season for a single location [10]. Section 5.1.3 further discusses the control of diversion fraction.

3.1.4.2 System-Wide Impacts of Diversion

If traffic information on an incident is provided before the start of the trip or early in the trip, motorists may choose to:

- Select an alternate route
- Select an alternative time for the trip
- Select a different mode

For most incidents, information reaching the motorist during his trip on the freeway will provide the motivation to divert, most often to a surface street. The previous section discussed likely motorist responses to this information. This section discusses system considerations in providing motorist information.

From a transportation system perspective, the objective of diversion is to minimize delay in the corridor and/or maximize mobility (throughput) in the corridor. While diversion, if properly implemented, will reduce delay to the vehicles diverting and reduce delay to the freeway vehicles that do not divert, it will incur additional delay to the vehicles that normally use the diversion route. Some of these vehicles may, in turn, divert to a roadway with a lower classification rating (e.g. from a principal arterial street to a minor arterial street) generally increasing the delay to these vehicles.

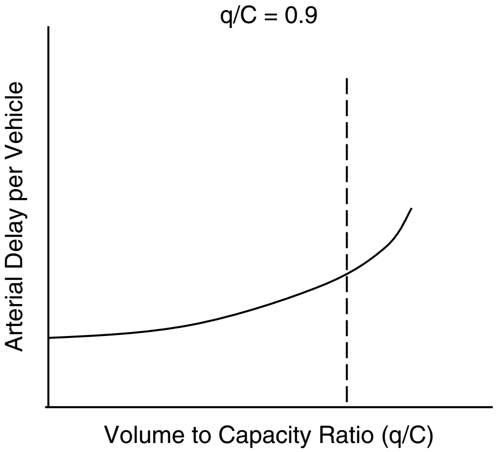

Fig. 3.5 Relationship of arterial delay to volume-to-capacity ratio

Most traffic management centers manage the provision of motorist information by means of operating procedures. These procedures reflect the policies of the agency and contain message structure guidelines as well as the circumstances that require messages. Dudek [12] provides a comprehensive discussion of these factors as well as a number of examples of policy statements for various aspects of message development and changeable message sign operation. For example, when explicit route guidance is provided:

- The DMS operator has current and continuously-updated knowledge of the traffic conditions on the alternative route; and
- The alternative route will result in a significant savings in time for the diverted motorists.

This policy is designed to apply to explicit diversion messages (e.g. message types 4, 5, 7, and 8 in Table 3.1). Although the other message types do not explicitly recommend diversion, they do, in fact, result in diversion, and the TMC operating procedures should reflect this.

Improvements in delay to non-diverting freeway traffic may be significant, even for relatively low levels of diversion. This is further discussed in Chap. 5.

Even low levels of freeway diversion may cause significant increase in the volume-to-capacity ratio on surface street alternates. When this volume-to-capacity ratio exceeds 0.9, the delay increases exponentially as shown in Fig. 3.5. Operating procedures must ensure that arterial delay does not become excessive.

3.1.5 Recurrent Congestion

Recurrent congestion is characterized by congestion that repeats on a day-to-day basis at the same locations, usually during peak traffic periods. Most motorists are familiar with traffic conditions on the freeway and on its alternates during these periods. Under these conditions, traffic distribution on the network is determined by Wardrop's Principles [13]. These principles are summarized as follows:

- Wardrops's First Principle (user equilibrium) indicates that the trip costs on all routes actually used are less than those that would occur if a vehicle used any unused route. Thus users choose the route that minimizes their own travel time.
- Wardrop's Second Principle (system equilibrium) indicates that cost of using the system is at a minimum. Users distribute themselves so that the average travel time on each origin-destination pair is equal for all users.

The costs include travel time and fuel consumption as well as other costs that might be perceived by drivers. According to these principles, there is nothing to be gained by selecting an alternate route, as such a selection will lead to a higher cost. These principles are based on the assumption that motorists are generally familiar with the alternate routes and the general traffic conditions associated with these routes. Knowledge of traffic conditions under recurrent congestion is markedly different from non-recurrent congestion. In the latter case, and without ITS motorist information provisions, the motorist has incomplete knowledge of network traffic conditions.

In recent years, traffic management centers have increasingly used travel time messages on DMS. These messages are supplemented by others when incidents occur.

Measures may be considered to increase traveler throughput under recurrent congestion by biasing the delays or motorists' cost in the network. Measures such as restrictive ramp metering and lane or roadway use controls provide motorists with an altered set of link travel times, and in some cases altered out of pocket cost. The application of Wardrop's principles to this new configuration will alter the travel pattern.

3.2 Performance and Benefit Assessment

Two types of evaluations may be conducted:

- Prospective Evaluations—During the project scoping process, prospective evaluations assist in deciding whether the system should be implemented, and provide the basis for the evaluation of design alternatives. As described in Chap. 2, Title 23 Section 940.11 of the Code of Federal Regulations (CFR) requires the consideration of design alternatives for a project to be considered for federal aid.
- Retrospective Evaluations—Performed after system installation and operation, retrospective evaluations provide the basis for developing "lessons learned" and for the future improvement of system design and operation.

Reference [14] provides an in-depth discussion of the issues concerning the selection of measures for freeway applications. Table 3.4 [15] provides a set of recommended measures for highway applications. Gordon [16] describes methodologies for developing many of the measures that are used for ITS evaluations.

3.2.1 *Performance Measures to Facilitate System Design*

This book is primarily concerned with development and evaluation of design alternatives, Therefore it emphasizes economic benefits and costs for design and prospective evaluation purposes.

Many of the measures in Table 3.4 represent different ways of expressing the same economic benefit to be achieved by ITS. In order to be useful for the purposes

Table 3.4 Recommended performance measures for highways [15]

Outcomes (operational) performance measures
• Quantity of travel (users' perspectives)
– Person-miles traveled
– Truck-miles traveled
– VMT
– Persons moved
– Trucks moved
– Vehicles moved
• Quality of travel (users' perspectives)
– Average speed weighted by person-miles traveled
– Average door-to-door travel time
– Travel time predictability
– Travel time reliability (of trips that arrive in acceptable time)
– Average delay (total, recurring, and incident-based)
– Level of Service (LOS)
• Utilization of the system (agency's perspective)
– Percent of system heavily congested (LOS E or F)
– Density (passenger cars per hour per lane)
– Percentage of travel heavily congested
– V/C ratio
– Queuing (frequency and length)
– Percent of miles operating in desired speed range
– Vehicle occupancy (persons per vehicle)
– Duration of congestion (lane-mile-hours at LOS E or F)
• Safety
– Incident rate by severity (e.g., fatal, injury) and type (e.g., crash, weather)
• Incidents
– Incident induced delay
– Evacuation clearance time
Outputs (agency performance)
• Incident response time by type of incident
• Toll revenue
• Bridge condition
• Pavement condition
• Percent of ITS equipment operational

of evaluating alternatives and developing recommendations for design implementation, it is necessary to select a subset of these measures that facilitates the evaluation of the following categories:

- Economic benefits. For evaluation purposes, delay reduction, safety and fuel consumption will be considered in this category.
- Environmental Benefits (emissions).
- Mobility. This represents the quantity of service provided.
- Public satisfaction with ITS treatments.

To provide a basis evaluating alternatives and developing recommendations, it is necessary that the measures selected include all of the benefits in a category, but do not include the benefit more than once. For example, the measures selected for economic evaluations should include an estimate of all of the economic benefits but should not include the same effect (e.g. travel time and delay) more than once. Table 3.5 suggests a reduced set of measures that may be used to evaluate system designs.

Measures intended for design evaluations are often based on analytic or simulation processes, whereas ongoing evaluations or before and after studies generally utilize measured parameters. *Economic benefit* analysis for transportation systems is often the key component of a design evaluation. It usually features a benefit vs. cost analysis [17]. The benefit to cost ratio is often a key indicator for the selection of the design alternative and for the decision to implement the project. Cost benefit analysis is discussed in Chap. 9.

Simple benefit to cost ratio comparisons, however, often fail to provide a complete basis for decision making. For example, consider Alternative 1 and Alternative 2 in the hypothetical example of Table 3.6. Although the benefit-to-cost ratio for Alternative 1 is better, if the project objective is to save 600,000 vehicle hours, Alternative 2 comes much closer to satisfying this objective while maintaining a

Table 3.5 Measures suggested for prospective ITS evaluation

Category	Measure	Possible units
Economic benefits	Reduction in passenger vehicle delay	Vehicle hours per year
	Reduction in commercial vehicle delay	Vehicle hours per year
	Reduction in commercial vehicle inventory delay	Vehicle hours per year
	Reduction in fuel consumption	Gallons per year
	Reduction in accidents	Accidents per year
Environmental	Carbon monoxide	Pounds per year
	Oxides of nitrogen	Pounds per year
	Volatile organic compounds	Pounds per year
	Carbon dioxide	Pounds per year
User satisfaction	Satisfaction with ITS treatment	$KS \cdot NT$

Where

KS is a satisfaction rating on a scale of −1.0 to +1.0

NT is the number of travelers to whom the issue applies

Table 3.6 Example of marginal analysis

	Alternative 1	Alternative 2	Marginal parameters of alternative 2 relative to alternative 1
Annual vehicle hours saved	250,000	500,000	250,000
Annual benefit	$5 M	$10 M	$5 M
Annualized project cost	$1 M	$2.5 M	$1.5 M
Benefit-to-cost ratio	5:1	4:1	3.33:1
Net benefit	$4 M	$7.5 M	$3.5 M
% of project objective satisfied	41.6	83.3	Not applicable

satisfactory marginal benefit to cost ratio (i.e. significantly in excess of 1) for the additional investment. The introduction of the concepts of *marginal values* and *percentage of objective satisfied* provides an important basis for project evaluation.

Travel time variation is an increasing popular ITS measure, however because of the difficulty in obtaining this quantity in a manner other than direct measurement, it is more suitable for retrospective evaluation rather than prospective evaluation.

While some projects or agencies ascribe monetary values to *environmental benefits*, these benefits may also be a key project objective, as they reduce emissions. This is particularly important in locations that do not conform to the national ambient air quality standard.

The economic and environmental measures do not account for the change in manifest demand that results from some ITS treatments. *Throughput* measures the facility's capability to service demand [18]. Sometimes termed *productivity* [19], it represents the vehicle miles that a facility can accommodate during a peak hour or peak period. The effect of the project on the change in this measure is difficult to anticipate in advance of implementation thus the measure is best used for retrospective evaluations.

Since the user is the ultimate judge of the perception of ITS effectiveness and value, the system designer must consider the factors that the user deems important. While these factors may be difficult to estimate on a prospective basis, previous studies provide some indication as to how *user satisfaction* may be rated. While Chaps. 5–7 discuss user satisfaction for different ITS treatments, some general issues are discussed below.

ITS treatments such as motorist information and motorist service patrols are generally well received by the public because no class of motorists is penalized by these ITS treatments. Motorists feel that these treatments improve their trip reliability and their sense of control [20]. Rating scales based on surveys may be used to quantify user satisfaction for this these types of ITS treatments.

Other treatments such as ramp metering and road pricing or restricted road use may provide improved mobility for some users, and on balance for the whole system, while providing reduced mobility for other users. The transportation system operator must consider how prospective treatments affect different users. Levinson et al. [19] describe an approach to measuring *equity*. The Lorenz Curve (Fig. 3.6)

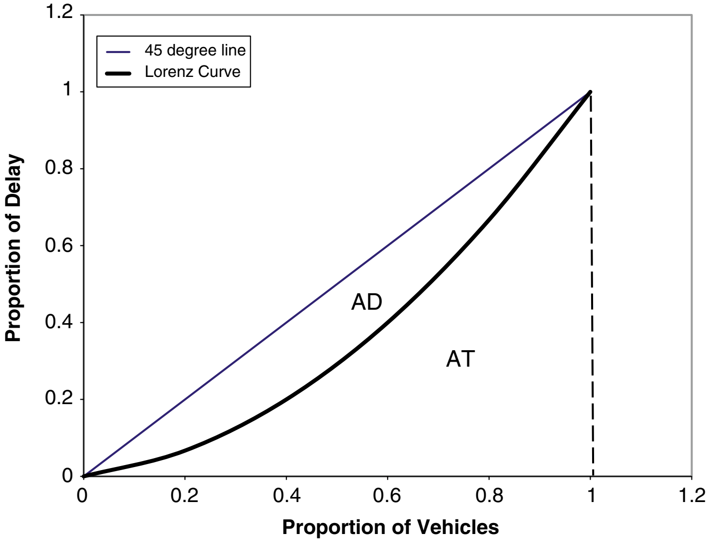

Fig. 3.6 Example of Lorenz Curve for a metered freeway entry ramp

identifies the relationship between the proportion of delay and the proportion of vehicles incurring the delay. Thus area AD in the figure identifies the users that are relatively disbenefitted by the treatment. The Gini coefficient is computed as

$$G = AD/(AD + AT) \tag{3.4}$$

It quantifies the level of inequality among users. Levinson et al. [19] describes a methodology for computing the Gini coefficient.

As an example of the importance of user satisfaction in ITS design and operation, the control strategy for ramp meter rates in Minnesota was revised in order to provide lower delays to entering vehicles, even at the expense of overall increases in delay [19].

3.2.2 *Performance Measures and ITS Planning*

Planning agencies such as metropolitan planning organizations (MPOs) are required to select and prioritize projects from a number of alternatives that may include different types of projects and, perhaps, different traveler classes. These projects may affect benefit categories such as those shown in Table 3.5 in different ways. *Multi-attribute utility analysis* is one methodology for comparing such projects [21, 22]. It enables stakeholders with different interests and responsibilities to proactively participate in the planning process. A simple example that compares and depicts the benefits from a candidate set of ITS projects is discussed below.

Table 3.7 Utility values for selected ITS classes

Alternative ITS project classes (S)[a]	Attribute (RIA)		
	1. Traveler cost reduced (0.6)	2. Emissions reduced (0.2)	3. Traveler satisfaction (0.2)
1. Improved incident clearance	High reduction (0.9)	Proportional to fuel reduced (0.9)	Little effect observed by motorists (0.2)
2. Restrictive ramp metering	Moderate to high reduction (0.6)	Proportional to fuel reduced (0.6)	May be significant opposition because of ramp delays and local impacts resulting from diverted traffic (0.1)
3. Non-restrictive ramp metering	Lower than candidate 2 (.3)	Proportional to fuel reduced (0.3)	Reduced opposition compared to Candidate B (0.3)
4. Motorist information	Moderate (0.4)	Proportional to fuel reduced (0.4)	Generally well accepted by public (0.8)
5. Motorist service patrol	Moderate (0.3)	Proportional to fuel reduced (0.3)	Well accepted by public (0.9)
6. Real time on-board and transit stop information	Little impact (0.1)	Little impact (0.0)	Well accepted by transit passengers (0.5)
7. Transit signal priority	Modest impact (0.3)	Little impact (0.1)	Transit time reliability improvement appreciated by transit users. Little impact on motorists (0.3)

[a] The candidate alternatives, except for candidates 6 and 7 are discussed in later chapters

This analysis uses two types of variables. RI_A denotes the relative importance of attribute A and U_{AS} represents the utility of alternative S for attribute A. RI_A may be developed by stakeholder consensus. The sum of these values for all attributes must equal unity. The attributes in the example are described by the categories shown in Table 3.5.

Table 3.7 lists the parameter values in parentheses under the attribute and utility designations. The first row of the table identifies examples of the attribute value. The following rows show examples of the utility values.

The first attribute column in Table 3.7 represents the reduction in traveler cost. Delay, fuel cost, and accidents are major components of this cost. The second attribute column represents emission reduction. As described in Chap. 4, for many ITS treatments emission reduction is proportional to motorist delay. The third attribute column is the utility for traveler satisfaction with the treatment.

Table 3.8 Multivariate utility values for example

Alternative ITS project classes (S)	Multivariate utility value (MU_S)
1. Improved incident clearance	0.76
2. Restrictive ramp metering	0.42
3. Non-restrictive ramp metering	0.30
4. Motorist information	0.48
5. Motorist service patrol	0.42
6. Real time on-board and transit stop information	0.16
7. Transit signal priority	0.26

Examples of utility values (U_{AS}) are shown in parentheses in the cells that denote the ITS treatments. Values for these measures may be obtained by simulation techniques or inferred from evaluations performed by other ITS projects. Maccubbin et al. [23] provides a compilation of ITS benefits.

The multivariate utility values for each alternative S (MU_S) are given by

$$MU_S = \sum_{A=1}^{3} RI_A \cdot U_{AS} \tag{3.5}$$

The multivariate utility analysis values for each alternative for the example are given in Table 3.8.

In most cases the utilities for alternatives selected for this analysis may be added if more than one alternative is chosen for inclusion, in some cases (e.g. candidates 2 and 3) a choice between alternatives is required.

The cost of alternatives may be treated in the following ways in connection with utility analysis:

- As an attribute. This can be done by the addition of a column in Table 3.7
- As a divisor for the MU_S values in Eq. (3.5)
- As an abscissa value in a utility vs. cost plot

In a number of cases, the alternatives may share certain ITS components, thus the cost for a combination of alternatives may be lower than for each alternative taken separately. Thus it is often desirable to define alternatives that take advantage of this. For example alternatives 1 and 4 in Table 3.8 share components such as communications and management centers.

3.3 Alternatives for Functional Design

Design alternatives are required because

- Systems engineering methodologies [23] generally require an alternatives analysis to insure that the design options are considered in the context of project objectives and constraints. A “do nothing” alternative is also usually considered and often constitutes the baseline for of benefits for the various design alternatives.

- To obtain federal aid for a project, Title 23, Section 940.11 of the Code of Federal Regulations requires the completion of a systems engineering analysis that includes alternative systems configurations and technology options to meet requirements.
- Many of the states and other agencies responsible for the design and operation of highway projects and ITS require an alternatives analysis in their project design process (see Ref. [24] for example).

Two classes of alternatives may be considered:

- *Alternative high level ITS project classes*
  As discussed in Sect. 3.2.2, constraints on regional ITS budgets may require the selection of a subset of projects from the set of alternatives. The first column of Table 3.8 describes the alternatives that were considered for the example.
- *Project class design alternatives*
  Alternatives may include the types of technologies to be included, the intensity of implementation (e.g. how many point detectors to include in a roadway section) and functional equipment placements (e.g. the best location for a dynamic message sign).

3.3.1 Design Constraints

Design constraints limit the selection of components and operations that are suitable for the project. Reference [25] provides the following discussion of constraints:

"The fulfillment of goals and the approaches to satisfy specific functional requirements are often constrained by resource, institutional and legacy issues. In some cases the necessity to resolve problems may justify the relaxation of constraints. Absent this situation, the use of constraint analysis has the potential to simplify the selection of design alternatives by eliminating alternatives lying outside constraint boundaries". Some of the more common constraints are:

Resource Constraints

- Capital funding.
- Funding for operations.
- Funding for maintenance.
- Staffing levels and capabilities.

Reference [24] identifies constraints as part of the project development process.

Federal regulations require that both long range and short range plans be financially constrained to reflect revenues reasonably expected to be available over the time period they cover [26].

Institutional Constraints

- Funding through long term planning processes.
- Requirements to use agency specific standard specifications.
- Requirements to use National ITS Architecture standards and protocols.
- Requirements to provide interoperability with other ITS in the same jurisdiction or other jurisdictions.
- General design constraints.
- Preservation of existing utilities.
- Right-of-way constraints.
- Economic, social, environmental and community considerations.

Legacy Constraints

- Requirements to use existing equipment to the extent possible.
- Requirements for new equipment to be compatible with existing equipment.

Early identification will result in either of the following situations:

- The potential benefits of the project or design approach indicate that a serious attempt be made to relieve the constraint.
- The project must be subject to the constraints. These constraints may eliminate some alternatives from further consideration.

3.3.2 Relationship of ITS Management Concepts to Objectives

Chapter 2 described general objectives that may be considered as candidates for a project. Table 3.9 shows how these objectives are related to a number of ITS freeway management concepts. This table may assist in developing candidate concepts and alternatives for the project.

While Table 3.9 shows the types of management concepts available to address objectives, another key functional design issue is the *intensity of deployment* for ITS treatment. Delay increases with volume-to-capacity ratio (e.g. Fig. 4.4) and the capability for a particular ITS treatment to reduce this delay also increases with volume-to-capacity ratio (q/C). Because higher q/C situations provide greater benefits for a given cost, deployments for those cases will provide higher benefit-to cost ratios. This is conceptually illustrated in Fig. 3.7, which shows that as the volume-to-capacity ratio increases, a given investment not only provides greater benefits but also a level of benefits that cannot be obtained at any investment level for lower a lower volume-to-capacity ratio.

Reference [24] describes an approach to categorizing traffic levels so that ITS deployment intensities may be selected to implement the concepts of Fig. 3.7. These levels are defined as follows:

- Level 3—A continuous section of roadway in one direction that includes peak hour level of service D or worse traffic for at least one half of the section.

Table 3.9 Relationship of ITS freeway management concepts to general objectives

Management concept Objective	Recurrent congestion detection techniques	Non-recurrent congestion detection and incident tracking	Traveler information	Ramp metering	Road weather Information system	Motorist assistance	Data collection and management for planning and performance evaluation	Monitoring of ITS equipment and inventory management, security
1. Reduce congestion/improve travel time								
(a) Recurrent congestion—significant section	√		√	√			√	
(b) Recurrent congestion—spot	√		√	√			√	
(c) Non recurrent congestion—significant section		√	√			√		
(d) Non recurrent congestion—spot		√	√			√		
2. Reduce accident rate								
(a) Over significant section	√	√	√	√	√	√	√	
(b) Spot	√	√	√	√	√			
3. Reduce emissions and fuel consumption	√	√	√	√		√	√	
4. Serve as a corridor link in a wider area highway system	√	√	√		√		√	
5. Serve as a diversion route in local corridor	√	√	√		√		√	
6. Special traffic management functions								
(a) Major roadway reconstruction	√	√	√	√		√	√	
(b) Minor roadway construction	√	√	√			√	√	
(c) High occupancy vehicles		√	√	√	√	√	√	
(d) Traffic information on roadway construction	√	√	√				√	

(e) Information on weather conditions, parking, special events, road weather		√	√		√		√	
(f) Traffic management for future major roadway reconstruction	√	√	√				√	
(g) Motorist information about detour routes			√					
7. Interoperability of ITS								
(a) Operator efficiency	√	√	√		√			
(b) Stakeholder involvement	√	√	√	√	√	√	√	√
8. Improvement of NYSDOT operations								
(a) Planning and/or evaluation data collection	√			√	√		√	
(b) ITS equipment monitoring							√	√
(c) Efficiency of operations					√			√
(d) Reduction of operating and/or maintenance cost					√		√	√
9. Provide assistance to disabled motorists		√				√		
10. Provide travel information related to tourism			√		√			
11. Security								
(a) Transportation system security								√
(b) Emergency operation		√	√		√			√
(c) Information system security								√
12. Commercial vehicle operations			√					

Fig. 3.7 Benefits and costs for ITS deployments

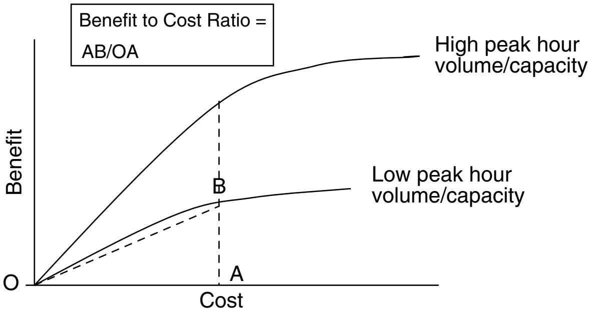

Table 3.10 Representative implementation characteristics for freeway ITS

Capability	Level 1—minimal	Level 2—moderate	Level 3—intensive
TMC site and staffing	Minimal site cost. May be part time or partial permanent staff	Moderate site cost. May be part time or full time staffing	Full time staffing
Computer system for central management of key ITS functions	May be a computer to provide a low level of management capability	Usually	Yes
CCTV coverage	Minimal	Significant	Full
Roadway mainline detector complement (point or probe detectors)	Typically none	Not continuous	Usually continuous
Dynamic message signs	Appropriate locations, possibly at major diversion points	Diversion locations and other key locations	Diversion locations, periodic intervals, possibly at key entry locations
Service patrols	Sometimes	Often	Yes
Ramp metering	None	Rarely	Frequently

- Level 2—A continuous section of roadway in one direction that includes peak hour level of service C or worse traffic for at least one half of the section. Conditions worse than level of service C may be present at scattered spot locations or for small sections. In this case, it may be appropriate to increase the concentration of field equipment at these locations.
- Level 1—Traffic conditions better than Level 2.

Table 3.10 [24] indicates the general deployment intensity of ITS devices or operations commonly implemented by many ITS and that generally conform to the benefit-cost concepts of Fig. 3.7.

Chapters 4 and 5 provide more detailed application factors for equipment deployment as a function of traffic level.

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Chapter 4
Non-Recurrent Congestion: Improvement of Time to Clear Incidents

Abstract The greatest benefit that freeway ITS can provide is to assist in the reduction of the time that it takes emergency responders to clear incidents and restore normal traffic operations. This chapter describes the ways that ITS can facilitate these operations and the benefits that result. Guidance for the field location of ITS components is provided. The chapter covers the following:

- Stages of an incident
- Effects of incident on roadway capacity and models of delay resulting from an incident
- Relationship of incident clearance time to delay
- Adaptation of delay models to local traffic data
- Design functions and technologies to assist in incident management
- CCTV coverage requirements and camera placement guidelines
- Traffic detector technologies and placement guidelines
- Improvement of traffic management center support of incident management
- Evaluation of incident management effectiveness

4.1 Definition of an Incident for ITS Design Purposes

A traffic incident is an unplanned, non-recurring activity on or near the roadway that causes a reduction of roadway capacity or an abnormal increase in demand. Such events include traffic accidents, disabled vehicles and spilled cargo. Highway maintenance and reconstruction projects are sometimes considered as incidents, but our definition excludes these activities. Emergencies such as natural disasters and terrorist attacks are also unplanned; and they can cause a reduction of capacity or an abnormal increase in demand. Their impacts and management requirements, however, extend well beyond the roadway.

The National Incident Management System (NIMS) is a comprehensive, national approach to incident management that is applicable at all jurisdictional levels and across functional disciplines. Appendix G summarizes the NIMS approach to managing incidents and provides a commonly used incident classification scheme.

Figure 4.1 shows the periods for the various incident phases [1]. Table 4.1 provides the definitions for the phases [1].

The ITS issues for incident management are discussed in Sect. 4.5.

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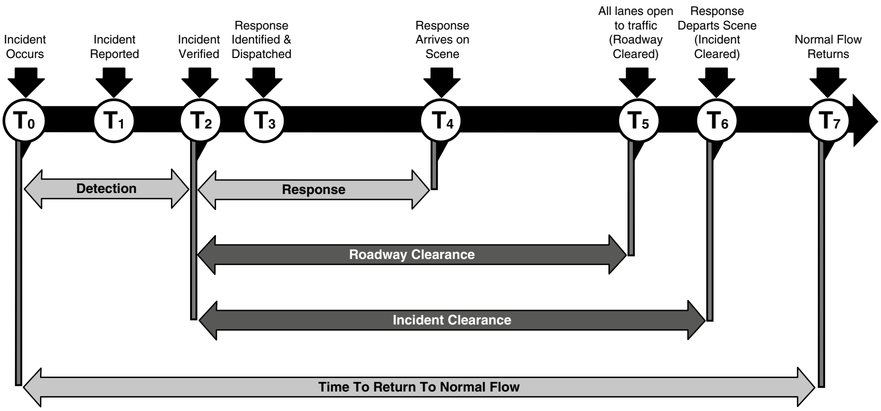


Fig. 4.1 Incident timeline

Table 4.1 Key incident times

Incident phase	Duration	Definition
Detection time	$T_1 - T_0$	The time between the incident occurring and the incident being reported. Detection time is typically not reported because the actual time the incident occurred is often unknown
Verification time	$T_2 - T_1$	The time between the incident being reported and the incident being verified
Response time	$T_4 - T_2$	The time between the incident being verified and the responder arriving on scene. Law enforcement may not be the first party to arrive on scene. Response time depends on the incident location and each responding party's proximity to the incident
Roadway clearance time	$T_5 - T_1$	The time between the first incident report and the first confirmation that all lanes are available for traffic flow
Incident clearance time	$T_6 - T_1$	The time between the first incident report and the time that the last responder left the scene

4.1.1 *Effect of Incidents on Capacity*

The effect of capacity reduction on a freeway is far greater than the physical reduction of roadway width. This effect is shown by Lindley [2] in Table 4.2.

4.1.2 *Secondary Accidents*

Secondary accidents are accidents that result from an existing primary incident. Many times these accidents occur at the end of queues that result from the primary incident. Raub [3] estimates that more than 15 % of the crashes reported by the police may be secondary accidents. Reducing the duration of queues resulting from incidents not

Table 4.2 Fraction of freeway section capacity available under incident conditions

Number of freeway lanes in each direction	Shoulder disablement	Shoulder accident	Lanes blocked One	Lanes blocked Two	Lanes blocked Three
2	.95	.81	.35	0	N/A
3	.99	.83	.49	.17	0
4	.99	.85	.58	.25	.13
5	.99	.87	.65	.40	.20
6	.99	.89	.71	.50	.25
7	.99	.91	.75	.57	.36
8	.99	.93	.78	.63	.41

Source: From Transportation Research Record 1132, Trransportation Research Board, National Research Council, Washington, DC 1987. Table 1

only reduces delay to motorists due to the incident but also results in a reduced rate of secondary accidents and consequent reduction in the total accident rate.

The Virginia Department of Transportation Operations Manual [4] identifies an incident as a secondary incident when it occurs within 4.5 miles upstream of the primary incident and in the same direction. The secondary incident also must occur within 30 min of the end time of the primary incident.

According to a study of 3,425 incident records by Murthy et al. [5], when incidents are not identified by TMCs and messages are not posted on DMS, secondary incidents are 2.33 times more likely to occur as compared to when these ITS management concepts are employed.

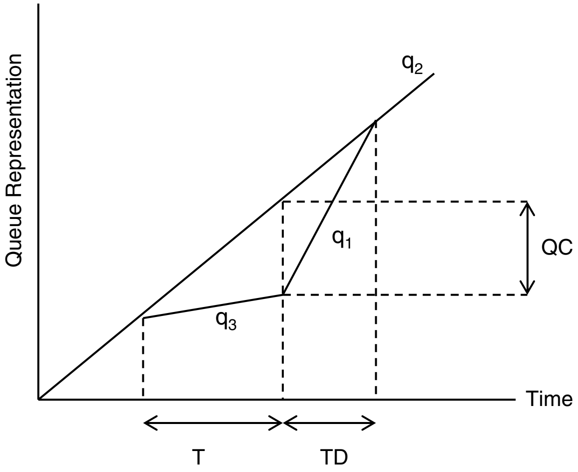
4.1.3 Work Zone Accidents

The difference between normal driving conditions and the conditions that the driver experiences when approaching and travelling in work zones provides the opportunity for additional accidents. In 2003 there were 1,028 fatalities and more than 40,000 injuries in work zone crashes in the U.S. [6]. Antonucci et al. [6] indicate that ITS related strategies and demand management programs to reduce to reduce volumes through work zones will reduce the number of crashes. The diversion strategies, motorist information, lane control and speed management strategies discussed in this book provide the basis for implementing these strategies.

4.2 Models of the Effects of Freeway Incidents

Deterministic queuing models are often used to analyze the delay and timeline associated with freeway incidents that restrict the capacity to below the demand volume. An example of a simple model is shown in Fig. 4.2. While models of this type do

Fig. 4.2 Delay and timeline model for incidents



not capture all of the details of the dynamic traffic flow characteristics, they provide approximations that are sufficiently accurate for design and evaluation purposes.[1]

The time for the queue to dissipate after the incident is cleared is given by:

$$T_D = (q_2 - q_3) \cdot T / (q_1 - q_2) \tag{4.1}$$

where

q_1 = Volume at incident clearance (roadway capacity)
q_2 = Volume entering incident location (demand volume)
q_3 = Volume when incident is present (restricted capacity resulting from incident)
T = Time from start of incident to incident clearance

The line q_2 in the figure represents the number of vehicles that enter the incident location while q_1 and q_3 depict the number of vehicles that are released from the incident location. The vertical distance between q_2 and either q_3 or q_1 represents the number of vehicles in the queue. QC is the queue length at the time the incident is cleared. D_I, the delay until incident clearance, is calculated as

$$D_I = (q_2 - q_3) \cdot T^2 / 2 \tag{4.2}$$

The delay from incident clearance to queue dissipation is given by

$$D_Q = (q_2 - q_3)^2 \cdot T^2 / (2 \cdot (q_1 - q_2)) \tag{4.3}$$

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[1] The model and the related model discussed in Sect. 4.3 do not incorporate the delay resulting from the additional vehicles delayed by the upstream propagation of the tail of the queue.

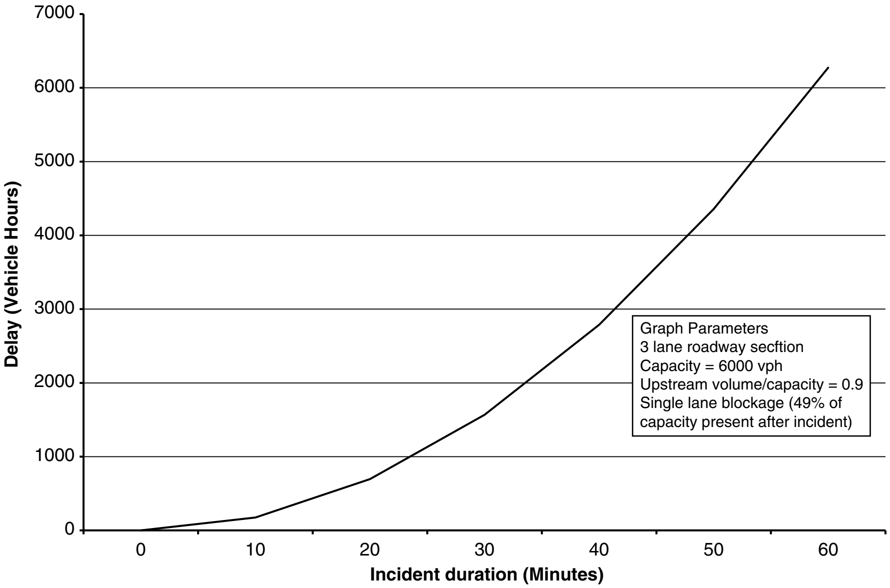


Fig. 4.3 Vehicle hours of delay vs. time to clear incident

Total delay is

$$\begin{aligned} D_T &= D_I + D_Q \\ D_T &= (q_2 - q_3) \cdot T^2 / 2 + (q_2 - q_3)^2 \cdot T^2 / (2 \cdot (q_1 - q_2)) \end{aligned} \tag{4.4}$$

A more complex model that includes a period of total closure is provided by Morales [7].

Figure 4.3 shows an example of incident delay as a function of the time to clear an incident blocking one lane of a roadway with three lanes in one direction for a typical peak hour condition without recurrent congestion. Figure 4.4 shows incident delay as function of volume to capacity ratio for the freeway upstream of that incident.

There is considerable variation in the accident clearance time data provided by different agencies. Osbay and Kachroo [8] provide data obtained in Northern Virginia for different types of incidents. For example, an analysis of lane blocking incident data on freeways in Long Island, NY prior to the installation of ITS showed that the average time to clear as 49.6 min, and data for similar conditions in the Atlanta area prior to ITS installation showed a 64 min period [9].

Sections 4.1 and 4.2 show that the delay corresponding to an incident varies significantly with the number of lanes that the facility has, the lane blocking effects of the incident, the time for the incident to be cleared and the demand volume in the absence of an incident. The practical evaluation of ITS improvements requires a relatively simple model that embeds these variations. Sections 4.3 and 4.4 describe an approach to the development of such a model.

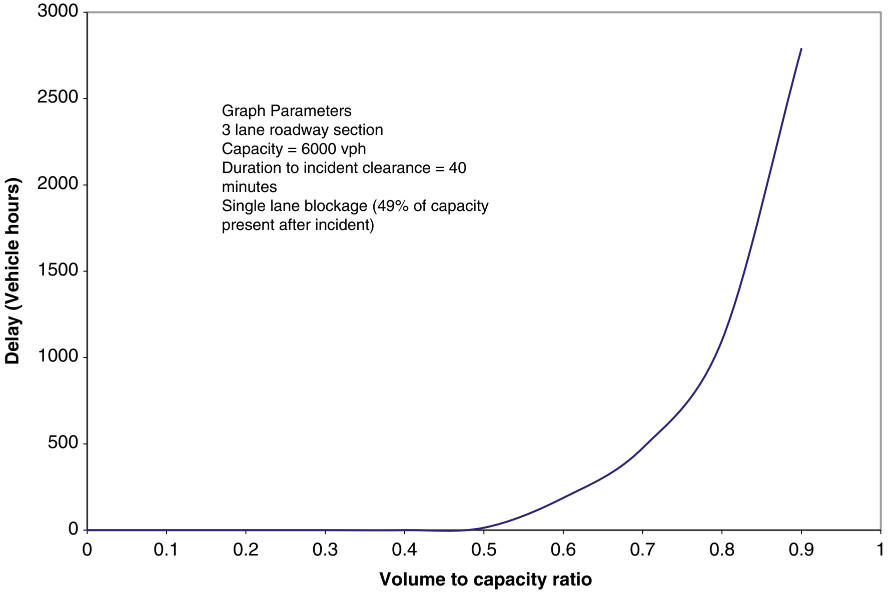


Fig. 4.4 Delay vs. volume to capacity ratio upstream of incident

4.2.1 Frequency and Severity of Incidents

The evaluation model described in Sect. 4.4 requires a value for the blockage time and severity (capacity reduction) of a representative incident. It also requires a value for the frequency of the incident (number of incidents per million vehicle miles). A model is shown in Fig. 4.5 that provides some of the required information.

The model does not contain information on incident frequency. Furthermore, the model shows wide variations in incident duration. While a good deal of this variation is likely due to differences in reporting styles, and even in the definition of an incident, a more appropriate approach for practitioners is to provide a model and procedure that may be calibrated on a local or area-wide basis. The model structure in Fig. 4.6 was developed by the New York State Department of Transportation (NYSDOT), and provides a framework for agencies responsible for freeway management operations to calibrate the model using locally obtained data [11]. The model treats accidents and non-accident incidents separately, thus enabling the widely reported accident rate data to be used directly. The model considers a section as the roadway portion between the centers of two interchanges. The data shown in the figure is based on observations in several upstate New York metropolitan areas. Since lane-specific data for incident blockage duration was not available from the NYSDOT incident data, Fig. 4.6 employs data from Kittleson and Vandehey [12] for this purpose.

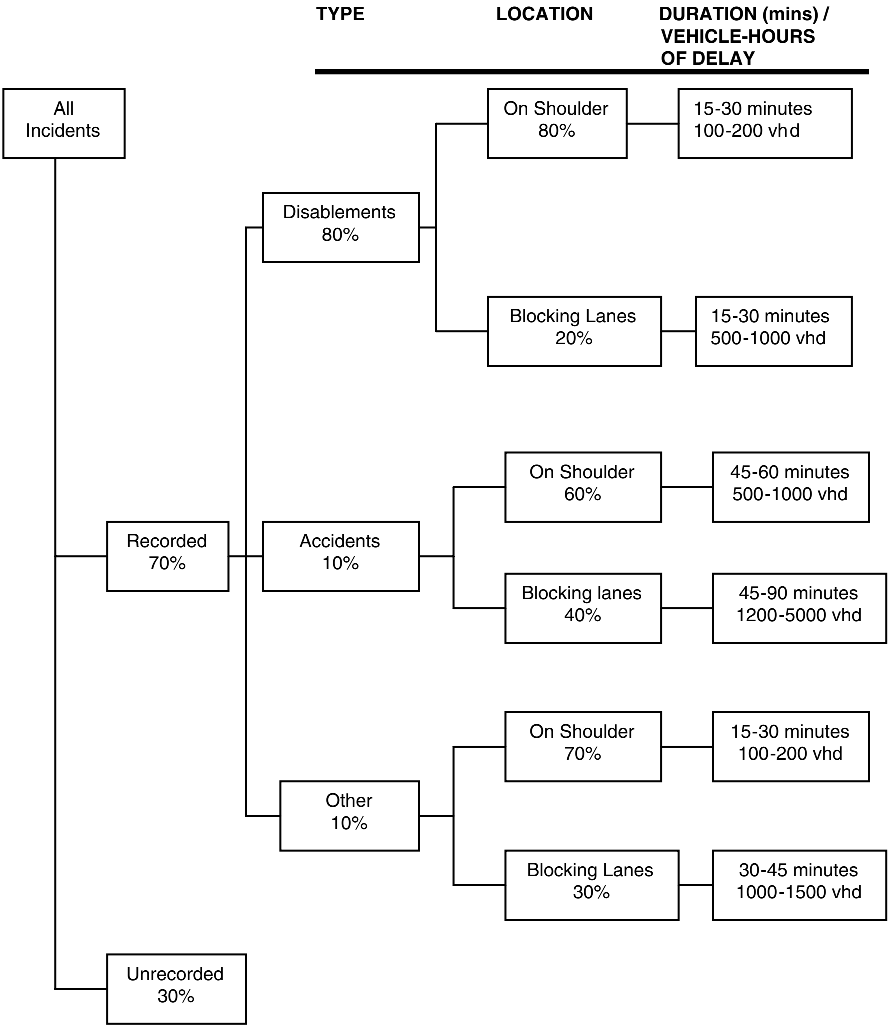


Fig. 4.5 Composite profile of reported incidents by type [10]

4.2.2 Data Collection for Development of Incident Model

Experience has shown that in many cases, historic data from the incident logs commonly provided by traffic management systems are often not provided with sufficient fidelity to enable non-accident incident rates and durations to be obtained. For example, the development of Fig. 4.6 required the documentation of data in more detail and in a different format than that provided by normal operation of the traffic management system. It is therefore recommended that a separate data set be collected for this purpose by traffic management center operators who have been

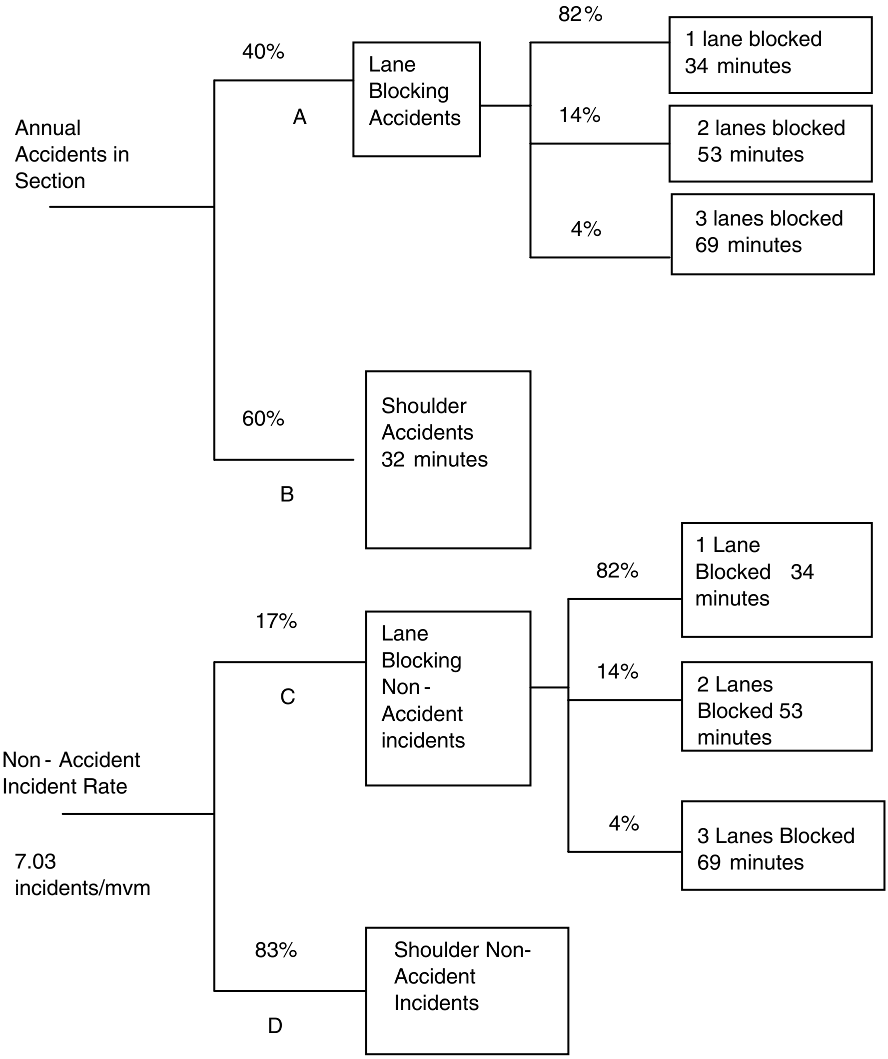


Fig. 4.6 Incident model structure

briefed on the model and its data collection requirements. This data set should be based on CCTV observations.

Data collection will be required for a number of sections to provide a sufficient data sample for analysis. The parameters required for analysis are:

- Roadway Section ID
- Incident ID
- Roadway direction
- Date
- Time incident detected
- Time incident cleared

- Accident or non-accident incident
- Shoulder or moving-lane incident
- Number of lanes closed
- Duration of lane closure

4.3 Relationship of Reduction in Delay to Reduction in Incident Clearance Time

The area abcd in Fig. 4.7 shows the effect on delay of a reduction in the time to clear the incident.

Equation (4.4) shows that the total delay is proportional to the square of the time interval from the start of the incident until incident clearance. Thus, (4.4) may be rewritten as:

$$D_T = K \cdot T^2 \tag{4.5}$$

The effect on delay of small changes in the time to clear the incident is given by the derivative of D_T with respect to T as

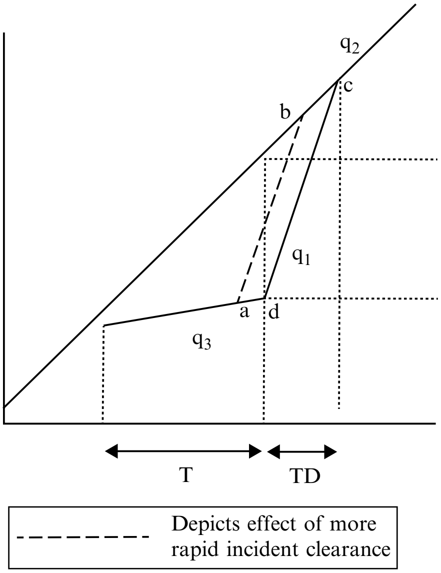
$$dD_T / dT = 2 \cdot K \cdot T \tag{4.6}$$

The ratio of change in delay to incident clearance time is

$$(1/T) \cdot (dD_T / dT) = 2 \cdot K \tag{4.7}$$

From this equation it is seen that a small percentage change in the reduction in the time to clear the incident results in twice that percentage of delay reduced.

Fig. 4.7 Delay reduction resulting from reduction in incident clearance time



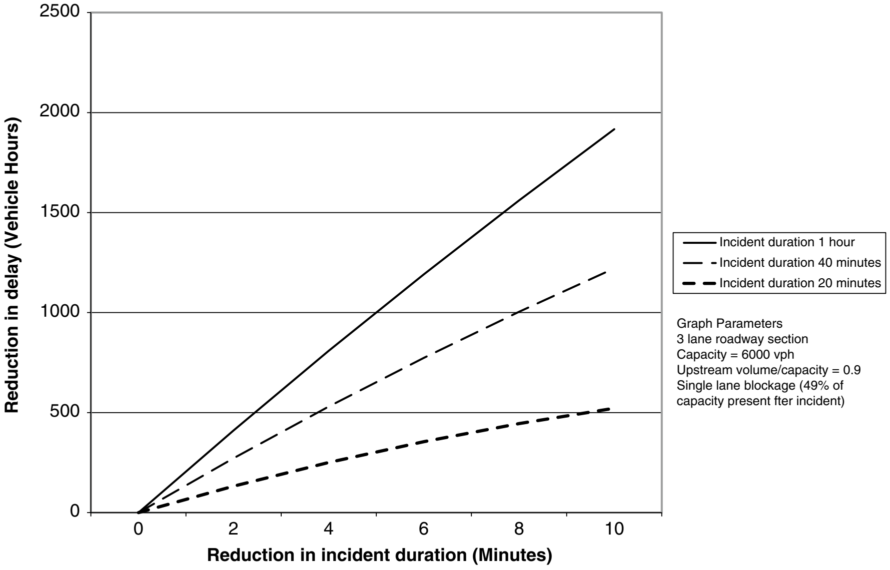


Fig. 4.8 Example of peak period reduction in delay as a result of reduction in time to clear incident

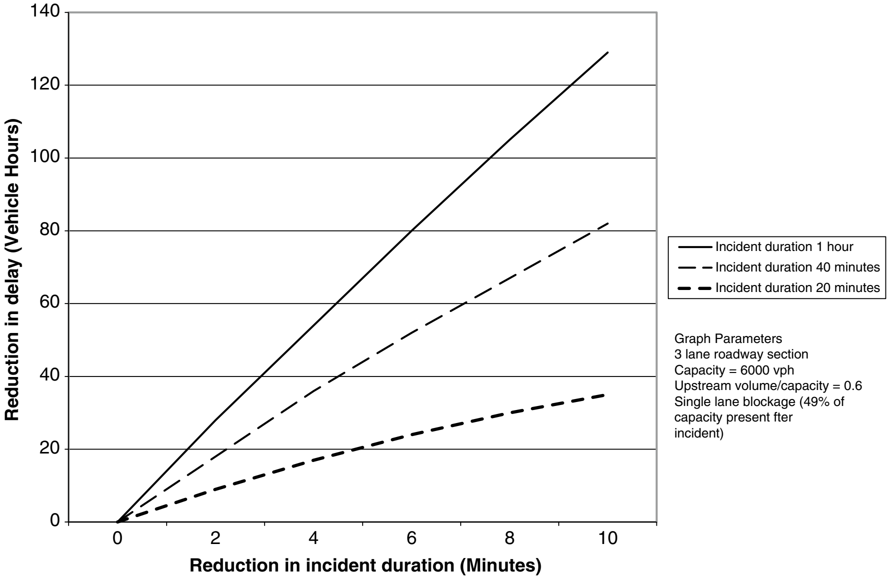


Fig. 4.9 Example of off-peak period reduction in delay as a result of reduction in time to clear incident

An example of the reduction in delay due to reduction in incident clearance time is shown in Fig. 4.8. It was computed using (4.4) by taking the difference of the delay prior to and after the reduction in incident clearance time. A similar graph for off-peak period incidents is shown in Fig. 4.9.

4.4 Interaction of Capacity Restrictions and Traffic Conditions

Because an incident may occur at any time, the impact on delay will depend on the volume at that time and the residual capacity as shown in Table 4.2.

Incident models of the types shown in Figs. 4.5 and 4.6 provide the basis for assigning a probability of occurrence to each blockage time. A general plan for developing a model for average incident delay is shown in Fig. 4.10. The plan depicts an approach that groups the likelihood of incidents into volume to capacity ratio based groups or “cohorts” that represent the effect of various types of incidents. Delay is computed for each cohort, and then the cohorts are assembled into the final delay estimate. Sections 4.4.1 and 4.4.2 discuss the details of the approach.

4.4.1 Cohort Model

In order to estimate the percentage of traffic at each volume to capacity level, the representative hourly traffic volumes may be classified into “cohorts” designed to capture the effect of the various lane blockage scenarios [11]. For example, for a freeway with three lanes in each direction, the cohorts for a single lane blockage

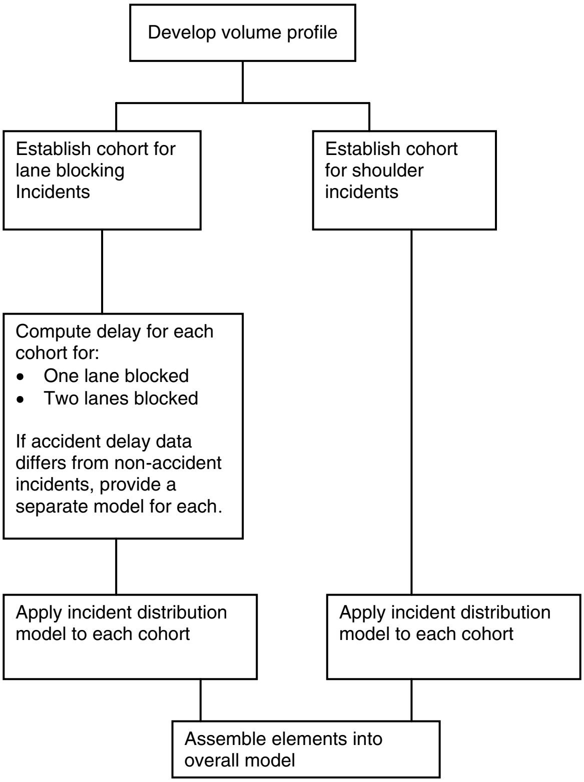


Fig. 4.10 Flow diagram to develop incident delay for freeway with three lanes in each direction

Table 4.3 Cohorts for freeway with three lanes in each direction

Cohort number	Volume to capacity ratio range in cohort	Representative volume to capacity ratio used in analysis
1	$0.7 < q/C$	0.8
2	$0.7 \geq q/C \geq 0.49$	0.6
3	$0.49 \geq q/C \geq 0.17$	0.33
4	$0.17 \geq q/C \geq 0$	0.1

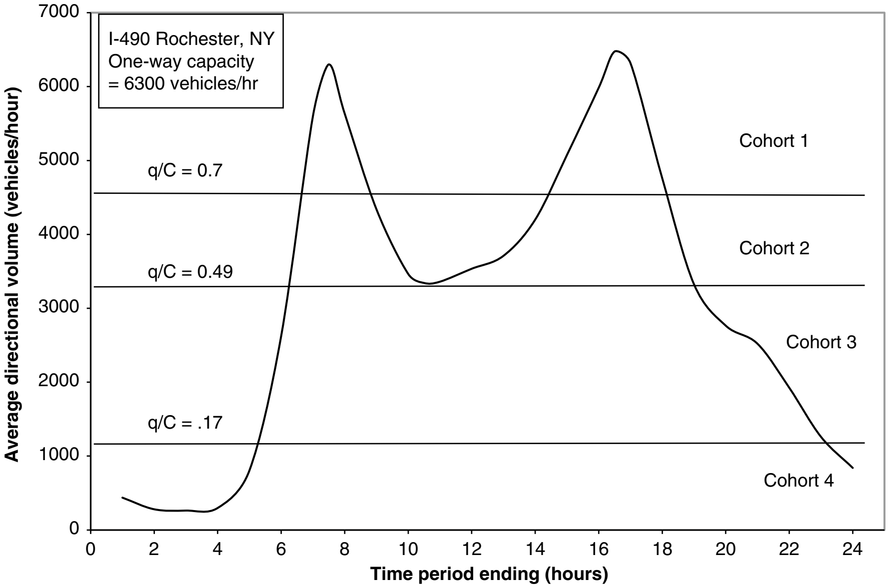


Fig. 4.11 Relationship of cohorts to volume profile

may be classified as shown in Table 4.3. Notice that the cohort range definitions (.49 and .17) correspond to the blocked lane capacities shown in Table 4.2.

The last column of the table provides a volume to capacity ratio characteristic of the cohort and that will be used in the computation of delay. Figure 4.11 shows the relationship of these cohorts to a typical weekday freeway volume characteristic. To develop the model, the hourly volumes are assigned to the proper cohort and summed. The data are then used to identify the fraction of the AADT that is present when different lane blockages occur.

Figure 4.12 shows an example of the worksheet used to develop the fraction of the AADT that is in each cohort. The figure shows the computation for a three-lane roadway.

Hourly volume for each roadway direction is entered into the worksheet along with the capacity for the roadway segment. The volume to capacity ratio is computed by the worksheet. The worksheet then sorts the volumes into cohorts using the cohort definitions in Table 4.2. The sorted volumes for each hour are then summed over the day to determine the daily volume for each cohort.

				COMPUTATION OF COHORT FRACTIONS (THREE LANE ROADWAY)												
	Data entry required															
	Roadway Segment				I-490 from I-390 to Mt. Read Blvd.										Cohort Volumes for	
Beginning	Direction			Est Cap	eastbound	westbound	Cohort Volumes for Lane Blocking Incidents								Shoulder Accidents	
Hour	Eastbound	Westbound	Total	1 way	v/c	v/c	eb	eb	eb	eb	wb	wb	wb	wb	eb	wb
							cohort 1	cohort 2	cohort 3	cohort 4	cohort 1	cohort 2	cohort 3	cohort 4	v/c>= .83	v/c>= .83
12:00 AM	284	671	955	6300	0.045	0.107	0	0	0	284	0	0	0	671	0	0
1:00 AM	164	519	683	6300	0.026	0.082	0	0	0	164	0	0	0	519	0	0
2:00 AM	164	490	654	6300	0.026	0.078	0	0	0	164	0	0	0	490	0	0
3:00 AM	222	468	690	6300	0.035	0.074	0	0	0	222	0	0	0	468	0	0
4:00 AM	441	519	960	6300	0.070	0.082	0	0	0	441	0	0	0	519	0	0
5:00 AM	1550	842	2392	6300	0.246	0.134	0	0	1550	0	0	0	0	842	0	0
6:00 AM	3831	2088	5919	6300	0.608	0.331	0	3831	0	0	0	0	2088	0	0	0
7:00 AM	5830	2769	8599	6300	0.925	0.440	5830	0	0	0	0	0	2769	0	5830	0
8:00 AM	4714	2300	7014	6300	0.748	0.365	4714	0	0	0	0	0	2300	0	0	0
9:00 AM	2751	1869	4620	6300	0.437	0.297	0	0	2751	0	0	0	1869	0	0	0
10:00 AM	2182	1832	4014	6300	0.346	0.291	0	0	2182	0	0	0	1832	0	0	0
11:00 AM	2142	2031	4173	6300	0.340	0.322	0	0	2142	0	0	0	2031	0	0	0
12:00 PM	2143	2180	4323	6300	0.340	0.346	0	0	2143	0	0	0	2180	0	0	0
1:00 PM	2201	2170	4371	6300	0.349	0.344	0	0	2201	0	0	0	2170	0	0	0
2:00 PM	2591	3064	5655	6300	0.411	0.486	0	0	2591	0	0	0	3064	0	0	0
3:00 PM	2869	4472	7341	6300	0.455	0.710	0	0	2869	0	4472	0	0	0	0	0
4:00 PM	2956	5282	8238	6300	0.469	0.838	0	0	2956	0	5282	0	0	0	0	5282
5:00 PM	2988	5148	8136	6300	0.474	0.817	0	0	2988	0	5148	0	0	0	0	0
6:00 PM	2151	2896	5047	6300	0.341	0.460	0	0	2151	0	0	0	2896	0	0	0
7:00 PM	1514	1905	3419	6300	0.240	0.302	0	0	1514	0	0	0	1905	0	0	0
8:00 PM	1261	1789	3050	6300	0.200	0.284	0	0	1261	0	0	0	1789	0	0	0
9:00 PM	1222	1659	2881	6300	0.194	0.263	0	0	1222	0	0	0	1659	0	0	0
10:00 PM	870	1207	2077	6300	0.138	0.192	0	0	0	870	0	0	1207	0	0	0
11:00 PM	505	1067	1572	6300	0.080	0.169	0	0	0	505	0	0	0	1067	0	0
Total =	47546	49237	96783			Total	10544	3831	30521	2650	14902	0	29759	4576	5830	5282
							cohort	fraction	Frac shoulder accidents with V/C>= .83				0.115			
							1	0.263								
							2	0.040								
							3	0.623								
							4	0.075								

Fig. 4.12 Worksheet for computation of cohort fractions

Table 4.2 depicting the percentage of freeway capacity under incident conditions on the shoulder, shows that for three lane freeways, a q/C of .99 must be present for the incident to have an effect. Since this condition is uncommon for the volume profile of Fig. 4.11, that type of incident was not considered in the development of Fig. 4.12. The table does, however, show that shoulder accidents may develop congestion under some conditions in Fig. 4.11. Thus the analysis shown in Fig. 4.12 also identifies the fraction of the AADT for which shoulder accidents will influence delay. The volumes in the example represent a situation with no recurrent congestion.

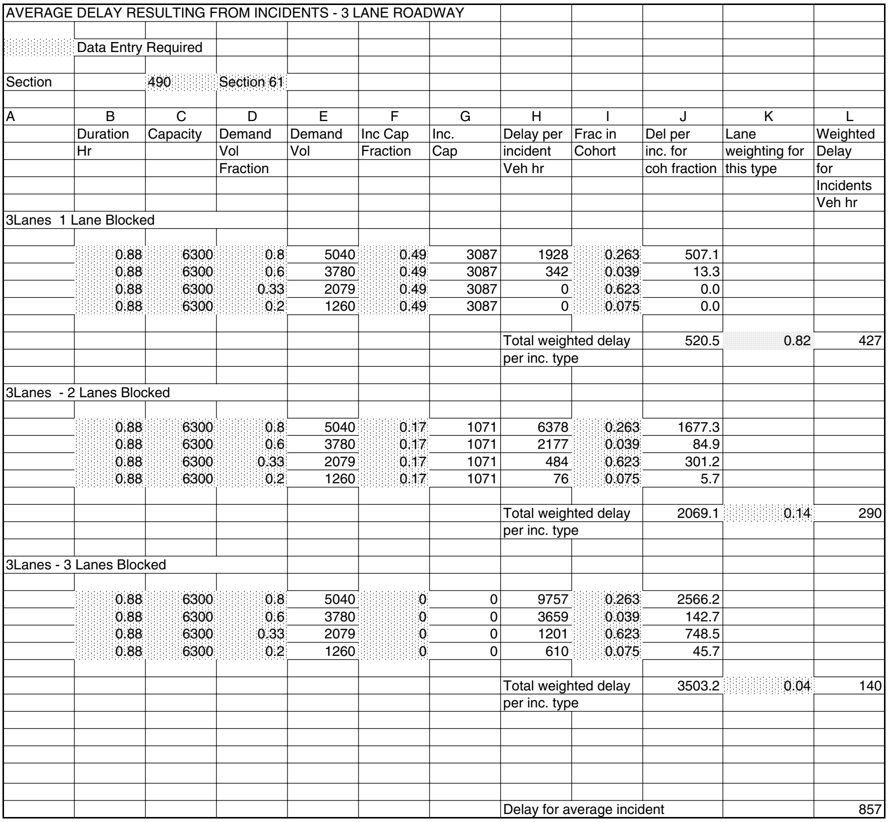
The website http://www.springer.com/us/book/9783319147673 contains the worksheet file Cohort Factors 3 Lanes file for Fig. 4.12.

4.4.2 Time Saved Per Incident

The cohort fraction data, such as that shown in Fig. 4.12 may be used in conjunction with the incident delay model in (4.4) to compute the delay for lane blocking incidents for each lane blocked scenario. These may then be used in conjunction with the percentage of incidents for which the lane groups are blocked (Fig. 4.6) to arrive at the average delay per lane blocking incident and shoulder accident. Building on the previous example, a worksheet example for this calculation is shown in Fig. 4.13. The website http://www.springer.com/us/book/9783319147673 contains the worksheet file Average delay resulting from incident.xls with the parameters of Fig. 4.13 for the three-lane case.

Each of the four rows for each set of computations provides the delay computation for a cohort. The worksheet columns are described as follows. The data to be entered by the analyst is indicated by an asterisk.

- Column B*—The incident duration from inception to clearance. An incident duration of approximately 53 min (0.88 h) was used for this example.
- Column C*—Roadway capacity in one direction is 6,300 vph
- Column D*—Demand volume fraction is the representative q/C associated with the cohort. These were obtained from Table 4.3.
- Column E—Demand volume is the product of roadway capacity (Column C) and demand volume fraction (Column D).
- Column F*—The incident capacity fractions were obtained from Table. 4.2.
- Column G—The incident capacity is the product of the roadway capacity (Column C) and incident capacity fraction (Column F).
- Column H—The delay per incident is provided by the application of (4.4) to the data in the previous columns.
- Column I*—The fraction of the traffic in the cohort is obtained from the cohort fraction analysis (Fig. 4.12).
- Column J—The delay per incident for the cohort fraction is the product of the delay per incident (Column H) and the fraction of the traffic in the cohort (Column I). These are then summed over all cohorts for the type of incident to provide total weighted delay for the incident type.
- Column K*—The lane weighting represents the fraction of lane blocking incidents for the data set. It was obtained from Fig. 4.6 and must be entered by the user if changes are desired.



AVERAGE DELAY RESULTING FROM INCIDENTS - 3 LANE ROADWAY											
▨	Data Entry Required										
Section		490	Section 61								
A	B	C	D	E	F	G	H	I	J	K	L
	Duration Hr	Capacity	Demand Vol Fraction	Demand Vol	Inc Cap Fraction	Inc. Cap	Delay per incident Veh hr	Frac in Cohort	Del per inc. for coh fraction	Lane weighting for this type	Weighted Delay for Incidents Veh hr
3Lanes 1 Lane Blocked											
	0.88	6300	0.8	5040	0.49	3087	1928	0.263	507.1		
	0.88	6300	0.6	3780	0.49	3087	342	0.039	13.3		
	0.88	6300	0.33	2079	0.49	3087	0	0.623	0.0		
	0.88	6300	0.2	1260	0.49	3087	0	0.075	0.0		
							Total weighted delay per inc. type		520.5	0.82	427
3Lanes - 2 Lanes Blocked											
	0.88	6300	0.8	5040	0.17	1071	6378	0.263	1677.3		
	0.88	6300	0.6	3780	0.17	1071	2177	0.039	84.9		
	0.88	6300	0.33	2079	0.17	1071	484	0.623	301.2		
	0.88	6300	0.2	1260	0.17	1071	76	0.075	5.7		
							Total weighted delay per inc. type		2069.1	0.14	290
3Lanes - 3 Lanes Blocked											
	0.88	6300	0.8	5040	0	0	9757	0.263	2566.2		
	0.88	6300	0.6	3780	0	0	3659	0.039	142.7		
	0.88	6300	0.33	2079	0	0	1201	0.623	748.5		
	0.88	6300	0.2	1260	0	0	610	0.075	45.7		
							Total weighted delay per inc. type		3503.2	0.04	140
							Delay for average incident				857

Fig. 4.13 Worksheet for calculation of average delay resulting from incident

- Column L—The weighted delay for incidents is the product of the delay per incident for the cohort fraction (Column J) and the lane weighting (Column K).

The delay for the average incident is the sum of the weighted delays for each incident type. The saving in delay due to ITS measures may be computed by taking the difference in the worksheet computation for which incident duration (Column B) is entered prior to ITS project implementation and after its implementation. ITS measures that result in more rapid incident clearance are discussed in Sect. 4.4.4.

4.4.3 *Classification of Incidents*

Agencies commonly employ severity classifications for responses to incidents. For example, The Chattanooga Urban Area Metropolitan Planning Organization and the Chattanooga-Hamilton County Regional Planning Agency have devised a classification system [13] that is based on traffic flow, impact/delay, incident characteristics and types of responders. A Level 4 incident is one that typically is causing traffic delays of less than 30 min where traffic is only slightly impacted and can be relatively easily routed around the incident. A Level 3 incident is one lasting more than 30 min but less than an hour, and a moderate impact on traffic flow. Typically a Level 3 incident involves a collision without or with just minor injuries. A Level 2 incident is one lasting more than 30 min, but less than 2 h. In a Level 2 incident, the impacts on the flow of traffic are significant, and the incident probably involves injuries to motorists. With a Level 2 incident, traffic management is essential and site management involves significant interagency cooperation. A Level 1 incident generally tends to represent major events that close the roadway and cause major area-wide congestion. This classification system is typical of those employed by operating agencies.

4.4.4 Incident Management Approaches

Incident management by TMCs may employ the following approaches:

- Assist emergency service providers by improving their access to the incident, reducing incident clearance time and protecting the safety of emergency service providers. Many of the policies implemented by agencies responsible for incident management focus on this objective. FHWA provides guidance [14] and many state DOTs and other agencies have developed plans that address their needs. TMCs provide congestion and lane access information to emergency responders, provide lane information to motorists and assist emergency responders to establish incident related traffic control measures.
- Provide incident location and lane guidance to motorists to smooth necessary lane changes and to avoid secondary accidents. Active transportation and demand management techniques (Chap. 10) support this management measure).
- Reduction of demand at the incident location by encouraging the use of alternative modes such as parallel transit services under incident conditions. Managed transportation corridors (Chap. 11) may be used to implement this management measure.
- Reducing traffic demand at the incident by encouraging diversion at the geographic level that is appropriate to the management of the incident, depending on the severity of its impacts (Sect. 4.4.6).

Many agencies have developed a formal management structure for managing incidents. Table 4.4 [15] shows the classification of incident levels by Delaware DOT and Table 4.5 [15] shows the TMC incident management responsibilities and action items for the incident levels.

4.4.5 Distribution of Traffic for Incident Conditions

Traffic diversion is commonly used by operating agencies to manage non-recurrent congestion resulting from such incidents as crashes, vehicle disablements, spilled loads, roadway surface problems, construction, weather related issues and security concerns.

Figure 4.14 shows a simplified example of volumes on a freeway (solid line) and an alternate route (dashed line) under normal conditions and incident conditions. V5 represents the volume for the diverting traffic.

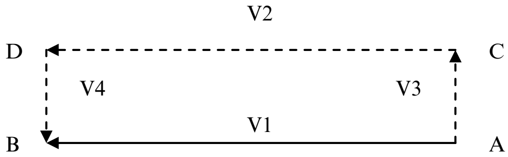
Table 4.4 Delaware DOT levels of response for planned/unplanned incidents/events

Level	Area of impact	Resources	Emergency Operation Centers (EOC) activation for unplanned events	Highest level of decision making	Examples
1	Site/area specific	Normal staffing.	Normal interagency communication—No EOC activation	Normal operations	Day-to-day operations
2	District wide or multi-district	Limited re-assignment of personnel and equipment—greater expertise may be needed. Primary agencies notified or activated	Elevated communications, local/county EOCs may or may not be partially or fully activated. State EOC on notice	District managers/chief traffic engineer/operations managers	Traffic may need to be diverted to other roads (i.e. blockage on main road); major accident; closing of a road; injuries; isolated road flooding; HAZMAT incident; power outage; bridge structural damage; large planned events (i.e., Dover Downs Races)
3	Multi-districts	Reassignment of personnel and equipment—greater expertise needed. Primary agencies activated. Support agencies notified. Federal agencies notified (FHWA, US ACE). Contractors may be activated	Higher elevated communications, impacted local/county EOCs may be activated if human needs are required (i.e. shelter, mass care). State EOC may be partially or fully activated—DelDOT liaison to county EOC and may be to state EOC, if activated	Division director or department secretary	Coastal storm; high volumes of rain or snow; major HAZMAT incident; limited evacuation
4	Statewide/multi-state	Total activation of personnel and equipment. Primary, contract, and support agencies activated. Ongoing federal coordination	Impacted local/county and state EOCs activated—DelDOT liaison to county EOC and state EOC if state EOC activated	Governor, DEMA, or Cabinet Members	Hurricanes; floods; blizzards; catastrophic HAZMAT incident; biological incident; weapons of mass destruction; acts of terrorism

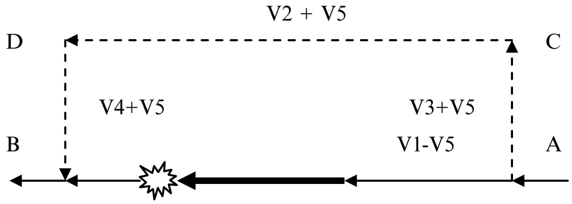
Table 4.5 Delaware DOT TMC responsibilities for incident management

Level	Notification	TMC			Resources/personnel	Preparedness/staging
		Control	Monitor	Information		
1	Normal communication and coordination	Normal operations transportation management systems (personnel, equipment, materials). Communicate with districts to determine alternate routes	Normal monitoring transportation management systems	Normal information dissemination to other agencies, departments, media, and neighboring transportation agencies (via the Information Exchange Network [IEN])	Daily assignments	Normal transportation management system checks, SOPs followed
2	Appropriate personnel per TMC SOPs. Possible bridge/conference call requested and/or initiated, if required	Set up and control of impacted routes. Adjust transportation management system based on impact of incident/event. Communicate with districts to determine alternate routes	Redirect monitoring of transportation management systems to concentrate on event. Normal monitoring activities of statewide system continues	Normal information dissemination to other agencies, departments, Public relations, and media via WTMC, variable message signs (VMS), kiosks, website, IEN	Evaluate status to handle short and long term events	Transportation management equipment/system tested and confirmed. Staffing reviewed
3	Appropriate personnel per TMC SOPs. Possible bridge/conference call requested and/or initiated, if required	Set up and control of impacted routes. Adjust transportation management system based on impact of incident/event. Communicate with Districts to determine alternate routes	Redirect monitoring of transportation management systems to concentrate on event. Normal monitoring activities of statewide system continues. Monitoring and re-directing requests from EOC and 911 centers	Normal information dissemination to other agencies, departments, public relations, and media via WTMC, variable message signs (VMS), kiosks, website, IEN	Evaluate status to handle short and long term wants events accountability; assess further impacts of situation on personnel and resources	Communications with supervisors
4	Appropriate personnel per TMC SOPs. Possible bridge/conference call requested and/or initiated, if required	Set up and control of impacted routes. Adjust transportation management system based on impact of incident/event. Communicate with Districts to determine alternate routes	Redirect monitoring of Transportation Management Systems to concentrate on event. Normal monitoring activities of statewide system continues. Monitoring and re-directing requests from EOC and 911 centers	Normal information dissemination to other agencies, departments, public relations, and media via WTMC radio station, variable message signs (VMS), kiosks, website, IEN	Evaluate status to handle short and long term wants events accountability; assess further impacts of situation on personnel and resources	Transportation management systems and data safeguarded. Prepare to evacuate and/or relocate TMC, if necessary

Fig. 4.14 Volumes on freeway and alternate routes



Volumes on freeway and alternate route under normal conditions



Volumes on freeway and alternate under incident conditions

The lower drawing in Fig. 4.14 shows diversion under incident conditions. The heavy line section on the freeway indicates a possible region of queuing resulting from the loss of capacity. The diverted traffic volume V5 is subtracted from the freeway route and added to the diversion route.

A *travel cost*[2] may be associated with each travel link. The travel cost for an incident can be represented as the sum the travel times for all vehicles on the network from the start of the incident until normal traffic flow is restored. For the mainline link on which the incident occurs (Link AB), travel cost may be expressed as follows:

$$T_{AB}=\sum_{n=1}^{N} f\left(V1-V5\right),RC) \tag{4.8}$$

$$\mathrm{C}_{\mathrm{AB}}=\mathrm{K}\cdot\mathrm{T}_{\mathrm{AB}} \tag{4.9}$$

where

C_{AB} is the cost of travel on link AB during the incident period
f is a function that depends on link inflow $(V1-V5)$ during the incident period and on RC, the residual capacity of the freeway prior to incident clearance. Table 4.2 shows an example of RC.
K represents the value of time
n is the vehicle sequence on link AB during the incident period
N is the total number of vehicles on the link until incident clearance
T_{AB} is the total travel time on Link AB during the incident period

The other links have similar cost functions, but without the residual capacity term.

Figure 4.15 shows an example of the cost on the links and for the network under (a) incident free (normal) conditions, (b) an incident where the diversion has been excessive and (c) where the diversion is approximately optimum. In the latter case, less traffic has been diverted from the freeway, resulting in a higher cost on link AB

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[2] Travel cost is usually taken to be the sum of travel time cost and out of pocket cost. For the current example, out of pocket cost is assumed to be largely independent of route choice.

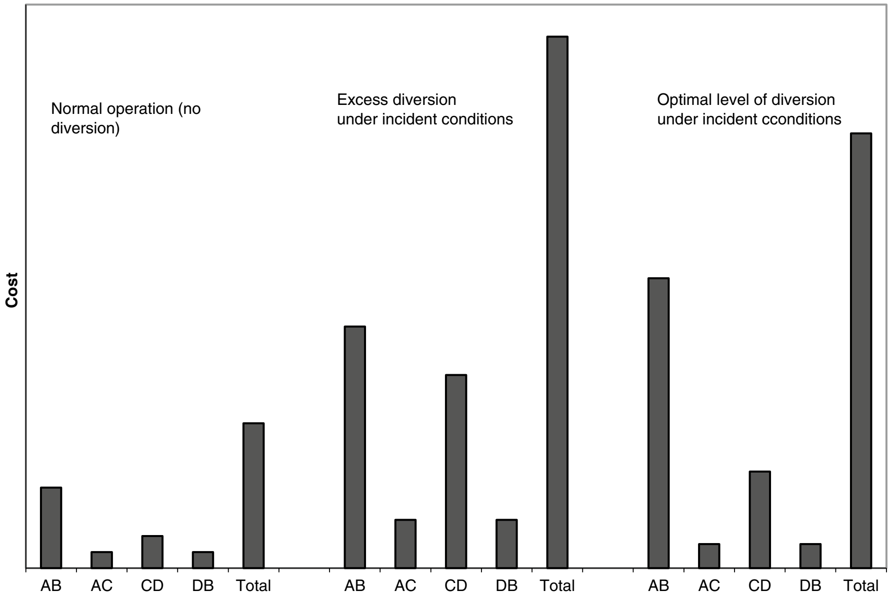


Fig. 4.15 Example of costs under incident conditions resulting from diversion

but a lower overall network cost. The network cost under incident conditions is seen to vary significantly with diversion.

The diversion fraction DF at an exit ramp may be defined as follows:

$$DF = V_{ED} / V_{AD} - V_{EW} / V_{AW} \tag{4.10}$$

where

V_{AD} is the volume upstream of the exit ramp when diversion is implemented at this ramp.

V_{AW} is the volume upstream of the exit ramp exit ramp volume when diversion is not implemented at this ramp. For diversion at a single ramp, $V_{AW} = V_{AD}$.

V_{ED} is the exit ramp volume when diversion is implemented at this ramp.

V_{EW} is the exit ramp volume when diversion is not implemented at this ramp.

4.4.6 Geographic Levels of Diversion

The incident management levels such as those described in Sect. 4.4.4 are related to the severity and expected duration of the effects of the incident, construction or weather. It is also useful to classify diversion routes by levels that generally represent the geographical extent of the diversion route and the diversion location in advance of the incident. The type of information provided to motorists may be related to the geographic diversion level.

Three geographic levels of diversion are described, starting at the local level (Level 1), progressing to the area level (Level 2) and extending to the regional level (Level

3). By diverting the largest number of vehicles possible before they reach the location at which the local level comes into play, congestion and queuing at the incident site are minimized, as is overall corridor delay. This is conceptually shown in Fig. 4.16.

Figure 4.17 shows the conceptual relationship among diversion levels. Regional level diversion roadways are usually freeways, local level diversion roadways are usually surface streets, and area level diversion roadways may be either. At the area level, a significant traffic volume may not complete the trip on the diversion route, as other routes may be more convenient.

The following sections describe the characteristics of the three diversion levels.

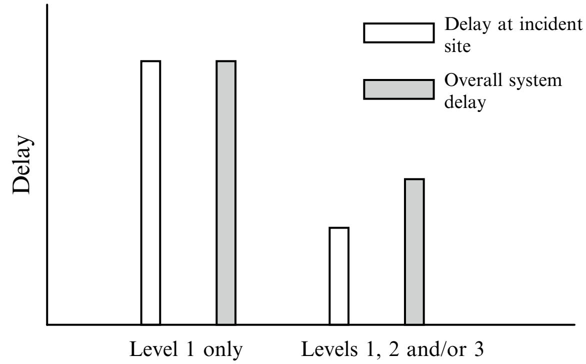


Fig. 4.16 Benefits for diverting at longer distances from the incident

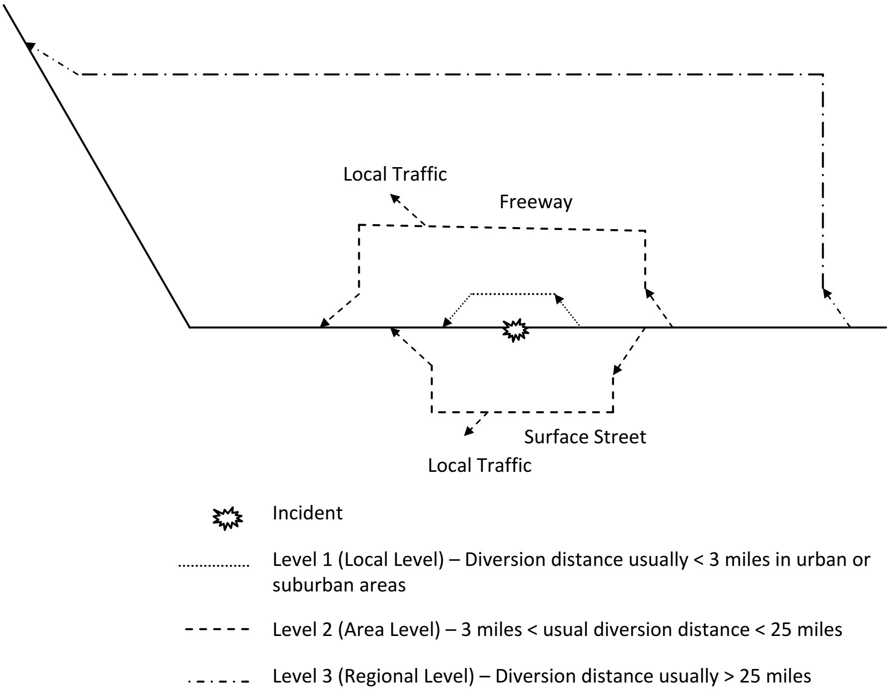


Fig. 4.17 Relationship among diversion levels

4.4.6.1 Local Diversion (Geographic Level 1)

Diversion at this level is usually accomplished by diverting to surface streets at the exit ramp just upstream of the incident and returning to the freeway at the next entry opportunity. The diversion route is usually in close proximity to the freeway. While this diversion level is commonly associated with the actions of emergency service providers that may be needed to manage severe incidents including roadway closures, most incidents do not involve closures or other highly aggressive forms of management.

Because emergency service providers often participate at this level, police, traffic management agencies and other stakeholders are often active in the development of formal diversion plans. Figure 4.18 shows an example of a Level 1 traffic diversion operation requiring inter-agency cooperation.

Figure 4.19 shows an example of a formal diversion plan of this type for a freeway in Connecticut.

The Connecticut plan includes:

- Diversion route identification and location. In some cases trucks may require a separate route.
- Diversion signs at turns.
- Location of traffic signals.
- Location of police monitors.
- Emergency contact information.
- Special requirements.

Fig. 4.18 Example of traffic diversion operation (Source: Washington State DOT)

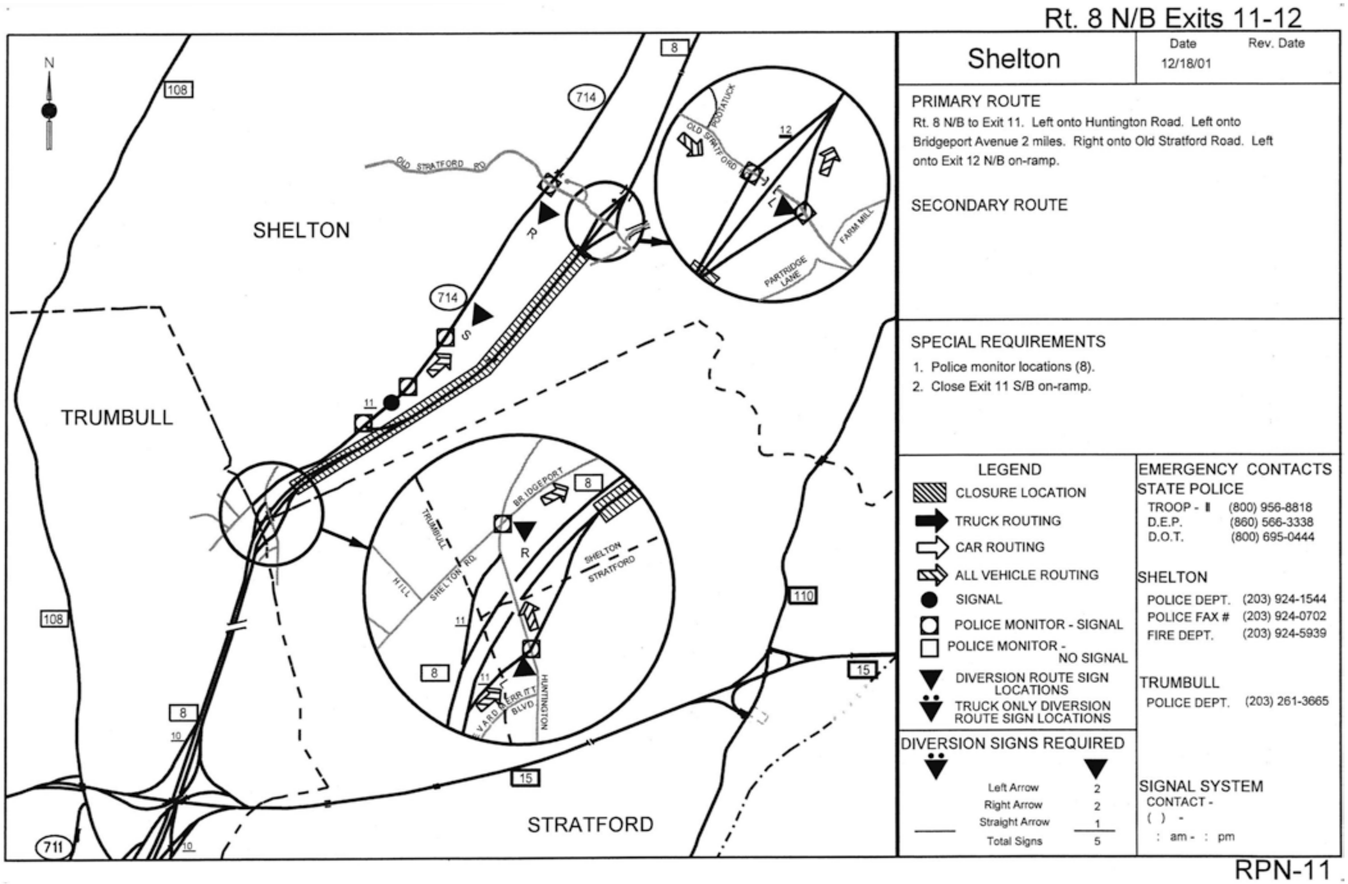


Fig. 4.19 Example of Level 1 diversion plan

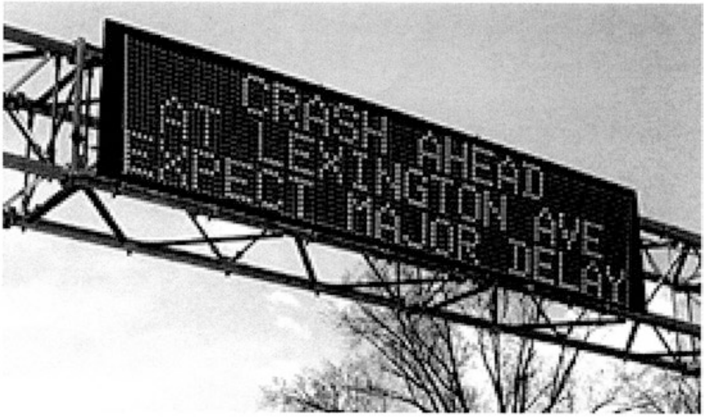


Fig. 4.20 Permanent DMS with moderate strength message

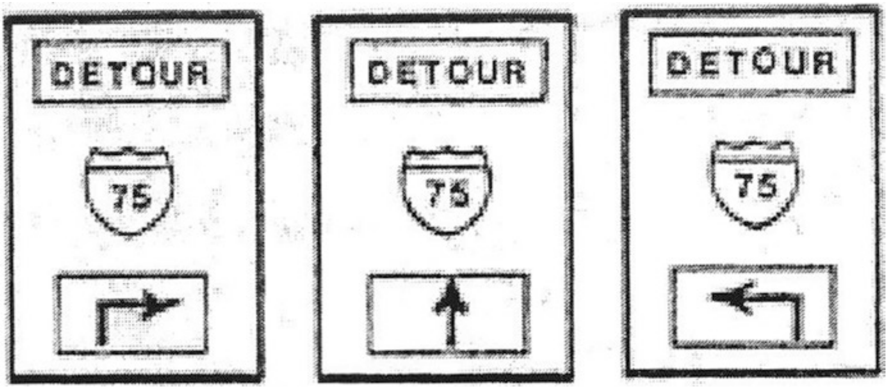


Fig. 4.21 Example of alternate route trailblazers

Since the majority of incidents do not require this level of intervention, diversion is often implemented by ITS devices alone, with little or no police activity to implement diversion.

The most common methodology employed by operating agencies to influence diversion is the dynamic message sign (DMS). An example of a moderate strength message on a permanent DMS is shown in Fig. 4.20 [16]. Permanent DMS are sometimes supplemented with portable DMS for prolonged incidents or construction.

Diversion signs (trailblazers) may be used as shown in Fig. 4.19 to identify alternate routes. Figure 4.21 [17] shows a graphic of alternate route trailblazers. Colored markers are sometimes used to distinguish among multiple alternate routes.

Dynamic trailblazers are static signs with a section that may illuminated or otherwise changed to modify the message when diversion is in effect. Figure 4.22 [18] shows an example of a dynamic trailblazer. Under a "bypass" condition as shown in the upper variable panel, motorists are directed to the diversion route as indicated by the variable arrow. Under normal conditions, the "bypass" panel is blank and the arrow is pointed in the same direction as would a standard static route marker.

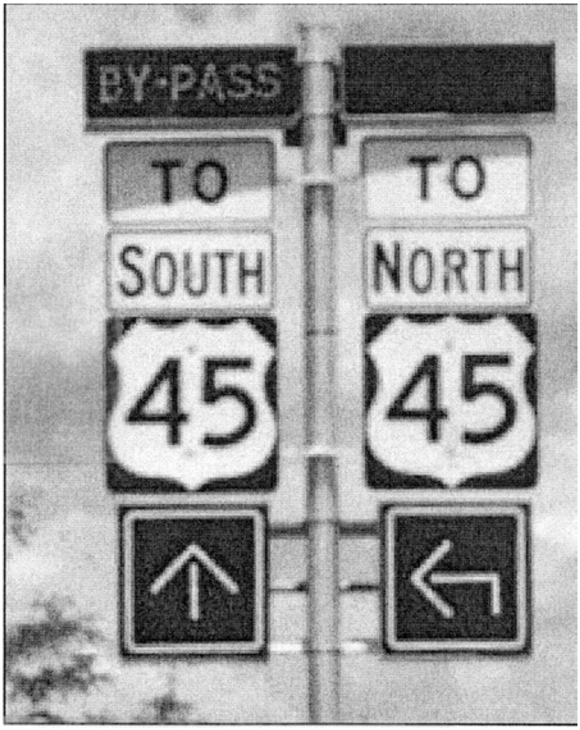


Fig. 4.22 Typical dynamic trailblazer assembly

4.4.6.2 Area Level Diversion (Geographic Level 2)

Characteristics of Area Level Diversion

Diversion routes at this level are often identified by the operating agency to enable diversion strategies and formats for motorist messages to be developed in advance of the diversion need. Diversion routes may consist, in whole or in part, of freeway routes, or may consist entirely of surface street routes. Multiple diversion routes may be employed. The motorist may be advised by means of highway information devices such as dynamic message signs (DMS) and highway advisory radio (HAR) as well as by private traffic information services. The state's 511 services may also be used for pre-trip and en-route information. A portion of the planned alternate route network may be used for a particular incident as shown in Fig. 4.23. The portion of the alternate route selected for diversion may change during the incident period as the queue changes.

The figure shows the portion of the diverted traffic that does not return to the freeway downstream of the incident.

Examples of Area Level Diversion Routes

An example of area level diversion routes in a section of an eastbound limited access highway corridor is shown in Fig. 4.24. This corridor section is in a suburban environment and consists of the eastbound sections of the Long Island Expressway (I-495) and the Northern State Parkway that lie between NY 135 and the Sagtikos

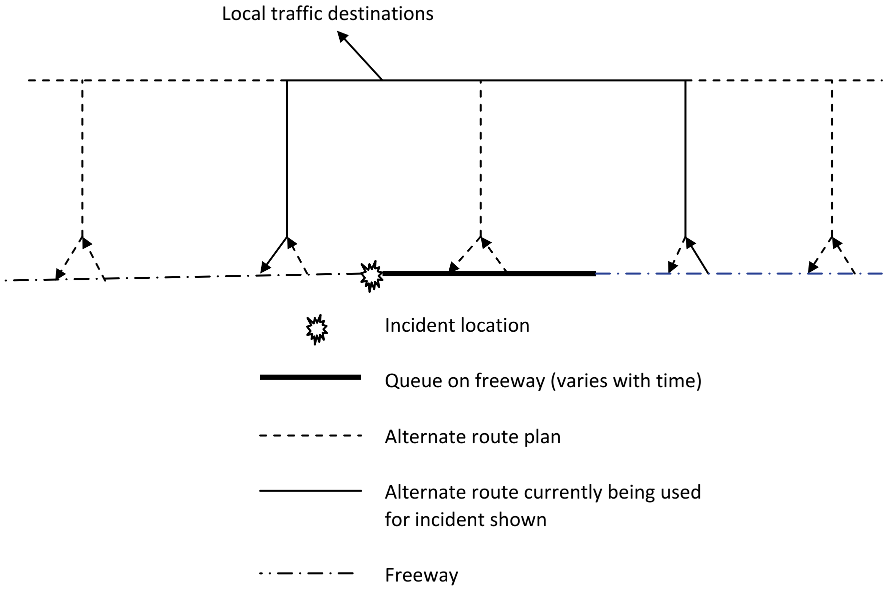


Fig 4.23 Example of Level 2 motorist diversion routing

Fig. 4.24 Area level diversion route alternatives in the Long Island Expressway Corridor

Parkway. The corridor section also has direct crossovers between the major eastbound routes and is approximately 11 miles long. The figure shows those movements that may be influenced by the diversion requirements. Similar Level 2 corridor sections are present to the west of the section shown.

An example of area level diversion that uses surface street alternate routes is shown in Fig. 4.25. It consists of a contiguous set of Level 1 sections. In the event of an incident, information may be used to divert motorists to the frontage road as

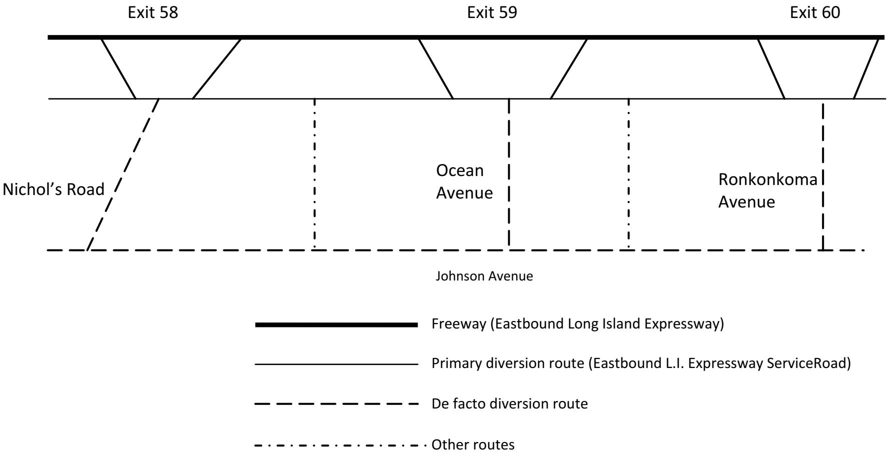


Fig. 4.25 Example of area level diversion routes using surface streets

an alternate (in any case, it is an obvious choice to motorists.) Incident management may call for a change in the signal timing plan on the frontage road to support diversion. Changes in the location of the end of the queue will result in diversion at different exit points. The appropriate diversion location will be described or implied by motorist information. As delays resulting from diverted traffic build up on the frontage road, motorists who are familiar with the local street system may choose de facto diversion routes such as the one shown by dashed lines, as well as others that are not shown.

Coordination of Area Level Diversion Plans

In some cases, area level diversion may require coordinated measures by more than one transportation management center (TMC) or more than one agency. *Concepts of operation* often provide the functional basis for such coordination. In certain locations, operating agencies may be members of a central agency charged with compiling, coordinating, and distributing traffic and incident data among member agencies as well as recommending coordinated response plans. For example in the New York City area TRANSCOM (Transportation Operations Coordinating Committee) operates an Operations Information Center for this purpose.

4.4.6.3 Regional Level Diversion (Geographic Level 3)

Major incidents are likely to cause long delays on the facility on which the incident occurs and on the area level alternates associated with this facility. Travelers whose destinations extend past the locations in the affected corridor may find their travel time reduced and travel reliability improved if they divert sufficiently upstream of the incident, even if such diversion adds considerably to the trip's distance. Limited access highways often constitute the diversion routes. An example of such a diversion is shown in Fig. 4.26. In this example, in the event of a major incident on

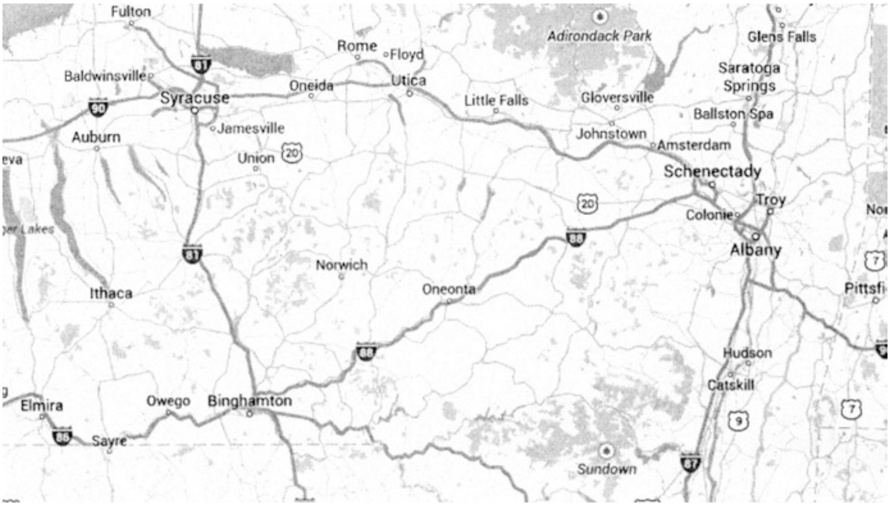


Fig. 4.26 Example of regional level diversion routes

westbound I-88, diversion of traffic originating or passing through the Albany/ Schenectady area and destined for the Binghamton, NY area or beyond might be appropriate. Although the diversion route consisting of I-90, I-481 and I-81increases the trip length from 104 to 169 miles, the congestion resulting from a major incident will, in many cases, result in greater travel time by remaining on I-88 than the additional time required for the diversion routing.

As with area level diversion, regional level diversion often requires the knowledge of traffic conditions from a number of operating agencies. In some cases regional organizations such as the I-95 Corridor Coalition provide traffic condition information to operating agencies and to the public.

4.5 Functional Requirements for Improving Incident Response and Relationship of Improvement Techniques

Traffic management centers implement the functions shown in Fig. 4.1 and discussed in Sect. 4.1.

Incident management is a multi-agency function involving a number of emergency responders. ITS and traffic management centers can assist in incident management by helping to plan management of incident, by providing surveillance and monitoring capability and by facilitating communication among incident responders. Table 4.6 describes a number of functions that can be provided by ITS and traffic management centers.

Table 4.6 ITS and TMC related incident management functions

Incident management function	Stages of incident management			
	Detection and verification	Response	Clearance	Recovery
Coordinate development, archiving and update of incident response plans	√	√	√	√
Integrate traffic incident management needs into operations planning and ITS design	√	√	√	√
Detect an incident and identify its properties (lanes blocked, location)	√			
Classify incident into type and severity	√			
Notify responding agencies of location and character of incident	√			
Improve conventional traffic operations		√	√	
Select response plan. Implement: • Lane and ramp controls • Emergency signal timing plans • Motorist information		√	√	√
Facilitate operations for emergency responders		√	√	√
Provide traffic conditions and/or route guidance to emergency responders		√	√	√
Provide incident information to motorists (see Chap. 5)		√	√	√
Provide tail of queue detection		√	√	√
Terminate incident management functions				√

The relationship between incident management functions and a number of traffic operations and ITS technologies is shown in Table 4.7. Sections 4.5.1 and 4.5.2 discuss the effective application of certain of these operations and technologies. Chapter 5 discusses motorist information.

4.5.1 Improving Incident Detection and Verification

The following sections discuss commonly used approaches to incident detection and verification.

4.5.1.1 Public Service Access Points

Most freeway incidents are detected by motorist cellular telephone calls to public service access points (PSAPs) providing 911 service. In many cases, this information is provided to traffic management centers on a data channel using filters to restrict the

Table 4.7 Traffic operations and ITS technologies for incident response

Operations and technologies	Functions						
	Incident detection and verification	Incident classification	Response plan implementation	Emergency responder operations	Traffic information for emergency responders	Tail of queue detection	Termination of incident management
CCTV	√	√	√	√	√	√	√
Traffic detectors	√		√		√	√	√
911 service	√	√					
Traffic reporting service	√		√		√		
Service patrols	√	√		√			
Police services	√	√	√	√			
TMC information displays	√	√	√				
Lane controls			√				
Ramp meters			√				
Emergency signal timing plans			√				
Incident command system		√	√	√			
Surveillance and travel time on alternate routes			√	√	√		
Traffic information for emergency service providers				√	√		
In vehicle information for emergency service providers				√	√		

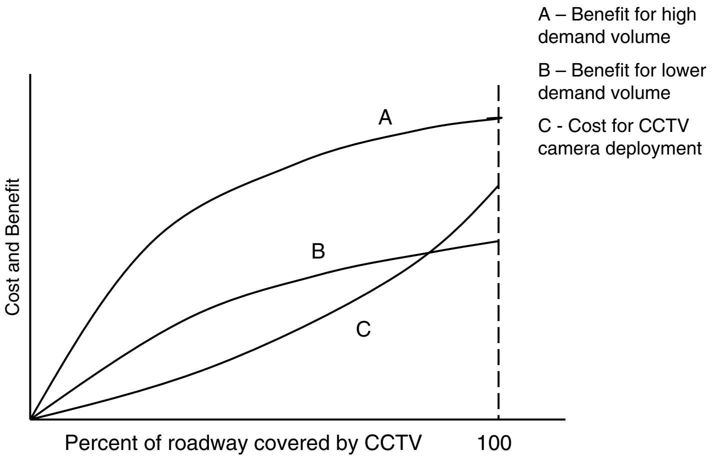


Fig. 4.27 Benefit and cost of CCTV coverage

information to traffic related incidents. When the call originates from a vehicle involved in an incident, position information is automatically available. In some cases the information is suitable for verification, but in other cases other verification techniques (usually CCTV observation, police responses or motorist service patrols) are required.

4.5.1.2 CCTV

CCTV and traffic detectors may detect incidents more rapidly than other techniques such as 911 calls. CCTV provides the capability to identify the type of incident and its properties, thus providing verification as well as detection. This information may be used to determine the types of emergency services required. Verification by CCTV is often the fastest way to accomplish this function. In many cases, the number of CCTV cameras on the freeway far exceeds the number of monitors available in the traffic management center. When this occurs, automated camera "tours" are commonly employed to allow the operator to rapidly monitor large sections of the roadway.

Incidents that are not the result of accidents are generally distributed evenly along the roadway. Accidents more frequently occur within or near interchanges. Furthermore accidents generally require more time to clear. Thus the benefits for cameras are greatest when they are placed in the interchange area. Figure 4.27 shows the general relationship for cost and benefits of CCTV placement. Curve A in this figure represents the benefit as a function of percent coverage for the case where demand volumes are high. The concave shape results from the higher benefits of the cameras at or near the interchange area where the accident rate is generally higher than in the roadway portion away from the interchange. Curve B shows the benefits when the demand volume is lower (see Fig. 4.4 as an example of incident delay sensitivity). Curve C is the cost of installing CCTV cameras. Curve C is convex because as the percentage of the roadway covered increases, the likelihood of overlapping camera coverage increases. This increases the number of cameras employed per mile of roadway. For each deployment alternative (represented by a value for the roadway percent covered) the line segment between the benefits curve and the cost curve represents the net benefits. The net benefit can possibly become negative when excessive CCTV coverage is provided for low demand volume situations.

Reference [11] provides guidance for the initial consideration of camera locations as a function of traffic conditions. As discussed in Chap. 3, it defines traffic conditions in terms of deployment "levels" as follows:

- Level 3—A continuous section of roadway in one direction that includes peak hour level of service D or worse traffic for at least one half of the section.
- Level 2—A continuous section of roadway in one direction that includes peak hour level of service C or worse traffic for at least one half of the section. Conditions worse than level of service C may be present at scattered spot locations or for small sections. In this case, it may be appropriate to increase the concentration of field equipment at these locations.
- Level 1—Traffic conditions better than Level 2.

Guidance for the initial consideration of camera placement is shown in Table 4.8 [19]. Because the classification levels and application factors cover broad ranges of conditions, the consideration of deployment alternatives is recommended.

Appendix B describes a measure for the relative effectiveness (RTV) of CCTV coverage based on the fraction of incident periods observable by CCTV. An example of this measure for a particular roadway section is shown in Fig. 4.28. A worksheet (*RTV*) for computing RTV from section accident data is described in Appendix B and is provided on the website http://www.springer.com/us/book/9783319147673.

4.5.1.3 Traffic Detectors

Traffic flow at any point on the roadway is governed by the general traffic equation discussed in Sect. 3.1.1.1 and repeated below:

$$q = k \cdot u \tag{3.1}$$

where

q = volume (vehicles per hour per lane).
k = density or concentration (vehicles per mile per lane).
u = space mean speed (miles per hour).

Table 4.8 Considerations for preliminary location of CCTV cameras

Deployment level	Application factor
1	High accident rate locations. Other locations as deemed necessary
2	High accident rate locations, freeway-to-freeway interchanges, spot congestion locations. Other locations as deemed necessary
3	Continuous coverage (average 1.5–2.0 cameras per centerline mile)

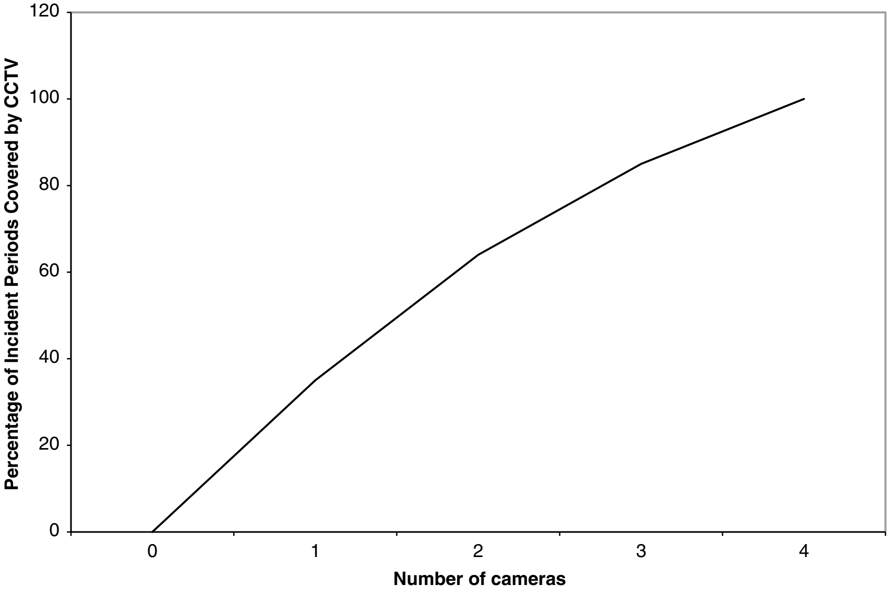


Fig. 4.28 Incident periods covered vs. number of cameras

Point and probe detectors are discussed in the following sections. Point detectors can sense a sufficient complement of variables in each lane to enable the application of (3.1) to each sensed lane of traffic. Probe detectors essentially provide a sample of travel times from which speed may be computed for the sensed section. The probe technologies discussed in this section are generally not lane specific.

Point detectors

Point detectors sense lane volume, speed and lane occupancy at a particular location. All detector types do not necessarily sense all variables. Most point detectors can provide data for each traffic lane. Aggregation of detector data into the traffic parameters is performed periodically.

Detector technologies that are commonly used for freeway monitoring include:

- *Inductive loop detectors* (*ILDs*). The ILD provides measurements of lane volume and lane occupancy (the fraction of time that the vehicle occupies the loop in the pavement.) ILDs may be used in pairs or singly in a lane. When used in pairs, time mean speed may be accurately measured by the time between activations of each detector in the pair. This may be converted to space mean speed by means of (3.2) and density may be computed from (3.1). When used singly, in addition to volume, the ILDs sense lane volume and lane occupancy (the fraction of time that the vehicle spends over the inductive loop). When a single detector in each lane is used, in order to calculate speed an assumption must be made about the average vehicle length and the average apparent loop length. While many agencies use a constant coefficient for this value, Caltrans uses a "g" factor to relate occupancy to speed for each detector as a function of time of day as shown in

(4.11) [20]. The following relationship of the g factor to speed is given by Jia et al. [21].

$$v(t) = g(t) \times \frac{c(t)}{o(t) \times T} \tag{4.11}$$

where

v(t) is the average time-mean-speed.
c(t) is the number of vehicles crossing the detector during the averaging period.
o(t) is the fraction of time that a vehicle is sensed.
T is the averaging period.

While probably the most accurate point detector type, the difficulty of maintaining inductive loop detectors over long periods of time has led some agencies to use non-pavement-invasive technologies that do not require lane closures for maintenance.

- *Frequency modulated continuous wave radar detectors*. This type of detector has found increasing use because of its adequate performance and non-pavement invasive feature. Volume and time-mean speed are usually detected quite accurately, however very slow speeds may affect performance.
- *Magnetometer detectors*. Recent improvements in technology have resulted in a type of detector consisting of a battery powered magnetic sensor that is installed flush with the pavement and a wireless link to a roadside processor. Battery life is a function of traffic volume. Maintenance includes installing another sensor unit when the battery life is exceeded.
- *Video processing detectors*. The need to clean and readjust these detectors from time to time as well as lighting, sun glint and weather considerations has encouraged some agencies to select alternative technologies for freeway applications.

Klein [22] discusses detector technologies in detail. Detector data is most commonly displayed in the traffic management center as a map presentation that is color coded according to speed. Closer detector spacing improves the location of the lower speed indications that may result from an incident. Using historical experience, operators often infer the presence of a potential incident, and use other means such as CCTV, 911 information, service patrols and police reports to confirm the incident and to provide additional information. Point detectors also provide information for other than incident detection functions as described in Chaps. 5–7. Reference [19] provides guidance for point detector spacing. For urban freeways with significant congestion, spacing of 0.3–0.4 miles (0.48–0.64 km) is recommended. A general approach for placing detectors is:

- Identify sites for mainline stations required for ramp meters if they are to be employed.
- Add additional stations so that mainline roadway portions between each entry and exit location has a station.
- Add detectors so that gaps do not exceed 0.33 miles (0.53 km).
- Modify detector locations to avoid very short spacing.

Typical spacing on freeways with ramp metering may average 0.25–0.33 directional miles (0.40–0.53 directional kilometers).

Traffic detectors often malfunction or provide data that is not accurate. In order to maintain the functionality of the applications requiring this data, freeway management systems often include techniques that identify malfunctioning detectors and synthesize data to replace the bad or missing data. List et al. [23] provide a detailed discussion of imputation concepts that use data from surrounding detectors.

Point detectors may be used for incident detection as described in the following sections.

4.5.2 Point Detectors For Incident Detection Without Incident-Detection Algorithms

Although other techniques such as CCTV, 911 calls and police reports are the primary sources on incident detection, many agencies use point detectors to help assist in incident detection. For example, map displays show the speed for zones in the roadway. The zone is usually defined as the approximate midpoint between the locations of two detector stations. While the display does not directly indicate an incident in the zone, an experienced operator, using his historical knowledge of expected traffic conditions, may often infer the possible presence of an incident, particularly when the incident occurs in off-peak periods. This tentative detection requires confirmation by other means.

When a traffic incident occurs that results in the demand upstream of the incident exceeding the remaining capacity of the roadway, a queue begins to form at the incident site, thus increasing density and reducing the speed upstream of the incident. The queue builds with time and causes a shock wave to propagate upstream of the incident. The time required for this shock wave to reach the traffic detector determines, in large measure, the time delay in the operator's ability to detect the incident in this way. The following discussion provides an example of how this time may be estimated. The equation for the velocity of propagation of the shock wave is [24]

$$w_{AB} = \left(q_A - q_B\right) / \left(k_A - k_B\right) \tag{4.12}$$

where k and q are as defined above. Subscript A identifies the conditions in the queue downstream of the shock wave boundary and subscript B describes the conditions upstream of the boundary.

The following is an example of the average incident detection time for point detectors when applied in this way. Figure 4.29 diagrams the propagation of the shock wave and describes the conditions found in the example.

The following parameters were used for the volume and density upstream and downstream of the incident

$q_A = 1100$ vehicles per hour.
$q_B = 1600$ vehicles per hour.
$k_A = 110$ vehicles per mile.
$k_B = 26.7$ vehicles per mile.

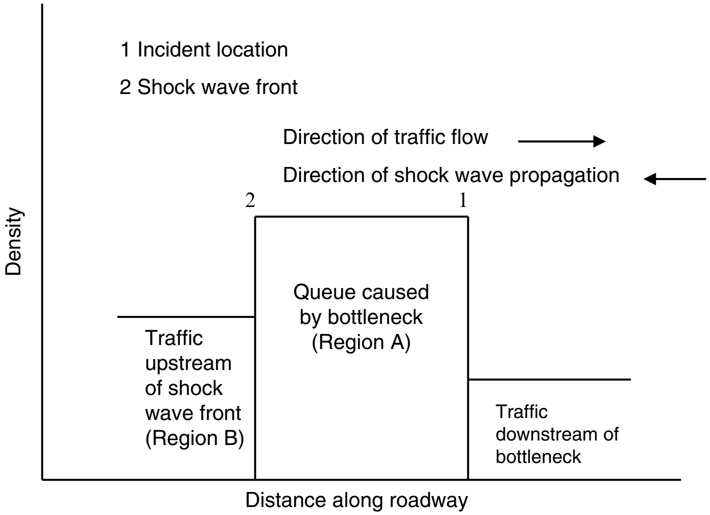


Fig. 4.29 Shock wave propagation for a bottleneck caused by an incident

Applying (4.12), a shock wave propagates upstream of the incident at a speed of 6 mph. If detector stations are spaced at intervals of 0.25 miles, the wave will take 2.5 min to travel that distance. Assuming that incidents are randomly spaced between detectors, an average propagation time of half of this value will result. To this must be added the time to smooth and process the detector data (typically 1 min). Figure 4.30 shows the average detection times for different detector spacing based on this example.

Since detection time depends on the incident scenario, it is useful to define a parameter B1 to represent the timely detection probability for a range of scenarios for different detector spacing. The models for incident management effectiveness discussed in Sect. 4.6.3 employ parameter B1. An example of a value set for B1 is provided by the following expression based on average point detector spacing.

0.4 mi ≥ spacing, B1 = 0.9.
0.7 mi ≥ spacing > 0.4 mi, B1 = 0.7.
1.0 mi ≥ spacing > 0.7 mi, B1 = 0.5.
2.0 mi ≥ spacing > 1.0 mi, B1 = 0.3.
Spacing > 2 mi, B1 = 0.1.
No detectors, B1 = 0.0.

4.5.3 Point Detectors With Automatic Incident-Detection (AID) Algorithms

The previous section describes a manual technique for incident detection. Although not employed by most agencies, techniques that process point detector data have been used, with varying degrees of success, to alert the operator to the possible presence of an

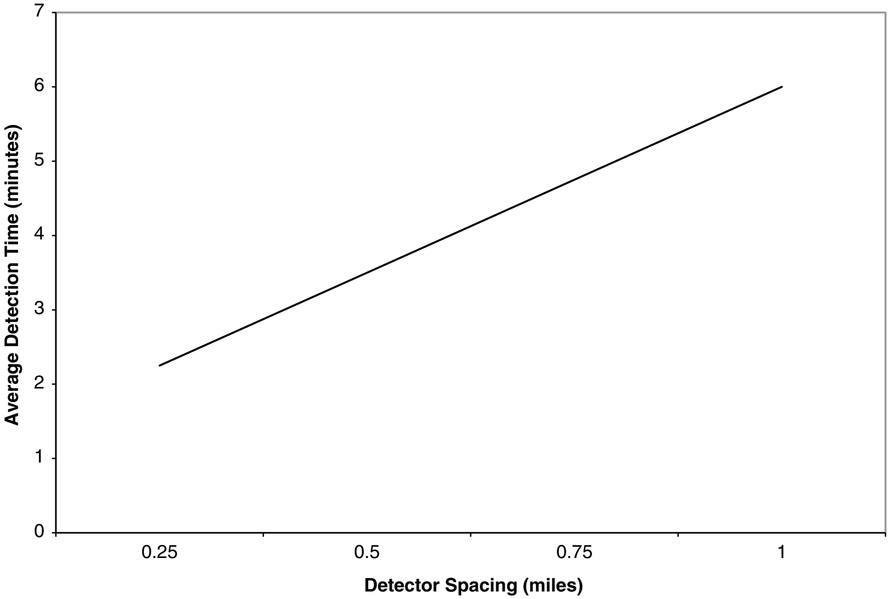


Fig. 4.30 Example of average detection time

incident [4, 25, 26]. Criteria for assessing the quality of AID algorithms include detection rate, false alarm rate and time to detect. Based on these criteria, the performance of these algorithms has generally not measured up to that achievable by other means. Martin [25] concludes that "the use of video coverage on the freeway systems and ever-expanding use of cell phones has made the need for AID algorithms less important."

Probe detection. Probe detection consists of determining the difference in arrival times of a vehicle at two pre-established locations. Some technologies use roadway equipment to establish these locations, other technologies may provide virtual locations. This process has been termed vehicle matching or vehicle re-identification. Common probe detection technologies include:

- *Toll tags and toll tag readers*. A high percentage of vehicles are equipped with toll tags in locations where toll facilities are commonly used. Vehicle matching techniques employed by public agencies protect the identity of the vehicle. The TRANSMIT system is a probe system based on the use of toll tag readers is an example of this approach. Test results showed the probability of incident detection to be approximately 89 % on the New York State Thruway and 72 % on the Garden State Parkway. False alarm probabilities ranged from 10–22 % on the New York State Thruway and from 16–32 % on the Garden State Parkway. In recent years the TRANSMIT system has been extended in the New York City metropolitan area, and to other locations on the New York State Thruway [27]. Incident detection time, and the precision with which an incident may be located depends on the distance between the locations used to estimate the travel times. In the case of infrastructure based readers, reducing this distance requires significant expenditure.

- *Private traffic information services based on GPS technology*. With the motorist's permission and cooperation, cellular telephone communication or other communication techniques transmit the vehicle's location to a privately operated center for re-identification, development of speed, travel time and routing information. Cooperating motorists may also provide other information such as incidents, construction and weather conditions. In some cases, the firm combines the probe information with information from TMCs and other sources.
- *Bluetooth readers*. Bluetooth is an open, wireless communication platform used to connect myriad electronic devices. Many computers, car radios and dashboard systems, PDAs, cell phones, headsets, or other personal equipment are, or can be, Bluetooth-enabled to streamline the flow of information between devices. The interconnection between Bluetooth devices is achieved through the transmission and acceptance of a 48-bit Machine Access Control, or "MAC", address between inquiring and receiving devices. A small transceiver is constantly transmitting its device-specific MAC address in an effort to find other devices with which to communicate. Once a Bluetooth device is connected to another, the transmission of this MAC address continues. Although duplicates may exist, manufacturers typically assign unique MAC addresses to Bluetooth-equipped devices. These unique addresses are not tracked or readily available when devices are sold within the marketplace, making them a personal information-free identifier. The constant broadcast of these MAC addresses is detectable and measurable without establishing a relationship to personal or otherwise sensitive information, keeping the traveling public and their information anonymous. Matching the MAC addresses between two locations establishes the travel time between these locations. A general rule of thumb is to achieve three matched pairs every 5 min, or nine matched pairs per 15 min, 36 matched pairs an hour, or 864 per day [28]. Match rates ranging from 3.5 to 4.7 % were experienced on I-76 in Philadelphia [28].

While probe detection is most commonly used to provide travel times, it can provide incident detection capability through a comparison of current and historic travel time.

4.5.3.1 Motorist Service Patrols and Police

Motorist service patrols are available in many locations during significant portions of the work-week. They may be available at other times as well. Motorist service patrols not only detect and confirm incidents but also help clear minor incidents and assist other responders in incident clearance and traffic management.

Police patrols also detect and confirm accidents. Police are often the first responders when incidents have been detected.

In some cases, logs from other agencies may be used to assist in traffic management. Figure 4.31 [29] shows an example of an incident management log provided by the California Highway Patrol. Detailed information is shown in the lower portion of the figure for a particular incident.

CHP Traffic Incident Information Page

Golden Gate Communications Center

Number of Incidents: 16

Updated as of 3/15/2013 6:49:08 AM

☐ Auto Refresh Off ● List ○ Map

	No.	Time	Type	Location	TBM/LATLON
Details	**00355**	**6:45 AM**	**Trfc Collision-Unkn Inj**	**Sr121 / Sr128**	38.445540 -122.1964
Details	00011	6:43 AM	Trfc Collision-No Inj	Us101 S / Us101 S Lucky Dr Ofr	37.939346 -122.5163
Details	00352	6:41 AM	Trfc Collision-No Inj	Us101 S / Us101 S Lucky Dr Ofr	37.939346 -122.5163
Details	00010	6:39 AM	Reporting Car Fire	I280 S / I280 S Alemany Blvd Ofr	37.732277 -122.4149
Details	**00350**	**6:38 AM**	**Hit and Run No Injuries**	**3839 Emery St**	37.828943 -122.2804
Details	00009	6:38 AM	Traffic Hazard	I680 S / I680 S Gold Hill Rd Ofr	38.185908 -122.1361
Details	00346	6:37 AM	Car Fire	I280 S / I280 S Alemany Blvd Ofr	37.732277 -122.4149
Details	00345	6:34 AM	Traffic Hazard	I680 S / I680 S Gold Hill Rd Ofr	38.185908 -122.1361
Details	00007	6:26 AM	Traffic Hazard	I880 N / I880 N High St Ofr	37.763330 -122.2161
Details	00333	6:24 AM	Traffic Hazard	I880 N / I880 N High St Ofr	37.763330 -122.2161

Incident: 00352 Type: Trfc Collision-No Inj Location: Us101 S / Us101 S Lucky Dr Ofr TBM/LatLon: 37.939346 -122.516389 Close

Detail Information

6:51 AM	9	[14] A34-010 4 LNS BLKD [Shared]
6:48 AM	8	[13] [Notification] [FSP]-FSP 97,BIG RIG IS MOVEABLE,BUT DELIVERY TK IS NOT--TRYING TO CLR BIG RIG TO RHS AT THIS TIME--PLZ KEEP CHP ROLLING [Shared]
6:44 AM	7	[12] 1039 MARIN CO FIRE [Shared]
6:44 AM	6	[11] LL FIRE [Shared]
6:43 AM	5	[3] UNK IF DELIVERY TK CAN MOVE OO RDWY
6:43 AM	4	[2] BLKG SLOW LN
6:43 AM	3	[8] [2] BLKG LN # 3 [Shared]
6:43 AM	2	[1] BLU/WHI BIG RIG VS WHI DELIVERY TK
6:42 AM	1	[7] [1] BIG RIG VS LARGE BOX MOVING TK [Shared]

Unit Information

6:48 AM	3	Unit Assigned
6:48 AM	2	Unit Enroute
6:51 AM	1	Unit At Scene

Fig. 4.31 California Highway Patrol traffic incident information page

4.5.4 *Improving Incident Response, Clearance and Recovery Through ITS*

Agencies often classify incidents by severity and provide response measures according to these classifications.

4.5.4.1 Incident Response Plans

The coordination of incident response planning is generally accomplished by the stakeholders, often through a group or committee established for that purpose. The traffic management center's responsibilities typically include:

- Development a coordinated set of motorist information messages.

- Identification of suitable alternate routes and development of emergency signal timing plans to support diverted traffic.
- Operation of ancillary controls and displays such as lane control signals, blank out signs and dynamic trail-blazers.

Figure 4.32 [30] shows how a selection of a response plan is influenced by the incident classification level and by expected traffic conditions.

		Lanes Impacted / Action Level			
Time of Day	**Estimated Duration**	0 Lanes	1 Lane	2 Lanes	>2 Lanes
0000 - 0600	< 2 hours	0	0	1*	3*
	2-4 hours	0	0	2*	3*
	>4 hours	0	0	2*	3*
0600 - 1000	< .5 hours	1	1	2	3
	.5 - 2 hours	1	1	2	4
	> 2 hours	1	2	3	4
1000 - 1500	< 2 hours	1	1	2	3
	2-4 hours	1	1	2	3
	> 4 hours	1	2	3	3
1500 - 1900	< .5 hours	1	1	2	3
	.5 - 2 hours	1	1	2	4
	> 2 hours	1	2	3	4
1900 - 2400	< 2 hours	0	0	1*	3*
	2-4 hours	0	0	2*	3*
	> 4 hours	0	0	2*	3*

Level 0	No special action required
Level 1	Implement Response Plan to notify appropriate PSAs Turn on Level 1 CMS and HAR
Level 2	Implement Response Plan to notify appropriate PSAs Turn on Level 2 CMS and HAR Turn HAR flashing lights on a level 2
Level 3	Implement Response Plan to notify appropriate PSAs Turn on Level 3 CMS and HAR Turn HAR flashing lights on a level 3 Provide Advisory Alternate Routing
Level 4	Implement Response Plan to notify appropriate PSAs Turn on Level 4 (and above) CMS and HAR Turn HAR flashing lights on a level 4 Provide Mandatory Alternate Routing

Level n CMS	n = number of decision points prior to the incident corridor
Level n HAR	n = number of times the related advisory is repeated in a HAR cycle (e.g. within a 3 minute cycle)
Level n*	* = notification of operations personnel may be required to implement outside normal duty hours

Fig. 4.32 ARTEMIS incident response plan selection

4.5.4.2 Improved Interagency Communication

Many of the states structure their incident response approach according to the guidelines provided by the National Incident Management System (NIMS) and the Incident Command system (ICS). Appendix G provides a discussion of these systems.

Cooperation and coordination among agencies that provide incident responders are important to the success and efficiency of the incident management and clearance process. Important elements of this process include the following:

- Concept of Operations. The Conops defines the roles and responsibilities of the participating agencies. An example of this is shown in Table 4.9 from the Concept of Operations for the Philadelphia area [31]. The agencies and their responsibilities are summarized in the chart.

Table 4.9 Philadelphia area incident management roles and responsibilities

Area	Stakeholders	Roles and responsibilities
Traffic management centers	NJDOT STMC/TOC South	• Conduct traffic surveillance, identify incidents • Notify 9-1-1 center that an incident has occurred • Dispatch ESP vehicles for traffic control • Post information on VMS signs • Enter incident information into 511 • Notify other entities via RIMIS • Modify traffic signal timings on detour routes • Request maintenance crews for clean up • Provide information to ISPs and media • Develop/implement traffic control plan for special events
	PennDOT District 6-0 RTMC	
	BCBC TOC	
	DRJTBC Offices	
	DRPA TPC	
	NJ County TOCs	
	NJTA TMC	
	Philadelphia TOC	
	PTCOCC	
	SJATOC	
9-1-1 call centers	NJ County 9-1-1 s	• Receive 9-1-1 call from the public • Dispatch first responders • Verify incident from traffic management video • Dispatch additional police, fire, EMS resources
	NJSP Troop Dispatch	
	PA County 9-1-1 s	
	PPD Radio Room Dispatch	
	PSP Norristown CDC	
Emergency responders	NJSP	• Determine first responder resources needed • Conduct traffic investigation, traffic control • Implement ICS procedures • Request additional resources as needed
	PSP	
	BCBC Police	
	DRPA Police	
	Municipal Police, Fire, EMS	
	PPD Philadelphia Fire Dept.	
Information service providers	NJDOT 511/Traveler Info	• 511 systems update their databases and maps • Update ISP/TMAs databases and maps • Issue traveler alerts to people signed up for them
	PennDOT 511/Traveler Info	
	NJTA 511/Traveler Info	
	PTC Traveler Info	
	SJTA 511/Traveler Info	
	ISPs	
	NJ and PA TMAs	

(continued)

Table 4.9 (continued)

Area	Stakeholders	Roles and responsibilities
Maintenance offices	NJDOT Maintenance	• Receives request for assistance from 9-1-1, police, or traffic management • Dispatched maintenance crew
	PennDOT District 6-0 County maintenance	
	DRPA Bridge Maintenance	
	BCBC Maintenance	
	DRJTBC Offices	
	NJTA Maintenance	
	NJ County Public Works Departments	
	Philadelphia Streets Department	
	PTC Maintenance Offices	
	SJTA Maintenance	
Special events operators	Event operators	• Notify traffic management about upcoming special events

- Interagency agreements that may be needed to implement these responsibilities.
- A center-to-center communications plan and architecture for sharing text, voice and video. Figure 4.33 shows the incident related communications flow for the Illinois Tollway [32].

Improved sharing of information and coordination of response operations may be facilitated by the following:

- Co-location of management centers. Those which are most commonly co-located include operations centers for freeway traffic management, traffic signal control, police operations and emergency management centers.
- Use of ITS standards protocols. These protocols facilitate the migration of information among management centers. Management centers commonly support the National Transportation Communications for ITS Protocol (NTCIP) [33] and the IEEE 1512 standards suites [34].

4.5.4.3 Provision of Traffic Information to Responders

The detector technologies described in Sect. 4.5.1.3 may be used to provide speed, travel time or routing to emergency responders and to motorists. Private traffic information services may also be used. If the information for the freeways and major surface streets is provided to emergency service providers, they often have the capability to alter their access routes to the incident, or to use vehicles located more favorably with respect to congestion patterns. This information is best provided in the form of speed or congestion maps, or by instructions depicting the quickest route. Updated traffic information may be provided by in-vehicle visual and audio displays. Provision of this capability to emergency responders requires knowledge of travel times on the freeway and on the alternate routes that may be employed to access the incident.

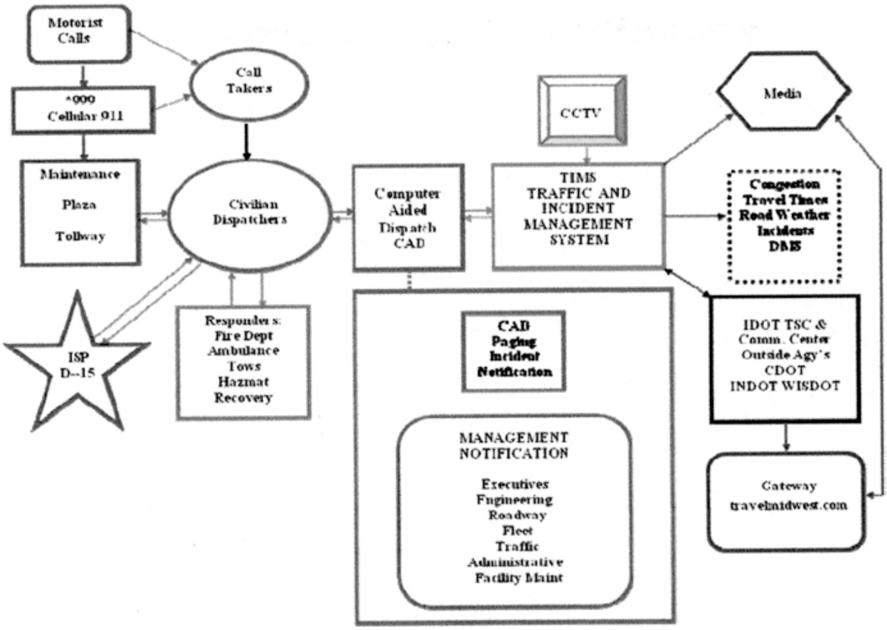


Fig. 4.33 Incident communication flow for Illinois Tollway

4.5.4.4 Definition and Management of Major Response Routes

The following emergency route management measures will facilitate more rapid access.

- Traffic signal preemption. Techniques include preemption of individual traffic signals by the use of wireless, optical or sonic communication links to the intersection. Traffic signals may also be preempted along pre-planned routes from designated dispatch centers such as fire department facilities.
- Establishment of priorities for roadway maintenance operations that benefit emergency response vehicles. Lane closures or other capacity reducing maintenance activities along routes commonly used by emergency responders may increase travel time on these routes. Planning maintenance activities so that lane closure time is minimized, and coordinating maintenance and construction so that alternate routes used by emergency vehicles are not simultaneously impacted is an important step to improving emergency vehicle access. Similarly, providing priority treatment for snow and ice removal along these routes will improve response time. Input from emergency service responders can assist in identifying specific locations for priority treatment.
- Emergency vehicle turnarounds on freeways. Travel times from emergency vehicle locations to high incident rate freeway sections may be improved by the use of appropriately located emergency vehicle turnarounds. Access to these turnarounds may be protected, if necessary, by the use of gates that are remotely operated by emergency vehicles.
- Coordination of construction planning with emergency vehicle route requirements.

- Coordination of traffic calming plans with emergency vehicle route requirements. Traffic calming treatments often have an adverse effect on the speed and accessibility of emergency service vehicles. It is important for the agencies involved in developing traffic calming plans to coordinate with emergency service providers. Atkins and Coleman [35] discuss the effect of traffic calming measures on emergency vehicle speeds. This research has led Portland, Oregon to classify a number of streets as major emergency response streets. Traffic preemption devices are emphasized and traffic-slowing devices are avoided on these streets. Other locations [36] have also addressed this issue.

4.5.4.5 Tail of Queue Detection

During the progress of an incident, the tail of the queue progresses upstream. The tail may be at a considerable distance from the incident site, thus making its location difficult to identify by on-site personnel. Point detectors and CCTV may be used to provide this information (CCTV provides a labor intensive solution that may be inappropriate when a number of incidents must be simultaneously monitored). Detecting the tail of the queue serves the following functions:

- Assists on site personnel to adopt appropriate traffic management measures.
- Assists emergency vehicles to find the best route to the incident.
- Assists in the selection of appropriate motorist information messages and routing plans. As the tail of the queue continues to build after the incident has been cleared, this function continues even after the emergency responders have left the scene. Section 10.4 provides additional descriptions of queue warning systems.
- Termination of queue. It is important to detect this event so that motorist information messages do not indicate the presence of an incident after the queue is cleared. Point detectors and CCTV may be employed for this purpose.

4.6 Measuring Incident Management Effectiveness

Incident management effectiveness may be viewed from a number of perspectives as described in the following sections.

4.6.1 Degree of Attainment for Recommended Management Functions, Operations and Technologies

FHWA has established a Traffic Incident Management Self-Assessment program for this purpose. An example of the type of issues covered and the score from responders is shown in Table 4.10.

Table 4.10 Example of Self-assessment questions and responses [37]

Question number	Question	% of assessments scoring 3 or higher
4.2.1.1.	Have established criteria for what is a "major incident"—incident levels or codes?	17 %
4.2.1.2.	Identify high ranking agency members available on 24/7 basis to respond to a major incident?	77 %
4.2.1.3.	Have a pre-identified (approved) contact list of resources (including special equipment) for incident clearance and hazardous materials response?	66 %
4.2.1.4.	Have the response equipment pre-staged for timely response?	44 %
4.2.2.1.	Train all responders in traffic control procedures?	30 %
4.2.2.2.	Utilize on-scene traffic control procedures for various levels of incidents in compliance with MUTCD?	29 %
4.2.2.3.	Utilize traffic control procedures for the end of the incident traffic queue?	14 %
4.2.2.4.	Have mutually understood equipment staging and emergency lighting procedures on-site to maximize traffic flow past an incident while providing responder safety?	16 %
4.2.3.1.	Utilize the Incident Command System?	54 %
4.2.3.2.	Have specific policies and procedures for fatal accident investigation?	51 %
4.2.3.3.	Have specific policies and procedures for hazardous materials response?	69 %
4.2.3.4.	Have quick clearance policies?	36 %
4.2.3.5.	Have a pre-qualified list of available and contracted towing and recovery operators (to include operators' capabilities)?	74 %
4.2.3.6.	Use motorist assist service patrols?	70 %

4.6.2 General Measures

While general ITS performance measures such as reduction in delay and crashes also pertain to incident management, measures that have been identified as directly pertinent to incident management include [38]:

- Roadway clearance time (the time between first recordable awareness of an incident and the time that all lanes are available).
- Incident clearance time (time between the first recordable awareness of an incident and the time that the last responder leaves).
- Secondary crashes.

4.6.3 Model for Evaluating Incident Management Effectiveness

The following sections discuss a model for evaluating alternative ITS design concepts as applied to incident management. The model computes a parameter (H) ranging from 0.0 to 1.0 that represents the potential ability of the ITS to effectively provide incident management support. The model is discussed below.

4.6.3.1 Relationship of Incident Management Functions to Techniques and Technologies

The parameter H considers the following functional requirements:

1. Timely detection of incidents (H_1).
2. Timely confirmation and classification of incidents (H_2).
3. Timely assistance provided by the TMC in managing incident response and clearance (H_3).
4. Timely detection of the tail of the queue and the termination of the queue (H_4).

The probability that each of the above events has the potential to be satisfied depends on the technologies and operations employed.

Table 4.11 uses the index g to represent these functional requirements. V_{ng} is a value that represents the potential ability of the technology or operation to satisfy requirement g. Representative values are provided in Table 4.12.

Table 4.11 Probability of satisfying functional requirement

Technologies and operations	Probability that requirement is satisfied
1. 911/PSAP information availability	V_{1g}
2. Police operations	V_{2g}
3. CCTV	$V_{3g} \cdot \mathrm{RTV}$
4. Motorist service patrols	$V_{4g} \cdot \mathrm{K35} \cdot \mathrm{K40}$
5. Electronic traffic detection (point or probe)	$V_{5g} \cdot \mathrm{B1}$

Table 4.12 Default Values for V_{ng}

	Technologies				
Functional requirements (g)	V_{1g}	V_{2g}	V_{3g}	V_{4g}	V_{5g}
1. Timely detection	0.6	0.3	0.9	0.5	0.4
2. Timely conf. and class.	0.3	0.6	.9	0.5	0.2
3. Timely assistance	0	0.9	.8	0.5	0.2
4. Tail of queue and termination	0	0.1	0.5	0.2	0.8

In the table

B1 = timely detection probability for a range of scenarios for different detector spacing (Sect. 4.5.1.3).
RTV = Fraction of roadway incidents observed by CCTV (Appendix B).
K35 = Correction factor for level of service patrols (Appendix F).
K40 = Scaling factor for service patrols (Appendix F).

The user may choose to modify these values based on experience or based on special considerations pertaining to the application.

4.6.3.2 Model for Incident Management Effectiveness Potential

A value H_g is required to represent the effectiveness potential for each of the incident management functional requirements. Since the contributions of the technologies towards supporting incident management overlap, a technique is required to model these interactions. The technique employed uses a combination of probability theory and Bayesian inference (for example see Klein [22]). To compute H_g

H_g = 1–probability that no technology satisfies function g.

Probability that no technology satisfies the function = (1 – probability of satisfaction by technology 1) • ………. • (1 – probability of satisfaction by technology 5).

Thus H_g is provided by

$$H_g = 1 - (1 - V_{1g}) \cdot (1 - V_{2g}) \cdot (1 - V_{3g} \cdot RTV) \cdot (1 - V_{4g} \cdot K40\,K35) \cdot (1 - V_{5g} \cdot B1) \tag{4.13}$$

Incident management effectiveness potential includes the following operations:

- Timely detection of incidents (H_1).
- Timely confirmation and classification of incidents (H_2).
- Management of incidents (H_M).
  - Timely assistance to emergency responders (H_3).
  - Timely detection of tail of queue and termination of queue (H_4).

Since H_3 and H_4 contribute to incident management, a measure of H_M may be provided by

$$H_M = Y \cdot H_3 + (1 - Y) \cdot H_4 \tag{4.14}$$

Where Y represents the timeliness of incident management operations (on a scale of zero to 1.0. A value of 0.8 or higher may be used for metropolitan areas that feature good response services.

The value of H is provided by

$$H = H_1 \cdot H_2 \cdot H_M \tag{4.15}$$

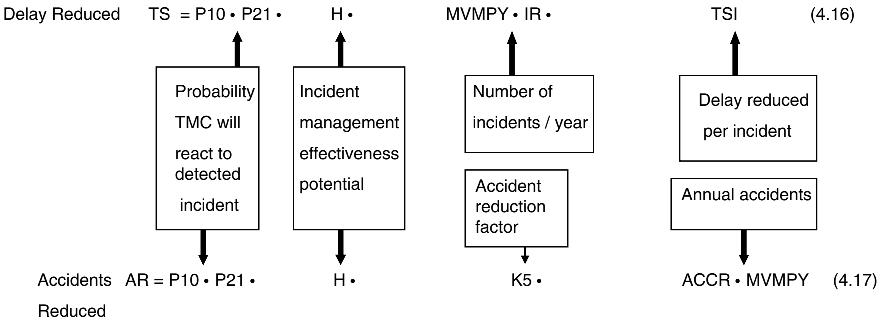
4.6.3.3 Benefits for ITS Incident Management Treatment

Reduction in incident clearance time produces the following benefits:

- Reduction in overall vehicle delay.
- Reduction in secondary accidents as a result of reduction in the time that the queue is present.
- Reduction in fuel consumption.
- Reduction in vehicle emissions.

The reduction in delay and accidents depends on a number of the parameters discussed earlier in Sect. 4.6.3 as well as others. A model describing the relationships for these benefits is shown in Fig. 4.34.

Representative values for certain of the parameters in the model are shown in Table 4.13.



P10 – Probability incident managed if TMC manned
P21 – Probability TMC manned when incidents occur
H – Incident management effectiveness potential
MVMPY – Millions of vehicle miles per year
IR – Incidents per million vehicle miles
TSI – Time saved peer incident
K5 – Accident reduction factor
ACCR – Accident rate

Fig. 4.34 Model for delay and accident reduction benefits

Table 4.13 Representative parameter values for delay and accident reduction benefits model

Symbol	Parameter	Representative value
P10	Probability incident is managed if TMC is staffed	1.0 if TMC operations manual or operating direction requires support of incidents.
P21	Probability TMC staffed when incidents occur	1.0 if TMC operates around the clock. If TMC is staffed on weekdays from 6 AM to 7 PM, 58.6 % of the vehicle miles traveled and accidents will occur during this period [11]
K5	Accident reduction factor (fraction of accidents reduced by ITS support of incident operations)	0.10 is used as the default factor

The computations for (4.13) through (4.15) are provided by the *Inc mgt effectiveness potential worksheet* on the website http://www.springer.com/us/book/9783319147673. An example of a design tradeoff to obtain benefits for alternative CCTV camera and detector deployments and an illustration of a worksheet is provided in Appendix C.

Procedures for the estimation of fuel consumption and emissions are described in Schrank et al. [38] and are based on the EPA's MOVES model [39].

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Chapter 5
Non-recurrent Congestion: Incident Information to Motorists

Abstract Chapter 4 discussed delay reduction resulting from reduction in the response time to incidents. This chapter describes the other significant ITS approach to mitigating non-recurrent congestion, namely providing motorists with information. Since messaging policies and diversion effects for recurrent and non-recurrent congestion may be different, these subjects are covered in two different chapters.

Motorist information can mitigate non-recurrent congestion in the following ways:

- Induce a motorist traveling on the freeway to divert in the event of an incident. Circumstances that induce diversion include:
  - Capacity reducing incidents on the freeway on which the motorist is traveling or on freeways that are accessed by the freeway on which the motorist is traveling.
  - Capacity reducing incidents and construction for special events on remote facilities. Avoiding the incident on the remote facility may require the motorist to modify his route on the facility that he is currently using.
- Prior to the start of a trip or early in the trip, induce a motorist to change his travel mode or the start time of his trip.
- Make the motorist aware of unusual conditions such as incidents, lane blockages and lane closures. Accidents are reduced by facilitating the motorists' earlier preparation for these events.

Section 3.1.4 discusses the general issues relating to diversion resulting from non-recurrent congestion and shows several diversion curves. It also discusses policy issues related to motorist information for non-recurrent congestion. The following topics are covered this chapter in connection with diversion to avoid incidents:

- The techniques for communicating with motorists.
- Strategies and policies or developing messages and the use of the content and the strength of the message to influence the percentage of motorists diverting.
- Semi-automatic and manually implemented strategies for controlling diversion.
- The effect of diverted traffic on alternate routes.
- Models for delay reduction resulting from diversion for the diverted traffic, non-diverted traffic remaining on the freeway and corridor traffic.
- The effect of diverted traffic on alternate routes and the necessity for controlling the impact.

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The chapter provides guidance and some simple models to assist the engineer in locating dynamic message signs. The importance of the quality of motorist information is discussed, and a simple evaluation measure is provided. The use of ITS for emergency evacuation is introduced and a model for generating and disseminating information is discussed.

5.1 Motorist Diversion

5.1.1 Motorist Messaging Techniques

5.1.1.1 Technologies for Communicating with Motorists

Traffic information is often developed by the agencies operating the highway facility. In some cases, the agency contracts with a private service to provide this information. Private services may also supply this information directly to motorists or to the vehicle. Table 5.1 identifies a number of technologies that provide communication with motorists.

Information dissemination techniques may be provided by the operating agency directly to the motorist through dynamic message signs (DMS) and by using highway advisory radio (HAR) transmitters in combination with vehicle radios. Other operating agency initiatives include 511 telephone information service that may be accessed in the vehicle or prior to the trip. These services, provided by many state departments of transportation, offer detailed traffic and roadway condition information along with transit related information.

Privately provided traffic information includes commercial radio station traffic broadcasts, satellite radio, television traffic condition reports and in-vehicle GPS based navigation systems that provide real-time traffic conditions and routing information. The traffic information updates for these navigation systems may be provided by cellular telephone or by satellite radio. The connected vehicle program [1] provides an emerging technology for distributing in-vehicle information using both roadside equipment and information from other vehicles.

Communication of traffic information may result in the motorist changing his lane, route, mode or the time he initiates his trip. Most mode and trip initiation time changes occur prior to starting the trip. This book primarily discusses route diversion issues that occur when the trip is already in progress.

5.1.1.2 Diversion Messages

Dudek indicates that operating agencies should only provide messages that contain information that the motorist does not already know [2]. According to this policy, messages should only deal with non-recurring events. FHWA, however, favors the policy of posting travel time on DMS even during non-incident periods [3].

Table 5.1 Techniques for providing motorist information

Technique	Message coverage characteristics	Limitations	Speed of response to incidents	Source of data
Dynamic message sign (DMS)	Coverage of roadway and possibly nearby roadways as generally used	Message length limited by readability considerations	Good	Agency ITS equipment based information may be augmented by private traffic information services
Highway advisory radio (HAR)	Coverage radius typically 3–5 miles	Message length limited by transmission coverage	Good	Agency ITS equipment based information may be augmented by private traffic information services
Commercial radio television	Wide area. May be used for pre-trip planning	Completeness of conventional radio incident coverage often limited by broadcast time allocation. Satellite radio generally provides better coverage	Fair	Private helicopters. Agency ITS equipment based information may be augmented by private traffic information services
Commercial television	Wide area. Useful for pre-trip planning		Fair	Agency ITS equipment based information may be augmented by private traffic information services
GPS in-vehicle navigation system (original vehicle or aftermarket based equipment or smartphone based)	Wide area	Visual information presentations may result in driver distraction	Varies depending on traffic information source	Private traffic information services may be enhanced by public based ITS information
E 511 service (public agency)	Wide area. Many states provide information organized by roadway section or other means to obtain specific information. May be used for pre-trip planning	In-vehicle selection of desired information may cause motorist distraction	Varies depending on traffic information source	Cellular telephone service cost

(continued)

Table 5.1 (continued)

Technique	Message coverage characteristics	Limitations	Speed of response to incidents	Source of data
Private website	Wide area	Useful for pre-trip planning. In-vehicle information must be used safely	Varies depending on traffic information source	Private information services may be enhanced by public based ITS information

1 Via: Grand Central Pkwy W; RFK - Triboro Brg
47 min. 39.1 miles

2 Via: Grand Central Pkwy W; FDR Dr N
1 h 06 min. 43.9 miles

3 Via: I-495 W
57 min. 30.1 miles

Fig. 5.1 Alternative routes

Messages that describe abnormal traffic conditions often result in the motorist diverting to another route. Diversion messages may be of either of the following types:

- Explicit diversion—Sometimes called active diversion, these messages indicate the need to divert, and may suggest an alternate route. In Table 3.1, the messages related to message strengths 4, 5, 7 and 8 are active diversion messages, and generally induce larger diversion levels than do implicit (or passive messages). Dudek [2] suggests that the policy described in Sect. 3.1.4.2 be implemented in the case of explicit diversion.

In recent years several smartphone and internet based services offer instructions for the fastest route, thus contributing to the explicit diversion traffic level. For

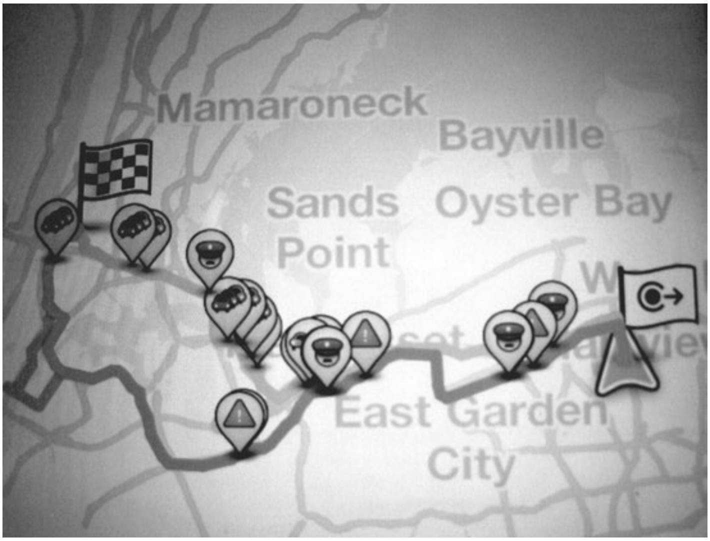


Fig. 5.2 Map based depiction of alternative routes

example, WAZE (https://www.waze.com/) provides fastest route directions for the measured traffic conditions. Figures 5.1 and 5.2 show representative WAZE displays of alternate routes with travel times (these are best used for pre-trip planning). Note the inclusion of a toll-free route. For the selected route, en-route turn by turn guidance is provided audibly at the appropriate location in the trip. Because explicit route guidance is provided based on the fastest route, this type of information may be considered as a component of explicit diversion.

- Implicit diversion—Messages that describe such events on the roadway as accidents, lane blockages and closures, construction, special events, delay and travel time above expectations may, depending on the delay that the motorist perceives, result in diversion. They are implicit or passive diversion messages. Messages 1, 2, 3 and 6 in Table 3.1 are implicit diversion messages. Travel time messages may also be considered as implicit diversion messages.

5.1.2 Operational Diversion Policies and Strategies

When an incident occurs on a freeway, diversion options include:

- Diversion around the incident and return to the freeway downstream of the incident.
- Diversion to alternate local routes when these more conveniently access the motorist's destination.

While in some cases direct diversion to another freeway may be possible, most diversion opportunities require use of the surface streets for some, or all, of the diversion route. During peak periods, diversion routes may have little spare capacity.

During non-peak periods, even modest diversion levels may also have the potential to congest surface street arterials that may serve as alternates. A simple example is shown by the midday scenario in Fig. 5.3 and in Table 5.2.

Figure 5.3 depicts a single lane freeway blockage during a midday period. A medium capacity arterial alternate is directly accessible from the freeway and returns to the freeway downstream of the incident. There is a DMS upstream of the incident that has the capability of diverting traffic. The residual capacity of the freeway under incident conditions is 49 % of the basic capacity (see Table 4.2). This results in a capacity deficit of 913 VPH.

With the signal, the alternate roadway has a capacity of 1,980 VPH. Figure 3.5 indicates that significant congestion on the surface street alternate is likely when the volume to capacity ratio exceeds 0.9. If a *policy* is adopted that does not permit excessive congestion on the alternate during non-peak periods, then only 1,782 total VPH may be accommodated, and only 412 VPH may be diverted from the freeway.

Such a policy may be needed to

- Maintain a lower travel time on the alternate route than on the route with an incident.
- Preserve acceptable conditions for traffic that normally uses the alternate route.

The *strategy* to implement this policy requires the diversion messages to limit the diversion volume to 412 VPH or a diversion fraction of approximately 10 %. Section 3.1.4.1 indicates that the propensity to divert can be controlled through the "strength" of the message. The low diversion fraction required for this example implies that only a low strength message (Table 3.1) would be appropriate. The example illustrates the need for closely monitoring traffic conditions on the alternate route to assure that the strategy is being properly implemented.

Fig. 5.3 Flow diversion during a non-peak period

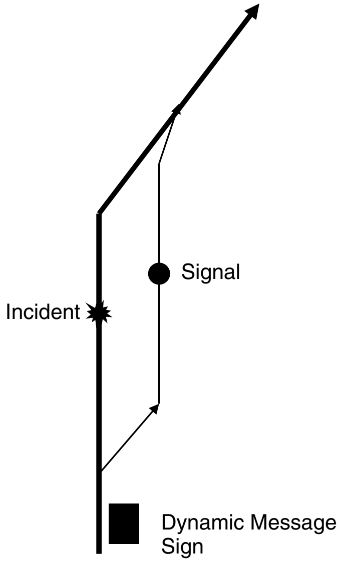


Table 5.2 Parameters for non-peak period diversion example

Parameter	Symbol or relationship	Value
Three lane freeway (one direction)		
Normal capacity	C	6,300 VPH
Number of lanes blocked		1
Residual capacity	$RE=0.49\cdot C$	3,087 VPH
Normal freeway volume	q	4,000 VPH
Capacity deficit	$CD=q-RE$	913 VPH
Arterial alternate (two moving lanes)		
One direction roadway capacity	RC	3,600 VPH
Green signal split along arterial	G	0.55
Capacity along arterial with signal	$CS=G\cdot RC$	1,980 VPH
Maximum flow without major arterial congestion	$MF=.9\cdot CS$	1,782 VPH
Normal arterial volume	qA	1,370 VPH
Maximum divertible freeway flow without major arterial congestion	$MDF=MF-qA$	412 VPH
Maximum diversion fraction for no major arterial congestion	$DF=MDF/q$	0.103

5.1.3 Strategic Network Management

Possible policies to manage the component of diversion controlled by the TMC include the following:

- Accept considerable congestion on alternate. In the example in Sect. 5.1.2 the strategy to implement this policy could result in raising the acceptable volume to capacity ratio to 0.96, resulting in a diversion volume of 531 VPH, corresponding to a diversion fraction of approximately 13 %. Transit on the arterial is also likely to experience considerable delay.
- Favor reducing delay on the freeway to the extent possible. Further increase in the diversion fraction will considerably increase delay on the arterial.
- Implement a strategy that minimizes traveler delay in the corridor.
- Avoid explicit diversion messages except for road closures or hazardous conditions.

By providing messages to motorists, agencies employ one or more of these policies. In some cases the agency has made a decision to adopt a policy while in other cases the selection of message formats implicitly defines a policy.

Policies may be supported by the traffic assignment and distribution models that are traditionally used for transportation planning. These models have a demand component (trip generation and traveler behavior) and a supply component (network characteristics). A model to optimize flow under changing network conditions requires more rapid adaptation of both the demand and supply component to short term changes. Dynamic traffic assignment (DTA) models address this need.

For example, DynaMIT [4] models short-term changes in traveler demand and network characteristics. In addition, it accepts real-time inputs from field surveillance data and from traffic controls.

5.1.3.1 Diversion Fraction

The diversion fraction is a key variable in diversion strategies that implement these policies. Diversion may be viewed as possessing a component (PDF) that is provided by private organizations through traffic information services and a public component (DF) managed by TMCs and influenced by messages provided by the TMC. Both contribute to the total diversion fraction (TDF) as follows:

$$\mathrm{TDF} = \mathrm{PDF} + \mathrm{DF} \tag{5.1}$$

Rewriting Equation 4.10, the public component of diversion fraction (DF) at an exit ramp may be defined as follows:

$$\mathrm{DF} = \left(\mathrm{V_{E2}} - \mathrm{V_{E1}}\right) / \mathrm{V_M} \tag{5.2}$$

where

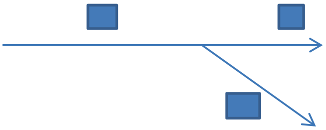
$\mathrm{V_{E1}}$ = Exit ramp volume before instituting diversion message
$\mathrm{V_{E2}}$ = Exit ramp volume after instituting diversion message
$\mathrm{V_M}$ = Mainline volume upstream of exit ramp

From an operational standpoint DF is best determined by measurements of mainline and exit ramp traffic flow changes in response to different types of messages. DF for a DMS message may be measured in response to a message and this same value may be used for that message type (as defined for example in Table 3.1) when suitable conditions require this diversion fraction. Figure 5.4 shows volume detection configurations that are appropriate for obtaining DF. Two of the three detection stations shown in the figure are required for this purpose.

The public diversion fraction includes the use of other public agency operated media such as highway advisory radio (HAR) and 511 sites that provide coordinated information.

By compiling historic public component diversion fractions, this database may be used to select the message strength appropriate to the incident. These databases may also be used as a starting point for operations when a new DMS is added.

Fig. 5.4 Detection location configurations



5.1.3.2 Diversion Fraction Model

If it is not feasible to use the measurement process described in Sect. 5.1.3.1, an analytic approach may be considered to estimate diversion probability. Peeta et al. [5] suggest that DMS message strength may be used to control the level of diversion by this means and provides the following binomial logit model as a basis for this control.

$$\mathrm{PD} = 1/\left(1 + \mathrm{e}^{-\mathrm{U}}\right) \tag{5.3}$$

where

PD is the diversion probability
U is the difference in utility between diverting and not diverting motorists

In Peeta's formulation

$$\mathrm{U} = \mathrm{KD} + \mathrm{NMV} + \mathrm{MV} \tag{5.4}$$

where

KD is a constant
NMV is a value that represents a set of variables that relate to factors other than the message type
MV is a value that represents the message type (presentation strength)

Based on the message types of Table 3.1, Table 5.3 [5] shows a set of model parameters for a particular set of motorist characteristics and the accompanying diversion probability.

Table 5.3 Diversion probability based on message strength [5] (redrawn)

Parameter	Message characteristics	Parameter value	Presentation factor (provided by author)
KD		−1.88	
NMV		+0.54	
MV for different messages shown in the following rows		Message type parameter (MV)	
Message 1	Occurrence of accident	0	0.20
Message 2	Location of the accident	−0.09	0.19
Message 3	Expected delay	+0.61	0.32
Message 4	The best detour strategy	+0.82	0.37
Message 5	Location of the accident and the best detour strategy	+2.08	0.67
Message 6	Location of the accident and the expected delay	+2.49	0.75
Message 7	Expected delay and the best detour strategy	+2.73	0.80
Message 8	Location of the accident, expected delay and the best detour strategy	+3.55	0.89

The Peeta study is based on a stated preference survey. “Real world” factors such as driver comprehension, DMS visibility and driver reaction time generally reduce the actual diversion probability. Mansoureh and Ardshirri [6] indicate a significant discrepancy between the diversion probability when determined by a stated preference survey and a driving simulator.

Because of the limitations of the results from stated preference surveys, the data shown in this section should be considered as an example in the technical literature of the effects of message strength on diversion.

5.1.3.3 Operational Considerations in System Design

The preceding sections discuss the parameters that influence the diversion fraction through motorist information. System designs that consider these issues are more likely to result in more effective performance. The relationships leading to the diversion fraction are, however, complex, and the parameters that result in diversion are difficult to establish with certainty and vary among roadway facilities.

5.1.4 Diversion Strategies

Diversion policies may be implemented by use of diversion strategies. Diversion strategies include open loop control (little or no capability for monitoring the controlled freeway and its alternate) and closed loop control. The following sections describe these strategies.

5.1.4.1 Open Loop Control

Strategy selection is based on policies that prescribe specific strategies corresponding to events such as incidents and their severity. Strategies may consist of diversion through motorist messages and may be supported by traffic controls such as ramp metering, special signal timing plans and lane use changes. Different pre-stored strategies may apply during different traffic periods. Simulation may assist in the development of these strategies. Open loop control provides little capability to adjust the control strategy (either manually or automatically) in response to actual traffic conditions that develop during the operation. It may occur when operating procedures are inadequate to respond to current conditions or when the TMC workloads exceed the capability to provide timely responses.

5.1.4.2 Closed Loop Control

Closed loop control implies the adjustment of the diversion fraction and other traffic controls based on traffic observations by the system operator or by measurement by means of traffic detectors. In some cases, detector data and/or CCTV images are available for both the roadway with the incident and for the major alternate route. In other cases, particularly when the alternate route is a surface street, appropriate information on the alternate is not available. The following sections describe several variations of closed loop control.

Closed Loop Manual Control

Figure 5.5 schematically shows this type of control. The operator, observing traffic conditions on displays of traffic detector data, CCTV displays and using incident information obtained from other sources implements messages according to established policies.

Information from traffic detectors is often shown as a color-coded map display to simplify its interpretation by the operator. This is the most commonly used form of control when traffic surveillance equipment is available.

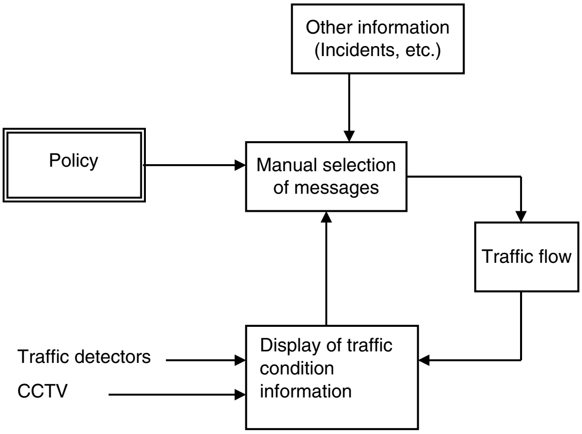
TMCs are often able to change surface street timing plans in response to diversion messages that increase surface street demand. Adaptive traffic signal control systems provide this capability automatically.

In recent years, traffic detection capability in the form of CCTV coverage and probe based information has increased. Commonly used sources of probe information for this purpose include Bluetooth readers, toll tag readers and privately developed GPS based probe information that is used by operating agencies.

Closed Loop Semi-Automatic Control

Examples of traffic condition states that may be used include speed, delay or traffic density. Implementing the control strategy automatically recommends a set of messages and controls based on policy rules and constraints. The message or controls may be modified by the operator based on additional information available to him such as CCTV observations and information from other sources. As with closed

Fig. 5.5 Closed loop manual control



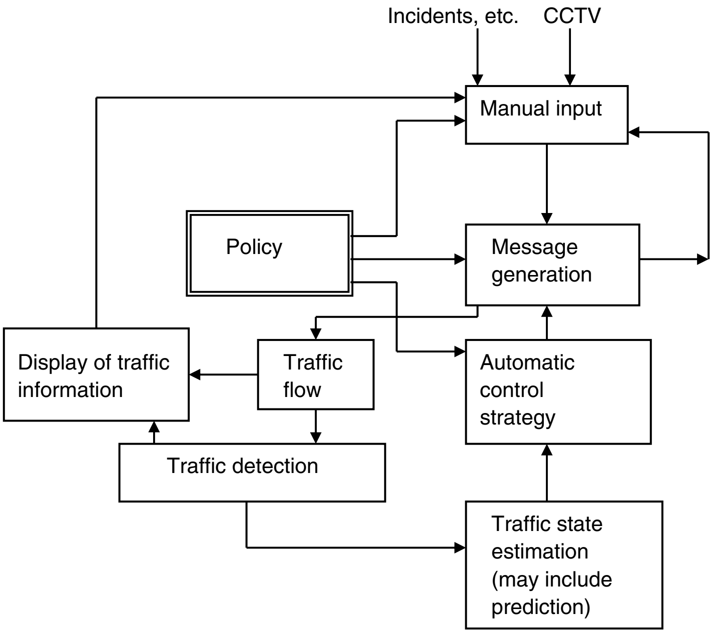


Fig. 5.6 Closed loop semi-automatic control

loop manual control, traffic condition information may be available on both the freeway being controlled as well as on the alternate route.

Figure 5.6 shows this type of control. Traffic detector information may be processed (possibly including the use of prediction) to include the traffic state(s) that may be employed by the control strategy. Traffic condition information may be available on the freeway being controlled as well as on the alternate route.

Since closed loop semi-automatic control is implemented by traffic detector data, it is generally employed for both recurrent and non-recurrent congestion. An example of closed loop semi-automatic control where the controlled freeway is monitored but the alternate route is not monitored is provided in Appendix D. An example with alternate route monitoring is described below.

Highway 401 in the Toronto, Ontario area features a set of express lanes and a set of collector lanes, with transfer opportunities between these lane groups every few miles. The COMPASS system provides dynamic message signs located on each roadway upstream of the transfer points. The DMS describe general traffic speed conditions on both routes. These speeds are measured by detector stations downstream of the transfer point. Figure 5.7 shows the general character of the control loop [7].

The diversion fraction between roadways is altered by providing messages on each DMS that indicate the conditions on both roadways. Table 5.4 shows the general COMPASS message structure for displaying these conditions on each roadway.

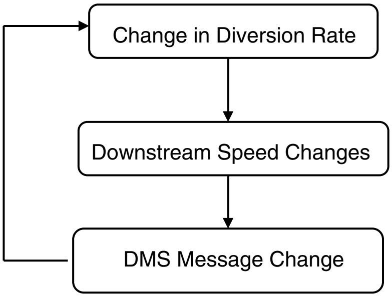


Fig. 5.7 Illustration of DMS feedback control loop (from Transportation Research Record: No. 2047, Transportation Research Board of the National Academies, Washington, DC, 2008, Fig. 5, p. 16. Reproduced with permission of the Transportation Research Board)

Table 5.4 Speed thresholds to determine message display where free flow speed is 100 km/h (62.1 miles/h) [7]

Current message	New message	Threshold speed
Moving well	Moving slowly	80 km/h (49.7 mph)
Moving well or moving slowly	Very slow	40 km/h (24.8 mph)
Very slow	Moving slowly	45 km/h (27.9 mph)
Very slow or moving slowly	Moving well	85 km/h (52.8 mph)

The COMPASS control strategy is a relatively simple example of closed loop semiautomatic control. Closed loop control does not require an explicit knowledge of diversion fraction resulting from the message because this type of control changes the strength of the message in response to measured traffic conditions. In the case of COMPASS, the control strategy approximately equalizes the speeds on the controlled roadways.

Closed loop control for other traffic management applications may be achieved by changing the message types. The design of closed loop systems requires an analysis to assure stability and satisfactory performance.

This type of control may also be implemented with strategies that employ more detailed traffic control models. For example, Kachroo and Ozbay [8] provide mathematical models for dynamic traffic routing. They discuss the use of feedback activated controls to optimize travel time and assure system stability.

5.1.5 Reduction in Freeway Delay Resulting From Diversion

The most significant reduction in overall system delay resulting from diversion often accrues to the freeway traffic that does not divert under incident conditions. Section 5.1.6 provides an example that illustrates this.

Figure 4.2 shows the effect of an incident on delay. Figure 5.8 is a similar figure that depicts the effect of diversion on the queues resulting in delay. It adds a line representing the new demand volume after diversion. The area enclosed by points a,

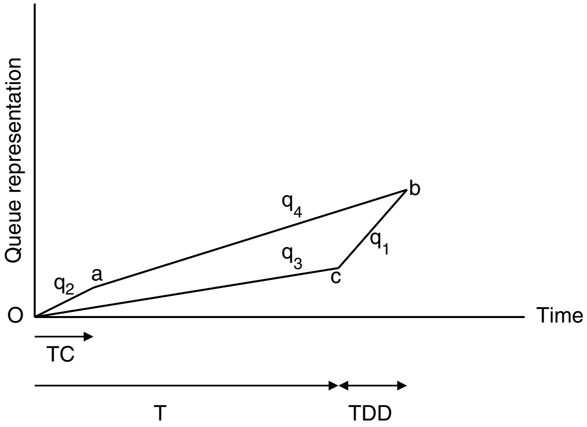


Fig. 5.8 Delay and timeline model under diversion conditions

b, c and O represents delay under diversion conditions. Diversion commences after incident detection and confirmation (TC). The vertical distance between the lines Oab and Ocb represents the number of vehicles in the queue at a given time.

The following definitions apply to Fig. 5.8 and to the following equations:

q_1—Volume at incident clearance (roadway capacity)
q_2—Volume entering incident location (prior to diversion)
q_3—Volume when incident is present (capacity under incident conditions)
q_4—Volume entering incident location after diversion
T—Time from incident occurrence until incident is cleared
TC—Time from the occurrence of the incident occurrence until diversion is implemented
TDD—Time period after incident clearance until queue clears under diversion conditions

Analysis of the geometrical relationships in Fig. 5.8 leads to the following equations:

Delay reduced prior to TC

$$\mathrm{DD} = 0.5 \cdot \mathrm{TC}^2 \cdot (q_2 - q_3) \tag{5.5}$$

Delay (DC) from TC to T

$$\mathrm{DC} = 0.5 \cdot q_4 \cdot (\mathrm{T} - \mathrm{TC})^2 + (\mathrm{T} - \mathrm{TC}) \cdot \mathrm{TC} \cdot (q_2 - q_3) - 0.5 \cdot q_3 \cdot (\mathrm{T} - \mathrm{TC})^2 \tag{5.6}$$

Time (TDD) from incident clearance to queue clearance

$$\mathrm{TDD} = (q_4 \cdot (\mathrm{T} - \mathrm{TC}) + q_2 \cdot \mathrm{TC} - q_3 \cdot \mathrm{T}) / (q_1 - q_4) \tag{5.7}$$

Delay (DQC) after incident clearance

$$DQC = 0.5 \cdot TDD^2 \cdot (q_1 - q_4) \quad (5.8)$$

Total delay for non-diverted freeway traffic (DIF) is given by

$$DIF = DD + DC + DQC \quad (5.9)$$

Equation (4.4) describes the total delay, $D_{T,}$ with no diversion. The total time for the queue to clear is $T + T_D$ where

T = Time from start of incident to incident clearance
T_D = Time for queue to dissipate after incident clearance (see Eq. (4.1))

The total number of vehicles served during this period (NND) is given by

$$NND = q_2 \cdot (T + T_D) \quad (5.10)$$

and the average vehicle delay during this period (ADND) is

$$ADND = D_T / NND \quad (5.11)$$

Similarly, for the case where vehicles are diverted, the number of diverted vehicles served until queue clearance is given by

$$ND = q_2 \cdot (T + TDD - TC) \quad (5.12)$$

and the average vehicle delay during this period (ADD) is

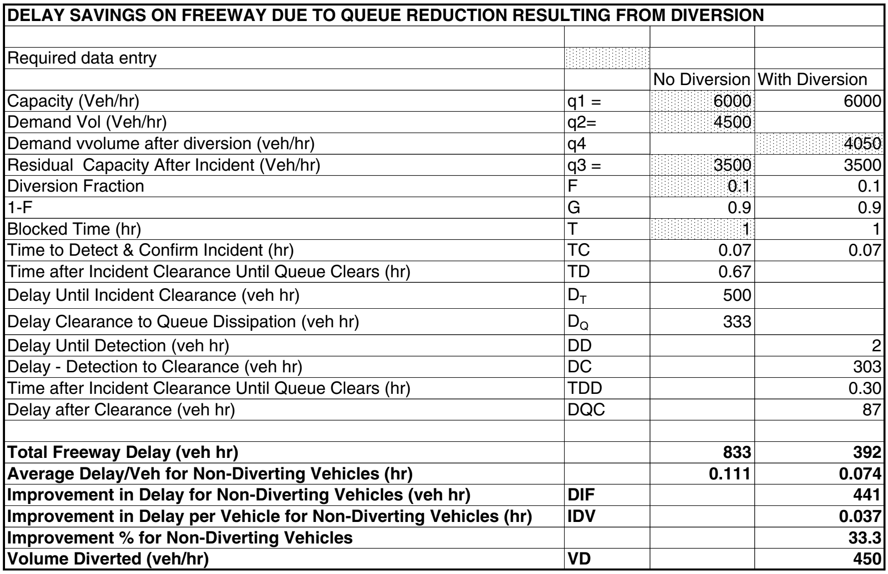
$$ADD = DIF / ND \quad (5.13)$$

Figure 5.9 shows an example of a worksheet *Delay improvement on freeway* (included in the website http://www.springer.com/us/book/9783319147673) to compute the key variables as well as DIF and the per-vehicle reduction in delay for non-diverting vehicles (IDV).

5.1.6 Effect of Diversion on Arterial Traffic

Preferred diversion policies and strategies require that:

- Motorists choosing to divert as a result of information explicitly or implicitly provided must benefit from such a diversion. Otherwise, the motorist may perceive that the information lacks credibility and may not use it in the future.
- The overall network must benefit from the diversion.



DELAY SAVINGS ON FREEWAY DUE TO QUEUE REDUCTION RESULTING FROM DIVERSION			
Required data entry	▨		
		No Diversion	With Diversion
Capacity (Veh/hr)	q1 =	6000	6000
Demand Vol (Veh/hr)	q2=	4500	
Demand vvolume after diversion (veh/hr)	q4		4050
Residual Capacity After Incident (Veh/hr)	q3 =	3500	3500
Diversion Fraction	F	0.1	0.1
1-F	G	0.9	0.9
Blocked Time (hr)	T	1	1
Time to Detect & Confirm Incident (hr)	TC	0.07	0.07
Time after Incident Clearance Until Queue Clears (hr)	TD	0.67	
Delay Until Incident Clearance (veh hr)	D_T	500	
Delay Clearance to Queue Dissipation (veh hr)	D_Q	333	
Delay Until Detection (veh hr)	DD		2
Delay - Detection to Clearance (veh hr)	DC		303
Time after Incident Clearance Until Queue Clears (hr)	TDD		0.30
Delay after Clearance (veh hr)	DQC		87
Total Freeway Delay (veh hr)		**833**	**392**
Average Delay/Veh for Non-Diverting Vehicles (hr)		**0.111**	**0.074**
Improvement in Delay for Non-Diverting Vehicles (veh hr)	**DIF**		**441**
Improvement in Delay per Vehicle for Non-Diverting Vehicles (hr)	**IDV**		**0.037**
Improvement % for Non-Diverting Vehicles			**33.3**
Volume Diverted (veh/hr)	**VD**		**450**

Fig. 5.9 Worksheet computing delay reduced on freeway resulting from diversion

- The effects of diversion, particularly to surface streets, resulting from traveler information, must not exceed impacts that are agreed to in advance by the local stakeholders. Special signal timing plans may be used to facilitate diversion and reduced the impact of diversion.

A simplified example using a single diversion route may be used to illustrate these concepts. Using the freeway data in Fig. 5.9, a freeway diversion fraction of 0.1 results in a diversion volume of 450 vehicles per hour. Table 5.5 provides the parameters for the example.

The policy constraint in this example restricts diversion to 396 VPH unless the signal timing is changed. In order to achieve the desired diversion level of 450 VPH, the use of an alternative signal timing plan is required.

The time saved by each diverting vehicle is the time saved by non-diverting vehicles (IDV) plus the additional improvement in delay on the diversion route (TOND). The total time saved by diverting vehicles (TSVD) is the product of this value and the number of diverting vehicles (ND). The expressions for these relationships are provided below.

$$\mathrm{ND} = \mathrm{VD} \cdot (\mathrm{T} + \mathrm{TDD} - \mathrm{TC}) \tag{5.14}$$

$$\mathrm{TSVD} = \mathrm{ND} \cdot (\mathrm{IDV} + \mathrm{TOND}) \tag{5.15}$$

where VD is the diversion volume.

Table 5.5 Example of surface street diversion impacts for off-peak period

Parameter	Symbol or relationship	Normal green signal split	Diversion plan green signal split
Roadway capacity (VPH)	RC	3,600	3,600
Green split on arterial[a]	G	0.4	0.5
Signal controlled capacity (VPH)	$CS=G\cdot RC$	1,440	1,800
Policy requirement	No significant off-peak additional congestion		
Maximum flow without significant congestion (VPH)	$MF=0.9\cdot CS$	1,296	1,620
Normal background traffic (VPH)	NFA	900	
Maximum acceptable diversion flow without significant congestion	$MDF=MF-NFA$	396	720

[a] Green split shown excludes lost time (queue start up + clearance lost time)

Figure 3.3 shows that for the assumed diversion fraction of 10 % the example, the delay saved by the diverting vehicles as compared with the non-diverting vehicles (TOND) is approximately 5 min. Using the example parameters yields

ND = 572 diverted vehicles
TSVD = 68.6 vehicle hours of delay reduction for diverting vehicles

The delay to non-diverting vehicles is reduced by 441 vehicle hours (difference between no diversion delay and diversion delay in Fig. 5.9). Since TSVD is considerably less than this value, the major system benefit for diversion results from benefits to non-diverting vehicles. This benefit results from the shorter queue on the facility with the incident. For this example the individual diverting vehicle benefits considerably more than the non-diverting vehicle.

5.1.7 *Reduction in Corridor Delay Resulting from Diversion for Incidents*

Total corridor delay reduction (CDS) includes the sum of the delay reduced by non-diverting vehicles and diverting vehicles less the additional delay incurred by the pre-diversion traffic on the diversion route (DAR). This may be expressed as:

$$CDS = DIF + TSVD - DAR \tag{5.16}$$

This simplified model assumes that all traffic diverting from an incident will utilize the planned diversion route, and that pre-diversion traffic on the diversion route will also continue to use that route. A traffic assignment model will provide a better estimate of the traffic actually using this route.

As diversion volume approaches the capacity of the alternate route, Fig. 3.5 shows that DAR begins to increase exponentially, and the value of CDS may be significantly reduced.

5.2 Design Considerations for DMS Locations

Dynamic message signs may take a number of forms ranging from simple blank-out signs and portable signs to large installations. Figure 5.10 shows some examples of the larger signs used for informing motorists of non-recurrent traffic conditions such as construction, incidents and weather conditions.

A DMS of this type requires a significant capital investment, and these DMS often incur a large portion of the cost of an ITS project. It is therefore important that the number and location of these DMS be selected based on cost effective principles. The exact location of a DMS depends on a number of factors such as the sight distance considerations, constraints on installation due to roadway construction features, nearby environmental issues, power access availability and maintenance considerations. A number of these issues are discussed in Dudek [2]. The following sections treat the selection of DMS sites from a functional point of view, i.e. the effect of the DMS on notifying the motorist of incidents and other traffic related issues.

5.2.1 Basic Considerations for DMS Functional Placement

The key functional objective for locating DMS is to place them so that the maximum number of viewers will be exposed to the DMS for incidents downstream of the DMS. An example of a methodology for implementing this principle on a network-wide basis is described by Abbas and McCoy [9].

5.2.2 Simple Models to Assist in DMS Functional Placement

Many ITS projects are of limited scope and address the requirements of a single freeway or a portion of that freeway. This section describes two simplified models that may assist in determining the functional placement requirements for DMS for that purpose. The discussion adapts concepts from Ref. [9]. The general concept is illustrated in Fig. 5.11. The figure illustrates the simple case of a DMS located upstream of the last diversion opportunity prior to encountering the incident. The

Fig. 5.10 (**a**) Dynamic message sign displaying construction information (Source: Parsons Brinckerhoff, Inc.). (**b**) Small dynamic message sign displaying incident information (Source: Daktronics, Inc.). (**c**) Dynamic message sign displaying weather information and controlling speed (Source: Daktronics, Inc.)

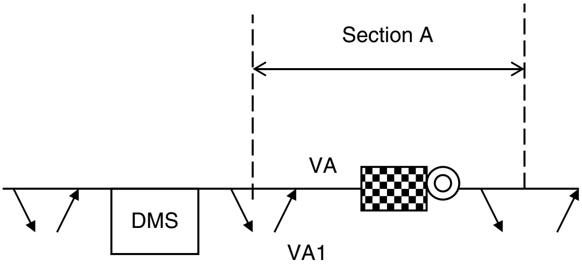


Fig. 5.11 DMS just upstream of traffic entering mainline before incident queue

double-circled symbol in the illustration denotes the incident location and the checkered region represents the congestion building back from that point.

The probability that the motorist encounters a DMS prior to the section containing the incident (P34) for Section A is given by the fraction of motorists that become candidates for diversion as a result of the DMS and prior to encountering the congestion and incident. In this case the value is:

$$P34 = \left(VA - VA1\right) / VA \tag{5.17}$$

where

VA = Mainline volume upstream of queue formed by incident
VA1 = Entry volume downstream of DMS and upstream of incident

Sections 5.2.2.1 and 5.2.2.2 discuss the simplified models for the following cases:

- Origin-destination data are available.
- Origin-destination data are not available.

5.2.2.1 Computation of P34 when Origin-Destination Data are Available

This section provides a model for computing P34 for a single freeway when origin-destination trip distribution information is available. This data may be obtained from the following sources:

- Planning models.
- Computer models that synthesize origin destination data (trip tables) data from traffic volumes.
- Special surveys employed for the collection of this data.

Consider the case where only one DMS is provided in the study roadway, and where no DMS is present upstream of the study roadway. This case is represented by the example shown in Fig. 5.12. The solid rectangle shows the DMS location.

Each of the E and X symbols represents a node at which the traffic enters or exits the roadway. Thus t_{23} represents the volume of traffic entering at node E2 and leav-

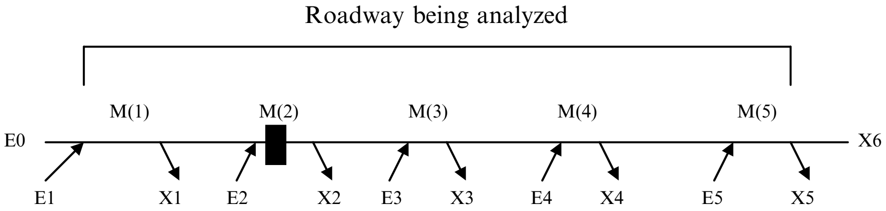


Fig. 5.12 Single roadway with one DMS

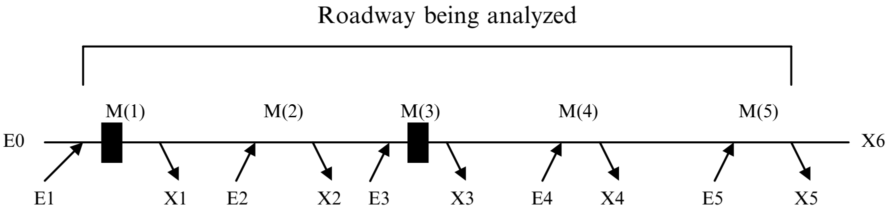


Fig. 5.13 Single roadway with multiple DMS

ing at node X3. E0 and X6 are the mainline volumes entering and exiting the study roadway. A DMS is shown as a shaded rectangle in Section 2. For an incident in a section, diversion will take place for traffic normally destined to exit at that section and beyond. Motorists destined for exits downstream of the section containing the DMS are candidates for diversion. The computation for P34 for Section J for the case shown is of the form:

$$\mathrm{P34}(\mathrm{J}) = \begin{pmatrix}\text{Sum of the traffic volumes passing the DMS}\\ \text{and exiting at or downstream of Section J}\end{pmatrix} / \mathrm{M}(D) \tag{5.18}$$

where D is the section containing the DMS.

For the example shown:

$$\mathrm{P34}(3) = (t_{03} + t_{04} + t_{05} + t_{06} + t_{13} + t_{14} + t_{15} + t_{16} + t_{23} + t_{24} + t_{25} + t_{26}) / \mathrm{M}(2) \tag{5.19}$$

$$\mathrm{P34}(4) = (t_{04} + t_{05} + t_{06} + t_{14} + t_{15} + t_{16} + t_{24} + t_{25} + t_{26}) / \mathrm{M}(2) \tag{5.20}$$

$$\mathrm{P34}(5) = (t_{05} + t_{06} + t_{15} + t_{16} + t_{25} + t_{26}) / \mathrm{M}(2) \tag{5.21}$$

When roadways being analyzed contain more than one DMS, each DMS provides diversion capability for incidents in the sections downstream of that DMS, until another DMS is encountered. This case is represented by Fig. 5.13, which show DMS in mainline sections 1 and 3.

For the last DMS in the study area, diversion will occur for incidents in the sections downstream of that DMS. Qualifying traffic volumes are identified as follows:

- Origin node—All entering nodes between the upstream DMS and the subject DMS.
- Destination node—All exiting nodes starting with the section analyzed. Start with section downstream of the DMS.

In terms of the example

$$P34(4) = (t_{24} + t_{25} + t_{26} + t_{34} + t_{35} + t_{36}) / M(3) \tag{5.22}$$

$$P34(5) = (t_{25} + t_{26} + t_{35} + t_{36}) / M(3) \tag{5.23}$$

For DMS upstream of the last DMS in the study area, qualifying traffic volumes are identified as follows:

- Origin node—All entering nodes upstream of the DMS. If there is a DMS upstream of this one, limit the origin nodes to nodes that are downstream of that DMS.
- Destination node—All exiting nodes starting with the section analyzed (downstream of the DMS) and extending to and including the section with the downstream DMS.

In terms of the example

$$P34(2) = (t_{12} + t_{13} + t_{14} + t_{15} + t_{02} + t_{03} + t_{04} + t_{05}) / M(1) \tag{5.24}$$

$$P34(3) = (t_{13} + t_{14} + t_{15} + t_{03} + t_{04} + t_{05}) / M(1) \tag{5.25}$$

5.2.2.2 Computation of P34 for a Single Roadway When Origin-Destination Data are not Available

This section describes the probability that the motorist encounters a DMS prior to a diversion point for an incident when origin-destination data are not available. It uses a simple trip assignment process based on freeway mainline and exit ramp volumes. The computation of P34 is based on a recursive process and is illustrated by the following example of Fig. 5.14.

The diagram shows a DMS in Section 2. Definitions are as follows:

M(J) is the mainline AADT for Section J (volume between entry and exit locations.

X(J) is the sum of the exit ramp AADT for Section J.

R(J) is the residual volume after the exit ramps for Section J.

M_D is the mainline AADT for the section with the upstream DMS closest to the section being analyzed.

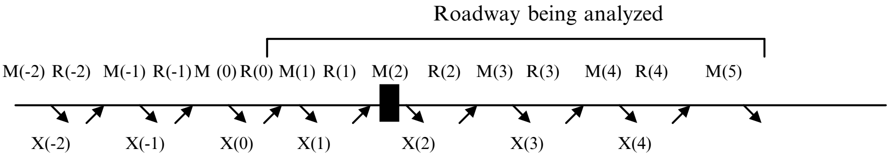


Fig. 5.14 Example of single roadway with single DMS when no origin-destination data are available

PROBABILITY THAT MOTORIST ENCOUNTERS DMS PRIOR TO INCIDENT (P34)

▨ Required entry deoending on roadway configuration

SECTION n	DMS ON SECTION	MAINLINE AADT	EXIT RAMP AADT	B	R	Basis	Intermed Comp	P34
-2	0	0	0	0.000	0	0		
-1	0	0	0	0.000	0	0		
0	0	0	0	0.000	0	0		
1	0	41800	4200	0.900	0	0	0.000	0.000
2	1	57200	5500	0.904	51700	57200	0.000	0.000
3	0	57150	5600	0.902	46634	57200	0.904	0.904
4	0	59750	5500	0.908	42341	57200	0.815	0.815
5	0	54700					0.740	0.740

Fig. 5.15 Worksheet showing computation of P34

In addition to the sections in the roadway under analysis (section numbers higher than zero in Fig. 5.14), provision is made in the model for the possible location of the DMS in sections that are upstream of the roadway being analyzed. These are represented by sections numbered less than 1 in the figure.

For sections following the DMS, the distribution model computes the traffic that has been exposed to the DMS after the section's exit point (denoted as P34(J)) as the product of the exposed traffic entering the section, R(J) and the ratio of the total remaining mainline traffic after the exit point to the total mainline traffic in the section (B_J). The equations that express this relationship are:

$$B_J = 1 - X(J)/M(J) \tag{5.26}$$

$$R(J) = R(J-1)\cdot B_J \tag{5.27}$$

$$P34(J) = R(J-1)/M_D \tag{5.28}$$

Figure 5.15 shows an example of the computation of P34. This worksheet, *Computation of P34*, is provided on the website http://www.springer.com/us/book/9783319147673. A "1" must be entered in the "DMS ON SECTION" column for each DMS on the roadway. Mainline volumes for a section containing a DMS upstream of the study roadway must be entered, along with volumes from that section to the study roadway. Exit ramp volumes for all sections upstream of the study region and in the study region (except for the last section) must be entered.

Using these equations or the worksheet, it is possible to determine the most effective placement for DMS (based on the probability that the motorist passes a DMS prior to the section containing the incident) by analyzing various numbers and locations of DMS.

5.3 Quality of Motorist Information

Support for ITS rests, in large measure, on its ultimate customers, i.e. the motorists and their perceptions of the value of the service. Customer satisfaction is traditionally measured by stated preference surveys. Some states proactively solicit feedback on ITS as well as on other transportation services. Delaware DOT, for example, solicits information on the importance of a service. In 2009, the survey reported performance on "information on when to expect delay, road closings" as 5.1 on a scale of 1–7 [10].

In some cases studies are conducted to identify the quality and value of particular services. Evaluation of 511 systems resulted in a customer satisfaction rate of 71 % in Arizona, 68 % in Washington State [11], 92 % in the San Francisco Bay Area and 90 % in Montana [12].

From the system designer's perspective, the quality or perceived benefit of motorist information depends on the following:

- Availability of technology and services to detect and confirm incidents and congestion related to incidents.
- Availability of traffic management center staff to implement messages at the time of the incident (a number of centers do not provide full time coverage).
- The ability of the motorist to receive and understand the message.

5.4 ITS and Technology Applications in Emergency Evacuations

5.4.1 Introduction

Many agencies at all levels of government participate in emergency evacuation planning and operations. Successful culmination of these efforts involves interagency coordination and appropriate use of the assets available to the participating organizations.

Situations that may arise include:

- Evacuations for which affected locations may or may not be anticipated in advance.
- The approximate time for the evacuation may or may not be anticipated in advance.

The types of situations that typically require evacuation include:

- Weather related incidents such as hurricanes.
- Hazardous material related incidents.
- Nuclear power plant incidents.
- Homeland security related events.

Emergency evacuations typically require planning and coordination by a number of agencies at all levels of government. The Freeway Management and Operations Handbook [13] provides an introduction to the subject.

5.4.2 ITS and Technology Applications

The principal role of ITS and ITS related technology to support emergency evacuations includes planning, traffic controls, and highway and traffic related information.

5.4.2.1 Planning

The following are commonly used tools to assist in the planning of multi-agency responses to emergency management and evacuation situations:

- By providing a common mapping reference for different agencies, the use of GIS systems facilitates the organization of emergency evacuations. Functions include disaster forecasts, vulnerability analysis, resource inventories, existing infrastructure inventory, shelter identification and status [14].
- Simulations to model traffic evacuation routes, demands, capacities and emergency response traffic control measures. An example of a simulation available for this purpose is the Oak Ridge Evaluation Modeling System (OREMS) [15].

5.4.2.2 Traffic Controls

Elements of the evacuation plan may include traffic controls. Examples of the use of traffic controls include:

- Special timing provisions for traffic signals. Provisions may include signal timing plans that support evacuation routes, usually by means of longer green split periods along the evacuation route and longer cycle lengths. In some cases it may be appropriate to provide a constant green indication along the route.
- Contra-flow lanes on freeways. HOV lanes and reversible lanes may be used for this purpose, or conventional lanes may be reversed in support of an overall traffic management plan. In some cases ancillary traffic controls such as lane control signals and ramp access gates may be used to support the plan.

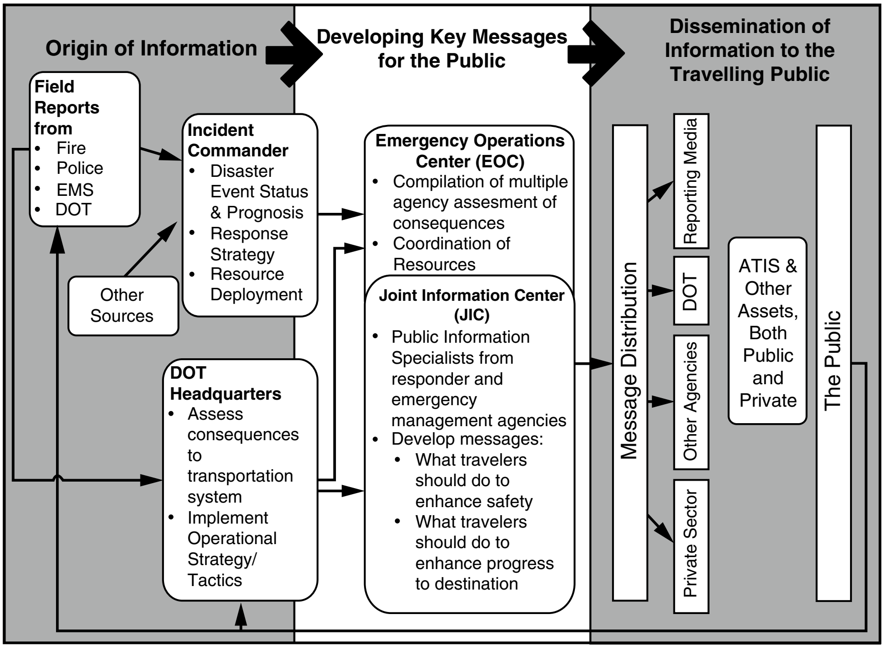


Fig. 5.16 Information dissemination model

- Static signing is often used to identify emergency evacuation routes to motorists.
- CCTV is used to assist traffic management centers to support clearance of traffic incidents along emergency routes.

5.4.2.3 Highway and Traffic Related Information

The motorist information delivery technologies listed in Table 5.1 are used to provide information during evacuations. During these events, the traffic management center serves as one element in the overall evacuation management process. The following discussion and Fig. 5.16 depicts an information dissemination model. It is abstracted from Ref. [16].

The information flows depicted in Fig. 5.16 are intended to illustrate the full range of information that is generated and communicated to the public throughout a disaster situation. There are elements of timing and dependency relationships that come into play as a disaster unfolds, as participants enter or exit the picture and as information evolves. Moreover, the information flow embodies a continuous feedback loop which incorporates the response of the public to the information received and the outcome of disaster mitigation.

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Chapter 6

Recurrent Congestion: Information to Motorists

Abstract Section 3.1.3 briefly describes the differences between recurrent congestion and non-recurrent congestion. This chapter further elaborates on recurrent congestion. Discussion includes practices employed by traffic management centers and others in the provision of motorist information. The time periods when recurrent congestion is experienced, along with the variations in these periods, is discussed. The chapter covers diversion under recurrent congestion conditions, and describes the opportunities for diversion during shoulder periods.

6.1 Nature of Recurrent Congestion

Non-recurrent congestion, discussed in Chaps. 4 and 5, is generally caused by a temporary reduction in the normal capacity of the roadway. Recurrent congestion generally occurs when demand for the facility use exceeds the facility's capacity and results in low average travel speeds, poor levels of service, and possible difficulty in access to and egress from the freeway. The demand trends and the resulting congestion are, within limits, generally repetitive. Severe recurrent congestion in major metropolitan areas is often experienced during peak commuting periods. Weekend shopping and recreation travel also often generate recurrent congestion. Congestion caused by special events is treated by some traffic engineers as recurrent congestion and by others as non-recurrent congestion.

6.2 Motorist Information During Recurrent Congestion

Section 5.1.1.1 describes the techniques and technologies commonly employed for providing motorist information. While the same technologies are used for providing information for recurrent and non-recurrent congestion, the types of information displayed may be somewhat different. Table 6.1 shows the types of information often provided by messaging technologies.

Figure 6.1 shows a typical recurrent congestion message. Travel time information, as recommended by FHWA is also often displayed [1]. When no congestion is present, the DMS may be left blank or a default message such as that shown in

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Table 6.1 Message content for recurrent and non-recurrent congestion

Technology	Recurrent congestion messages	Non-recurrent congestion messages
Information provided by state		
DMS	Travel time, delays, no delays, default messages, or blank sign representing no delays[a]	Location and nature of incident, delays, possible alternate route information, construction information
HAR	Rarely used	Location and nature of incident, delays, possible alternate route information, construction, weather, evacuation information
State website/511 website	Delays, travel time, traffic condition status map, travel time reliability	Location and nature of incident, construction, weather, evacuation information
511 telephone	Delays, travel time[b]	Location and nature of incident, weather, evacuation information
Information provided by others		
Conventional and satellite commercial radio	Delays, limited travel time information. Reports often emphasize common congestion locations such as water crossings. Estimates of delays are sometimes provided	Location and nature of incident, construction information, weather, evacuation information
Real time GPS based information service	Quickest route, travel condition map	Quickest route, travel condition map, location of incident and construction

[a] If policy requires provision of recurrent congestion information on DMS
[b] Some sites may indicate when conditions are clear

Fig. 6.2 may be used (motorists familiar with the system understand that such messages indicate that no congestion is present).

Semi-automatic message strategies of the type described in Sect. 5.1.4.2 based on point or probe detector information or on information from suppliers of traffic information may be displayed. Messages for these strategies are generally developed without any consideration of the cause of the congestion and thus they frequently provide recurrent congestion related information. When an incident occurs, in most cases the operator will replace the automatically developed message with another message that describes the incident, its location, and possible recommended remediation recommendations.

6.3 Variations During Periods of Recurrent Congestion

Recurrent congestion is common and pervasive during peak periods in major metropolitan areas, and is generally characterized by low speeds. Variations in day-of-week demands, monthly demands, and random demands result in day-to-day speed and travel time variations for the same trip made at the same time of day.

Fig. 6.1 Typical recurrent congestion message

Fig. 6.2 Typical default message implying lack of congestion

As an example of these variations, the horizontal tics in Fig. 6.3 show the mean speed measured at a location in Portland, Oregon for weekdays from April 1, 2008 until April 11, 2008. The vertical bars represent the range of speeds encompassing one standard deviation above and one standard deviation below the mean. Thus, for the hour ending at 4 PM, the northbound detector station at milepost 304.4 reported

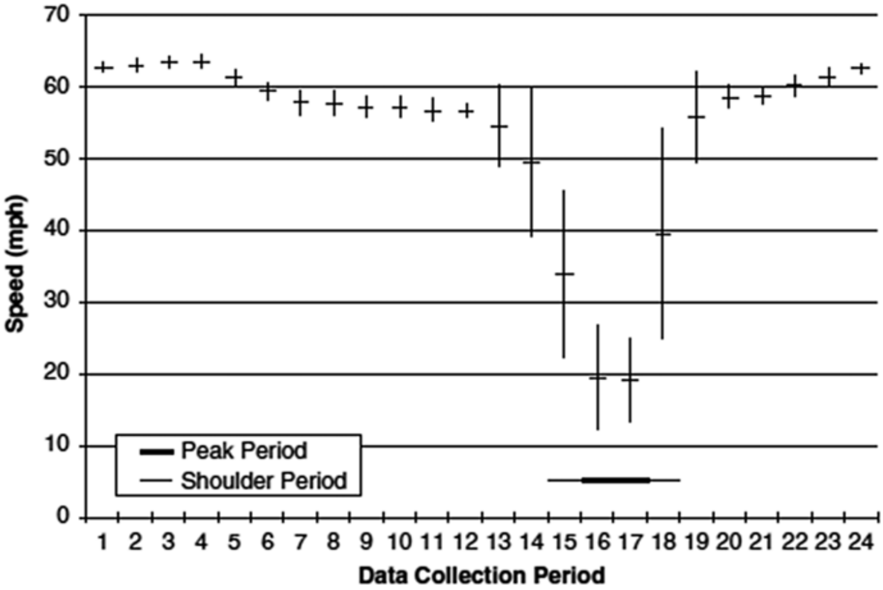


Fig. 6.3 Average speed and standard deviation for I-5 NB milepost 304.4. Data for this figure were developed using the Portland Oregon Regional Transportation Archive Listing (PORTAL). PORTAL was developed by Portland State University under the direction of Dr. Robert Bertini

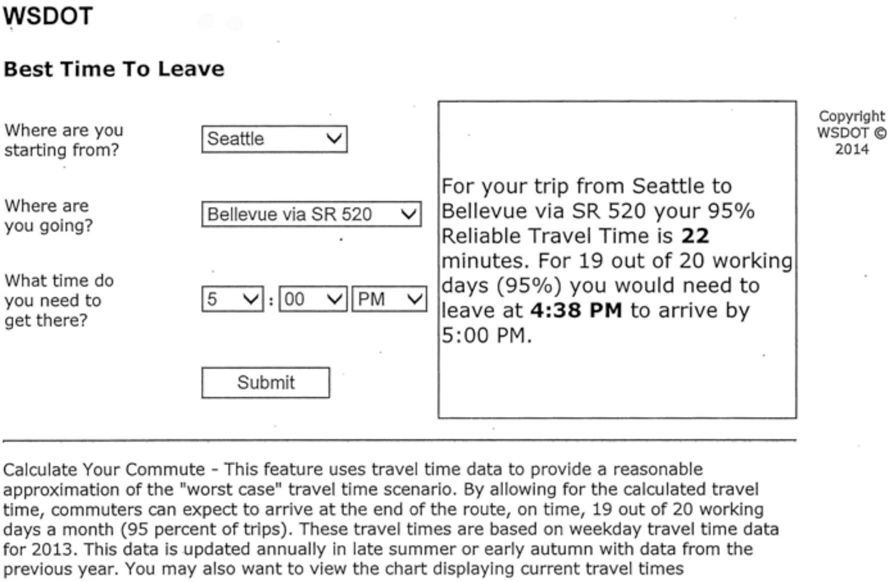
a mean speed of 19.6 mph for this period and a standard deviation of 6.3 mph. This peak period also extends into the next hour. Although the mean speed is above 30 mph for the hour preceding and the hour following the peak period, the standard deviation is also high for these *shoulder* periods.

Standard deviation is a measure of travel time reliability. Provision of congestion, speed or travel time information enables the motorist to reduce his/her anxiety level by providing an indication, at least in some cases, of his anticipated delay. In some cases it provides diversion opportunities. Figure 6.4 is an example of travel time reliability information provided by the Washington State DOT 511 website.

6.4 Diversion During Recurrent Congestion

Congestion patterns in major urban areas generally follow Wardrop's principles (see Sect. 3.1.5). These principles indicate that although recurrent congestion delays may be significant, diversion in the absence of non-recurrent congestion is not likely to be productive for either the individual motorist or for the entire system.

Wardrop's principles are, however, predicated on the assumption that conditions are invariant, and therefore that the motorist is aware of conditions on the routes in



Where are you starting from? Seattle

Where are you going? Bellevue via SR 520

What time do you need to get there? 5 : 00 PM

For your trip from Seattle to Bellevue via SR 520 your 95% Reliable Travel Time is **22** minutes. For 19 out of 20 working days (95%) you would need to leave at **4:38 PM** to arrive by 5:00 PM.

Calculate Your Commute - This feature uses travel time data to provide a reasonable approximation of the "worst case" travel time scenario. By allowing for the calculated travel time, commuters can expect to arrive at the end of the route, on time, 19 out of 20 working days a month (95 percent of trips). These travel times are based on weekday travel time data for 2013. This data is updated annually in late summer or early autumn with data from the previous year. You may also want to view the chart displaying current travel times

Fig. 6.4 Internet message for travel time reliability

the travel corridor. Figure 6.3 and similar data, however, show significant levels of variation during these periods. This variation may present opportunities to reduce delay under some conditions.

Although speeds may be low during peak periods, speeds on the alternates are usually also low during these periods, so that significant diversion opportunities are relatively rare. During shoulder periods, however, there are times when the freeway speed is low, as shown in Fig. 6.3, and since volume-to-capacity ratios on the alternate routes are generally lower than during peak periods, there may be opportunities for diversion during these periods.

Because diversion opportunities are limited and delay savings resulting from DMS recurrent congestion messages generally amount to only a few minutes per trip, system-wide savings are usually modest. The savings are, however, generally achieved at little or no marginal cost.

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Chapter 7
Ramp Metering

Abstract Ramp metering is commonly used in major metropolitan areas to reduce freeway delay and improve safety. It does this by 1) smoothing the flow of traffic at the merge and thereby increasing effective freeway capacity and safety and 2) reducing the traffic entering the freeway which reduces the volume to capacity ratio. Topics covered by this chapter include:

- Ramp meter physical installation requirements and ranges of metering rates.
- Traffic flow breakdown models and the role of ramp metering in improving breakdown.
- Ramp metering strategies including pretimed, traffic responsive, isolated and systemwide ramp metering.
- Ramp storage requirements and ramp queue control strategies.
- Ramp metering acceptance by the public.
- Ramp metering benefits model.

7.1 Introduction

Entry ramp control strategies include

- Ramp metering.
- Ramp closure.
- Special treatments including bus by-pass lanes on metered ramps.

Use of these treatments is described in the Freeway Management and Operations Handbook [1] and the Ramp Management Handbook [2]. These references provide guidance in the implementation of these treatments. Ramp metering is the most commonly used of these treatments and is the subject of this chapter.

Ramp metering is implemented by a traffic signal on a freeway entry ramp (Fig. 7.1). By smoothing the flow at the merge with the mainline, it increases the service rate (bottleneck capacity) of the mainline, and reduces the accident rate. If the metering rate is established at a value that is below the average arrival rate at the ramp (*restrictive ramp metering*), a queue will build on the ramp causing additional delay to the arriving vehicles. As a result, some of these vehicles will seek alternate routes, thereby reducing the demand volume at the entry ramp merge with the mainline.

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Fig. 7.1 Ramp meter signal display

This, in turn, reduces the demand volume-to-capacity ratio at the merge and downstream of the merge, and reduces the delay to the vehicles on the freeway mainline. Metering rates that are equal to the average vehicle arrival rate (*non-restrictive ramp metering*) build much smaller queues and generally do not result in significant volumes of traffic seeking alternate routes.

7.2 Background

7.2.1 Early Metering Projects

One of the first projects to establish the ability of metering to increase lane flow was conducted in the Lincoln Tunnel [3]. Lane changes are not permitted in the tunnel and bottleneck flows are frequently experienced at the foot of the upgrade in the tunnel. Early experiments showed that using fixed rate metering improved lane throughput from 1,200 cars per lane per hour to 1,320 cars per lane per hour. Once congestion set in, the higher throughput could not be sustained. A later experiment provided control based on volume and speed measurements. The results of the experiment are shown in Table 7.1.

Ramp metering projects started in the 1960s in Chicago, Detroit, Los Angeles and Houston These projects included pretimed metering and traffic-responsive metering have been expanded over the years. 28 metropolitan areas in the United States currently operate ramp metering systems, and other parts of the world also use this technology.

Table 7.1 Results of Lincoln tunnel metering experiment [3]

	Uncontrolled	Controlled
Average throughput (cars/lane/hour)	1,210	1,290
Maximum throughput over a half-hour period	1,260	1,430
Average speed (feet/second)	27.2	40.9
Average density (cars/mile)	75.8	47.5

7.2.2 Ramp Meter Installation Requirements

Several types of metering installations are employed depending on the metering rates to be used and the configuration of vehicle storage capability on the ramp. For example, a single lane or multiple lanes may be metered. Metering may permit only one vehicle to pass the stop line per signal cycle or may permit multiple vehicles to pass (*platoon metering*).

Figure 7.2 [1] depicts a common deployment for a single lane, single vehicle meter. A standard 3-section (red-yellow-green), or 2-section (red-green) signal display is provided. The signals may be either mast arm or pole mounted. A sign or beacon is often used to indicate that metering is in effect.

For single vehicle meters, the metering rate is established by defining a metering cycle equal to the reciprocal of the desired metering rate. If the previous cycle has timed out (turning the signal to red), the signal will change to green when a vehicle is detected by the check-in (or demand) detector. When the vehicle is sensed by the check-out or passage detector the green interval is then terminated. The signal will remain in red until the traffic cycle times out, at which time it will respond to the next arriving vehicle detected by the check-in detector.

Some ramp metering installations use merge detectors. The merge detector senses the presence of vehicles in the primary merging area of the ramp and freeway mainlines. When the merge detector senses a stopped vehicle blocking the merge area, the signal may be held in red for some preset maximum time in order not to congest the area and to reduce the possibility of a rear end collision [1].

One or more queue detectors are commonly used to prevent the queue from spilling back into the surface street traffic stream. Detection of vehicles by the queue detector increases the metering rate or terminates the ramp metering. Strategies for accomplishing this are described in Sect. 7.4.5.2. In some cases the queue detector may be used to limit ramp waiting time to a specified value [1]. As discussed in Sect. 7.4.5.1, the lack of adequate vehicle storage capacity often limits the effectiveness of restrictive ramp metering.

Mainline detector placement is closely related to the particular control strategy implemented (see Sect. 7.4). To be meterable, the physical and traffic demand characteristics of ramps must lie within certain values. Deployment requirements for ramp metering are listed in Sect. 7.4.5. Acceptable ramp meter rates are shown in Table 7.2.

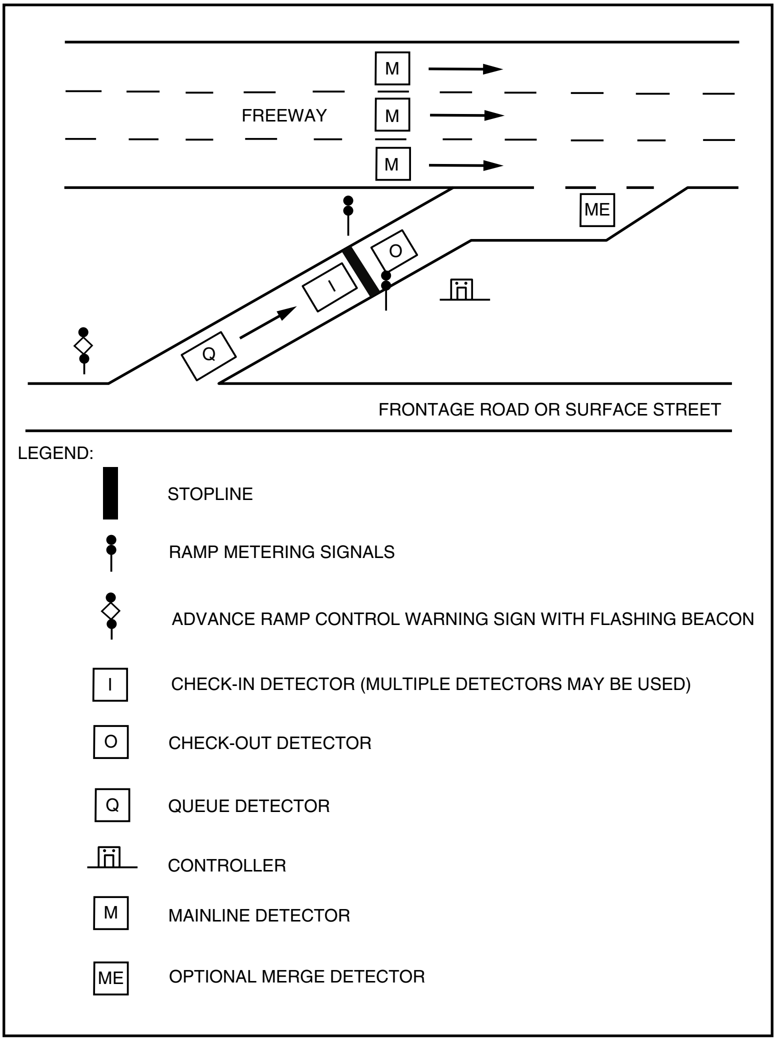


Fig. 7.2 Single-lane entry ramp metering system layout

7.3 Flow Characteristics and Freeway Capacity

7.3.1 Flow Characteristics for Near-Capacity Conditions

As traffic demand (i.e., volume) increases, density increases with a corresponding decrease in speed. As vehicle demand approaches highway capacity, traffic flow begins to deteriorate. Traffic flow is interrupted by periods of turbulence that disrupt efficiency. Traffic flow then begins to break down rapidly, followed by further deterioration of operational efficiency. An example of the breakdown in stable flow is shown in Fig. 7.3.

Table 7.2 Ranges of ramp metering rates [4]

Types of metering	Number of metered lanes	Approximate range of metering rates (v/h)	Comments
Single vehicle entry per green interval	1	240–900 v/h	Full stop at the meter usually not achieved at 900 v/h metering rate
Tandem metering—single vehicle entry per green interval per lane	2	400–1,700 v/h	Applies when required metering rate exceeds 900 v/h
			Requires two lanes for vehicle storage
			Vehicles may be released from each lane simultaneously or sequentially
Platoon metering—single lane multiple vehicle entry per green interval geometrics	1	240–1,100 v/h	Platoon lengths permit passage of 1–3 vehicles per green interval
			Principally used to increase metered volumes when geometrics do not permit use of more than one metered lane
			Requires changeable sign indicating permitted number of vehicles in green interval

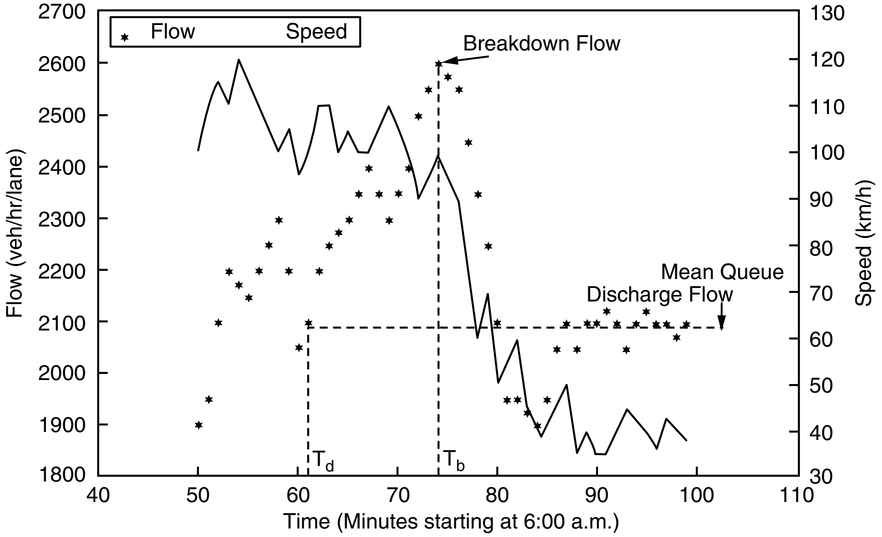
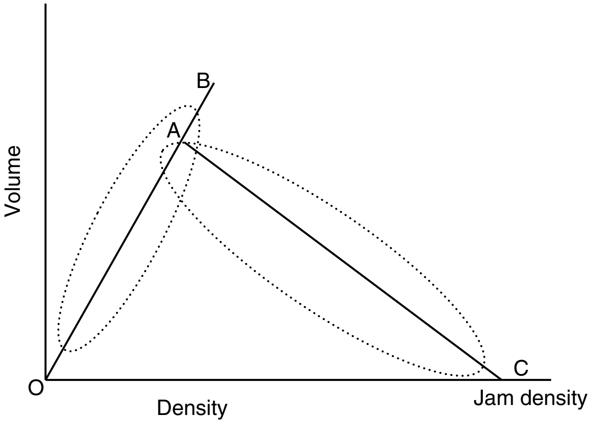


Fig. 7.3 Time trends for speed and flow during AM peak period. From, *Transportation Research Record*: *Journal of the Transportation Research Board*, *No. 1748*, Transportation Research Board of the National Academies, Washington, D.C., 2001, Figure 1, p. 111. Reproduced with the permission of the Transportation Research Board

Fig. 7.4 Conceptual volume vs. density diagram



There has been considerable research (e.g. References [5] and [6]) into identifying the properties of transitions between non-congested, stable flow and congested, unstable flow. Banks [6] suggests the models shown in Fig. 7.4. Line segments OAC constitute the inverted V model and line segment AB is added for the reversed lambda model. The dotted ovals indicate that considerable variation in the values of the actual data points is experienced. Jam density is the value of density when the traffic is stopped.

As volume increases, average density increases in an approximately linear relationship until the volume reaches the approximate location of Point A. This near linear relationship implies little speed change. When volume nears this point, the probability of the flow transitioning to an unstable state arises. This is generally characterized by lower volume, lower speed and higher density. The location in a section of highway at which this transition first occurs is termed a *bottleneck* location. Bottlenecks typically occur at or near entry ramps as a result of merged traffic volumes that exceed roadway capacity. Line segment AC depicts the general trend in the unstable state, however the actual data may vary widely from this trend. In Fig. 7.5 Shawki and Nakamura [7] show the best data point fit for the cumulative distribution for the maximum pre-breakdown flow and outflow rates (discharge flow from the queue after flow breakdown) on a section of a freeway in Tokyo.

Shawki and Nakamura [7] represent the cumulative probability distribution P(x) by the Weibull Logistic and Normal functions of the form

$$P(x) = 1 - \exp\left(-(x/\beta)^{\alpha}\right) \tag{7.1}$$

where

x = outflow (queue discharge volume in passenger cars per hour per lane)
α = shape parameter
β = scale parameter

For the location used for Fig. 7.5.

$\alpha = 28.7$
$\beta = 2{,}256$

An example of the flow breakdown probability in the Toronto area is shown in Fig. 7.6.

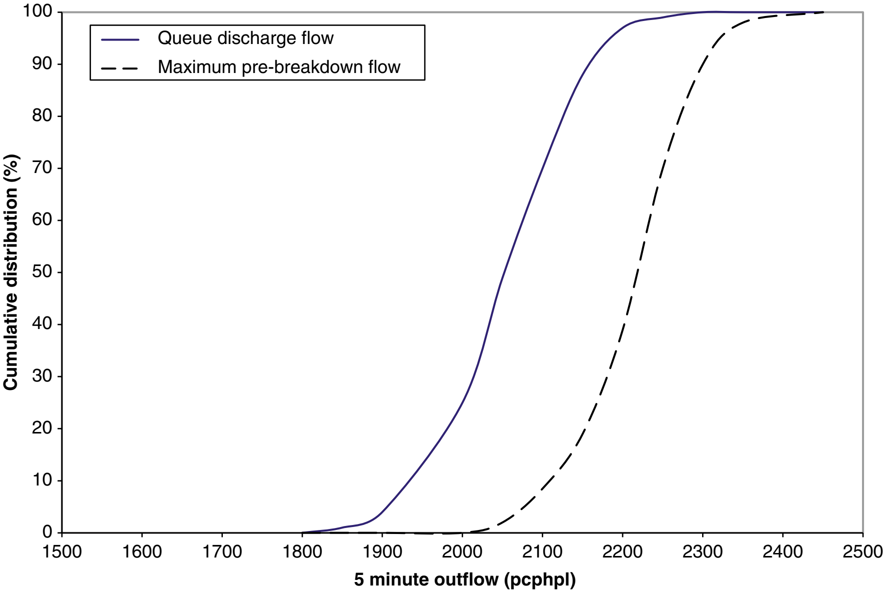


Fig. 7.5 Cumulative probability of distributions (redrawn). From, *Transportation Research Record*: *Journal of the Transportation Research Board*, *No. 2012*, Transportation Research Board of the National Academies, Washington, D.C., 2007, Figure 6b, p. 14. Reproduced with the permission of the Transportation Research Board

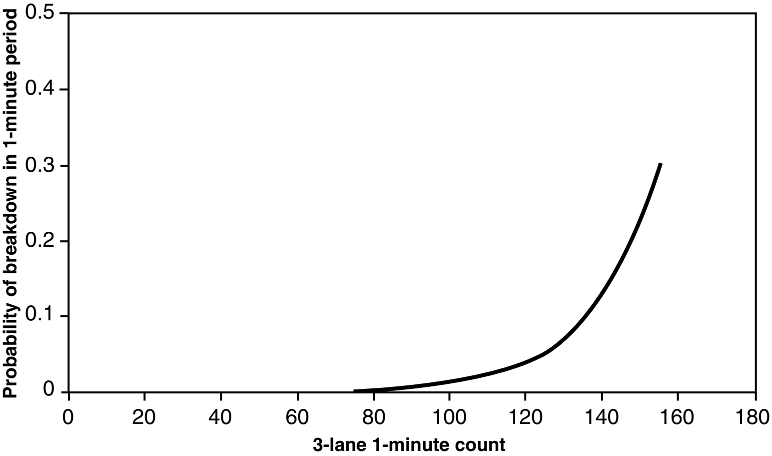


Fig. 7.6 Probability of flow breakdown for 1-min periods. From, *Transportation Research Record*: *Journal of the Transportation Research Board*, *No. 1748*, Transportation Research Board of the National Academies, Washington, D.C., 2001, Figure 5, p. 113. Reproduced with the permission of the Transportation Research Board

7.3.2 Effective Capacity Improvement Through Ramp Metering

This section describes the effect of ramp metering on the flow breakdown characteristics described in the previous section. The discussion uses the concepts and data described in Zhang and Levinson [8]. That reference examines the traffic flow characteristics at 27 PM peak period active bottlenecks in the Twin Cities area with and without ramp metering. The motivation for the test is discussed in Sect. 7.5.2.

Figure 7.7 shows the model used by Zhang and Levinson to analyze flow breakdown situations. As volume increases during the peak period and crosses the queue discharge flow level, a pre-queue transition period commences. The steady state queue discharge flow is shown by the dashed lines in the figure. The pre-queue transition period lasts until the flow equals the steady state queue discharge flow. During this period, several instances of flow breakdown and restoration to pre-breakdown conditions may occur. In time, the flow decreases below the values shown in the figure shown as a result of the decrease in demand. Ramp metering delays flow breakdown and results in higher discharge rates after breakdown.

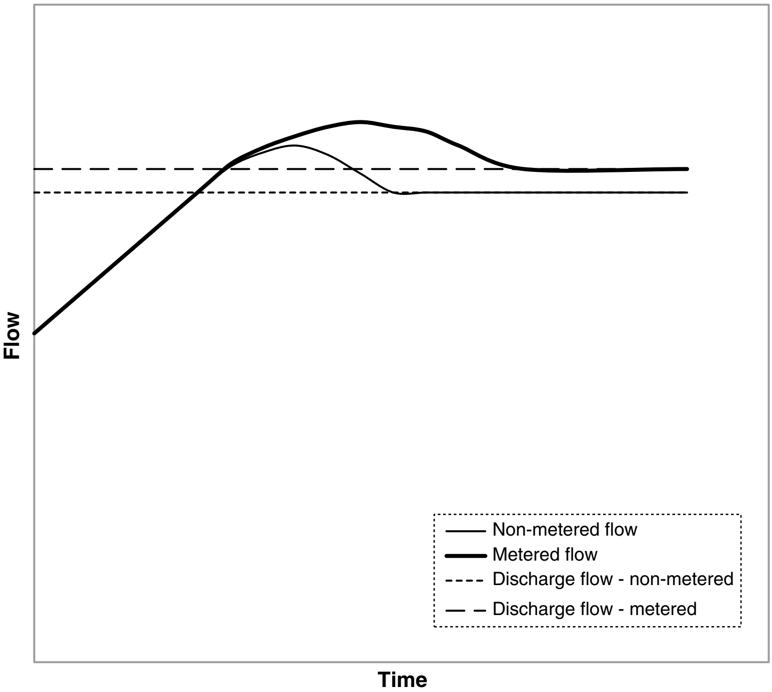


Fig. 7.7 Flow profiles at a bottleneck with and without ramp metering

While the results vary considerably from ramp to ramp, Zhang and Levinson's results revealed the following average improvements:

- Ramp metering increased the average pre-queue transition period from 60 min to nearly 2 h, a 73 % increase.
- The average flow during the steady state queue discharge period is 5.8 % lower than during the pre-queue transition period. Thus the extension of the pre-queue transition period results in a considerable reduction in delay.
- The average value of the flow during the pre-queue transition period is 3 % higher with ramp metering.
- The average value of the flow during the steady state queue discharge period is 2 % higher with metering.
- The average number of flow breakdown occurrences per afternoon peak period reduced from 1.2 without metering to 0.4 with metering. This occurs in part because of the elimination of flow breakdown at approximately half of the locations studied.
- Reducing the number of queues and their duration reduces the probability of spillback of these queues to the next upstream entry ramp.

In a subsequent paper, Zhang and Levinson [9] identify the following types of capacity increases resulting from ramp metering.

- Type 1—Capacity upstream of the bottleneck is improved because the queue formed by the bottleneck is shorter and flow remains stable for a longer period.
- Type 2—Capacity is increased at the bottleneck as described above.

7.3.3 Freeway Service Improvement Through Ramp Metering

Both non-restrictive and restrictive ramp metering improve freeway throughput, delay and safety in the following ways:

- Smoothing the merge flow through ramp metering has been shown to reduce the crash rate. A survey of management centers in eight cities found that ramp metering reduced the accident rate by 24–50 % [10]. The accident rate improvement includes the reduction of secondary accidents and the delays resulting from both primary and secondary accidents.
- A large number of studies report significantly reduced travel time resulting from ramp metering. For example, non-restrictive ramp metering on Long Island provided an improvement of 20 % [10]. Restrictive ramp metering may provide additional benefits as described below.
- Ramp metering may provide throughput increases. For example, system-wide restrictive ramp metering resulted in a 10 % increase in freeway volumes in the Minneapolis-St. Paul, Minnesota area [11].

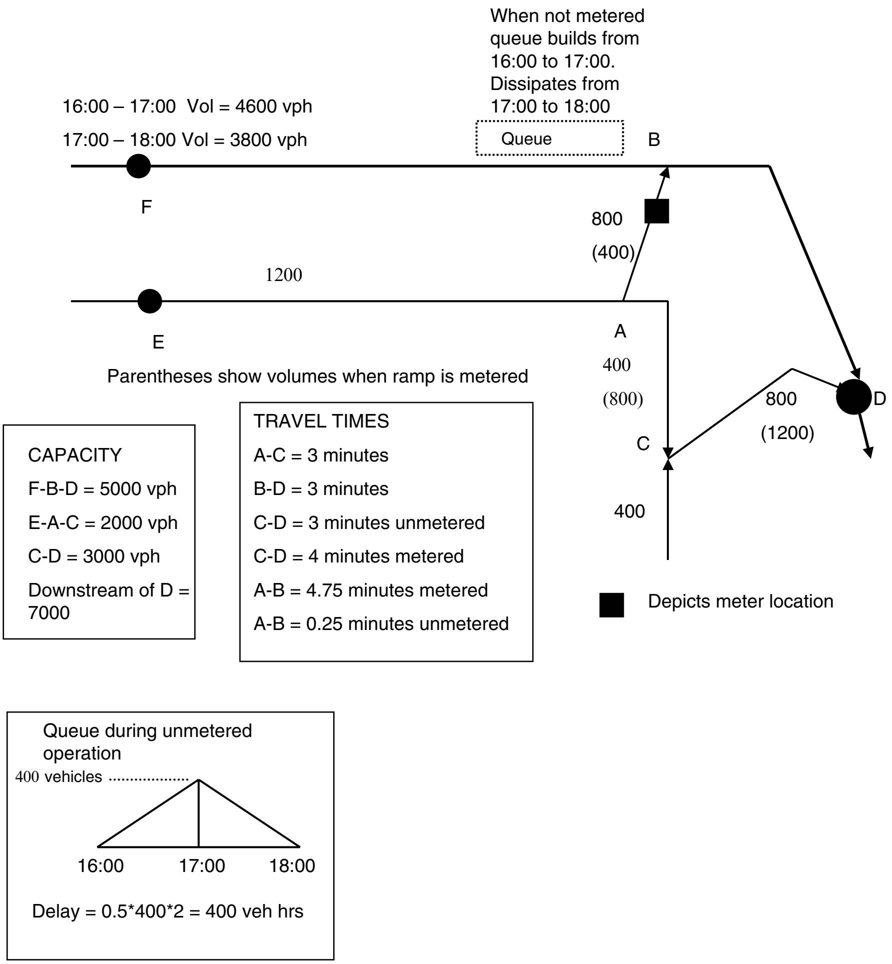
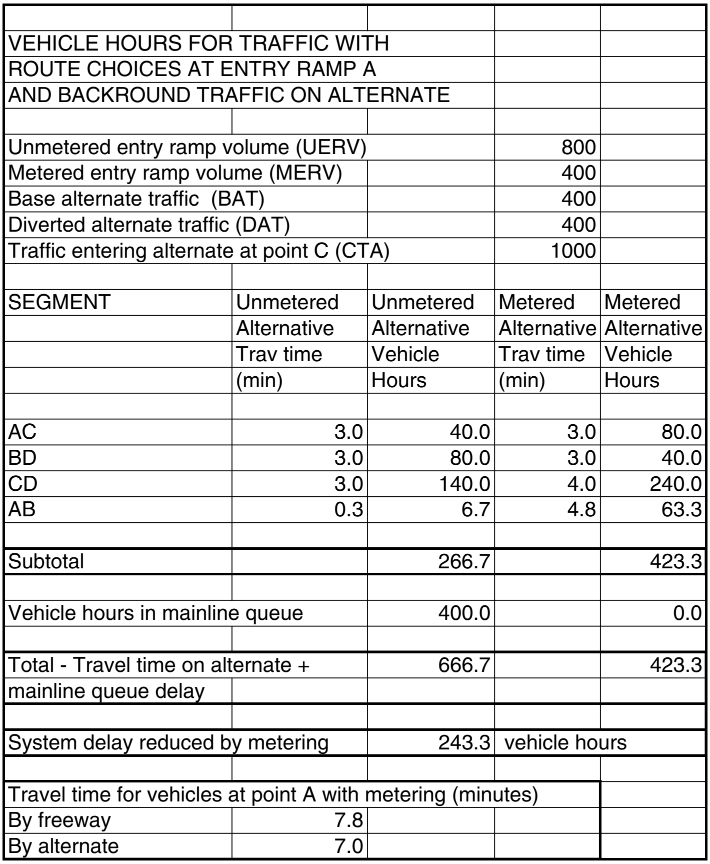


Fig. 7.8 Example of local restrictive ramp metering

Restrictive ramp metering provides an additional benefit resulting from the reassignment of traffic resulting in a decreased demand for the ramp. This concept is illustrated by the following simple example showing restrictive metering at a single ramp. Figure 7.8 shows a freeway (line FBD) and an alternate route (EACD). Prior to metering, the volume entering the ramp at location B exceeds the 5,000 vph capacity and causes a queue to build as shown in the figure, resulting in a delay of 400 vehicle hours during the 2 h peak period. Prior to metering, most of the vehicles on link EA that are destined for location D and beyond choose to use the freeway because the trip is 2.75 min shorter. The downstream merge volume of reassigned traffic with the freeway traffic at location D results in a volume that is below the freeway capacity at this point.



VEHICLE HOURS FOR TRAFFIC WITH				
ROUTE CHOICES AT ENTRY RAMP A				
AND BACKROUND TRAFFIC ON ALTERNATE				
Unmetered entry ramp volume (UERV)			800	
Metered entry ramp volume (MERV)			400	
Base alternate traffic (BAT)			400	
Diverted alternate traffic (DAT)			400	
Traffic entering alternate at point C (CTA)			1000	
SEGMENT	Unmetered Alternative Trav time (min)	Unmetered Alternative Vehicle Hours	Metered Alternative Trav time (min)	Metered Alternative Vehicle Hours
AC	3.0	40.0	3.0	80.0
BD	3.0	80.0	3.0	40.0
CD	3.0	140.0	4.0	240.0
AB	0.3	6.7	4.8	63.3
Subtotal		266.7		423.3
Vehicle hours in mainline queue		400.0		0.0
Total - Travel time on alternate + mainline queue delay		666.7		423.3
System delay reduced by metering		243.3	vehicle hours	
Travel time for vehicles at point A with metering (minutes)				
By freeway	7.8			
By alternate	7.0			

Fig. 7.9 Worksheet for restrictive ramp metering example

Figure 7.9 contains the pertinent data for the metered and unmetered situations. With the initiation of ramp metering at an entry rate of 400 vehicles per hour, the queue builds on the entry ramp until the travel time via the freeway route and the alternate route are approximately equal.

The vehicle hours traveled for the segments (other than the mainline queue) were computed by the relationship:

$$\begin{aligned}&\text{Segment Vehicle Hours Traveled} = (\text{Segment volume})\cdot\\&(\text{segment travel time in minutes}/60)\cdot(\text{duration of peak period})\end{aligned} \tag{7.2}$$

Restrictive metering of this ramp results in a significant reduction in system delay. These benefits are typically not, however, evenly distributed among all motorists. In this example, improvements resulting from the elimination of the mainline queue accrue to motorists on the mainline upstream of the ramp at location A.

Motorists on the alternate route destined for location D and beyond, whether entering the freeway ramp, remaining on the alternate route, or entering the alternate route at a location downstream of the metered ramp experience a longer trip time.

7.4 Ramp Metering Strategies

The previous sections provide the general background on ramp metering and describe the mechanisms that ramp metering provides for relieving congestion. There are, however, potential negative effects that may result from ramp metering. These include:

- Additional delay to motorists that normally enter the ramp, even if they elect to use an alternate route.
- Additional delay to motorists that do not normally use the ramp but that do use an alternate route.
- Possible spillback of traffic onto the surface street network.
- Motorist dissatisfaction resulting from the above.

The success of a ramp metering project depends, in part, on planning efforts to determine if metering is, in fact, feasible, and to select the metering strategy that best addresses the specific issues. Simulation is often a valuable tool for estimating the effects on the alternate routes, on the highway system in the vicinity of the metered ramp and on the additional travel time that the ramp users and divertees will experience. It may assist in selecting the ramp metering strategy to be employed.

7.4.1 Overview of Metering Strategies

The metering rate for non-restrictive ramp meters is established at a higher level than the average arrival rate. The ramp queues are relatively short, consisting essentially of vehicle platoons released from an upstream signal or small vehicle platoons where the surface street upstream of the ramp is not signal controlled. The queue usually clears before the arrival of the platoon released by the subsequent signal cycle. The instrumentation requirements are relatively low (no mainline detectors are required) and communication with the traffic management center is not essential.

Restrictive ramp metering strategies include local metering strategies, system-wide metering strategies and pretimed and traffic responsive metering strategies. Successful restrictive ramp metering treatments usually depend on detailed planning efforts. Table 7.3 provides a summary of the major characteristics of restrictive ramp metering strategies.

Restrictive ramp metering provides a higher level of overall system benefits than does non-restrictive ramp metering. As discussed in Sect. 7.5, restrictive ramp metering may result in perceived disbenefits to a significant number of motorists. Where agencies have encountered this issue or expect that the introduction of

Table 7.3 Characteristics of restrictive ramp metering strategies

	Pretimed		Traffic-responsive	
	Local metering	System-wide metering	Local metering	System-wide metering
Functions				
Safety improvements through flow smoothing	Useful	Useful	Useful	Useful
Capacity improvements through flow smoothing	Useful	Useful	Useful	Useful
Congestion at a bottleneck that can be mitigated by metering at a single ramp	Useful	Not required	Useful	Not required
Significant number of non-meterable ramps between metered ramps	Useful	Can possibly improve local metering performance	Useful	Can possibly improve local metering performance
Congestion at a bottleneck requiring metering at a number of upstream ramps	Not useful	Useful	Not useful	Useful
Traffic reassignment on a long term (strategic) basis	Useful	Useful	Can possibly improve pretimed metering performance	Can possibly improve pretimed metering performance
Traffic reassignment on a short term basis (including non-recurrent events)	Not useful	Not useful	Useful	Useful
Implementation issues				
Manual data collection	Usually required	Usually required	Not usually required	Not usually required
Mainline detectors	Not required but may be used to establish data base	Not required but may be used to establish data base	Required	Required
Management by TMC and field communication with TMC	Useful but not required	Useful but not required	Required	Required
High level of vehicle storage capability	Required	Required	Required	Required
Ramp queue spillback protection	Required	Required	Required	Required
Capital and maintenance cost	Relatively low	Relatively low	Higher per metered ramp	Highest per metered ramp

restrictive ramp metering may result in adverse publicity, the increased capacity and reduction in accident rate provided by non-restrictive ramp metering may provide a viable alternative. Ramp delays associated with non-restrictive ramp metering are usually minimal, and motorists often recognize the benefit of the smoother merge. Non-restrictive ramp metering may also be useful when sufficient storage space for restrictive ramp metering is not available.

7.4.2 Pretimed Restrictive Ramp Metering

Pretimed restrictive local ramp metering is appropriate for mitigation of recurrent congestion when the alternate routes downstream of the meter can accommodate the reassigned traffic and:

- Control of upstream ramps is not required to relieve congestion at the ramp merge or in the downstream section fed by the merge or
- It is not possible to meter upstream ramps.

A typical application is the mitigation of congestion at a single bottleneck as illustrated by the example in Sect. 7.3.3.

Pretimed restrictive system-wide ramp metering may be used to relieve recurrent congestion when:

- Metering a single ramp cannot provide a sufficient reduction in freeway volume. The lowest feasible metering rate at a ramp upstream of the bottleneck may not be sufficient to reduce demand to a level that is below bottleneck capacity. Metering of additional upstream ramps may be able to achieve or more closely approach this objective.
- The presence of multiple bottlenecks requires the consideration of metering at a number of ramps.

May [12] formulates relationships (termed demand-supply analysis) for a series of ramps in a manner that is generally similar to that shown in the example of Sect. 7.3.3. He describes the optimal control strategy for system-wide ramp metering as a linear programming procedure that maximizes mainline volume. His analysis treats the traffic diverted to the alternate route in a simple fashion.

Constraints in the linear programming formulation include the following:

- Volumes on each freeway link must be below capacity.
- Metering rates must fall within practical limits.
- It may not be possible to control some entry ramps. In this case the freeway entry volume equals the arrival volume at the ramp.
- There may be additional constraints such as limitations on the size of the ramp queue and limitations on the volume of re-assignable traffic resulting from capacity limitations on the alternates.

The design of this system-wide pretimed ramp metering strategies may be facilitated by the use of simulation [13].

7.4.3 Local Traffic Responsive Restrictive Ramp Metering

Local traffic responsive ramp metering provides the capability to adjust the metering rate to real time traffic conditions in the vicinity of the metered ramp. Local traffic responsive metering is also employed as a component of a number of system wide traffic responsive metering strategies.

7.4.3.1 Occupancy

By accommodating to day-to-day variations and shorter term variations in mainline traffic volume, local traffic responsive ramp metering can improve performance relative to pretimed metering. Many ramp metering control algorithms use occupancy as the key parameter to establish metering rates.

Occupancy is the ratio of the time that vehicles occupy the detection zone of a traffic detector to a specified time period. It is sometimes used in ITS as a surrogate for traffic density (vehicles per lane per mile).

Different types of traffic detectors provide different vehicle sensing distances on the lane, that is, the occupancy time of a vehicle as sensed by a detector is:

$$\mathrm{t_j = \left(LV + LD\right) / S_j} \tag{7.3}$$

where

$\mathrm{t_j}$ = occupancy period sensed by detector for vehicle j
LV = length of vehicle
LD = length of detector sensing area
$\mathrm{S_j}$ = speed of vehicle j

The values of t are summed over a time period and divided by that time period to obtain the occupancy as indicated by that type of detector according to:

$$\theta = \left(1/\mathrm{T}\right) \cdot \sum_{\mathrm{j=1}}^{\mathrm{m}} \mathrm{t_j} \tag{7.4}$$

where:

θ = occupancy over averaging period T as indicated by the detector
m = number of vehicles passing the detector during time period T

Shawky and Nakamura [7] relate flow breakdown probability to occupancy in the same way that they did for volume (Fig. 7.5). Figure 7.10 shows the best fit to the data points for a particular ramp merge. Shawshy and Nakamura indicate that the relationship between flow breakdown probability and occupancy is more consistent among different ramp locations than is the relationship to volume, and therefore may be more preferable to use as a control variable. This observation is reinforced by the Australian Freeway Ramp Signal Handbook which notes that the critical volume point ($\mathrm{o_{cr}}$ in Fig. 7.11 [14]) is more stable and consistent under varying weather and lighting conditions.

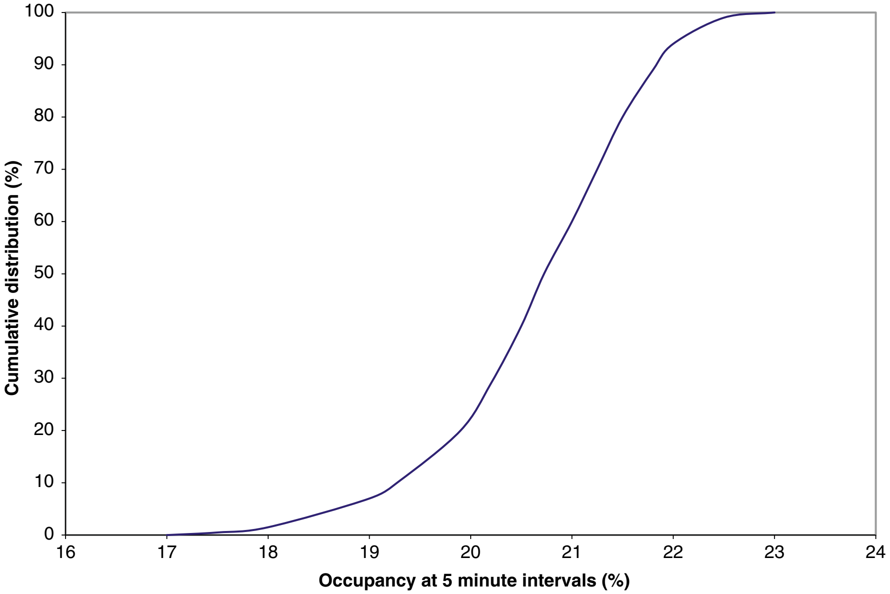


Fig. 7.10 Cumulative probability of flow breakdown vs. occupancy (redrawn). From, *Transportation Research Record*: *Journal of the Transportation Research Board*, *No. 2012*, Transportation Research Board of the National Academies, Washington, D.C., 2007, Figure 8a, p. 16. Reproduced with the permission of the Transportation Research Board

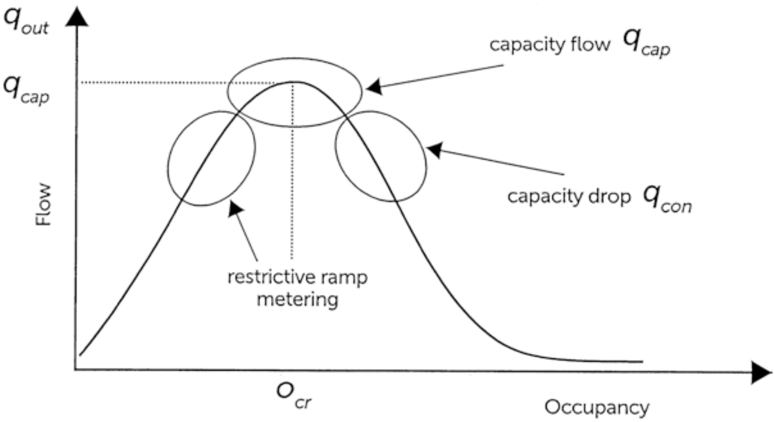


Fig. 7.11 Flow vs. occupancy regimes

Figure 7.12 shows a plot of volume vs. occupancy data for 1 min periods taken prior to the start of the PM peak period and continuing into that period. The trend lines in the figure may be compared to the trend lines in the volume vs. density plot of Fig. 7.4. The zero volume intercept of the congested condition trend line in

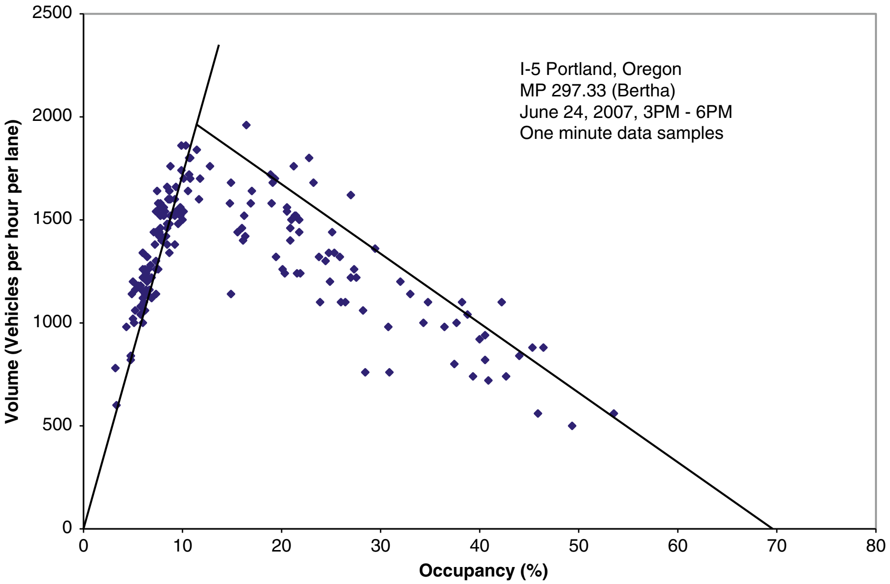


Fig. 7.12 Volume vs. occupancy data (Developed from Portland Oregon Regional Transportation Archive Listing—PORTAL)

Fig. 7.12 corresponds to the jam density point of Fig. 7.4. Its value is less than 100 % occupancy because, for most detectors, the apparent length that the detector itself contributes when each vehicle is sensed is less than the space between vehicles at jam density. For example, the sensed distance for the commonly used 6 ft square inductive loop detector is approximately 6 ft. The inter-vehicle distance at jam density is longer. Thus the average spacing between vehicles at jam density is greater than the detector's sensed distance along the of the roadway and an occupancy value of 100 % will not be obtained even under highly congested conditions.

7.4.3.2 Explicit Scheduling of Metering Rate

One commonly used control approach is to schedule the metering rate as a function of the occupancy measured during the previous time interval as shown in Table 7.4 [15]. Occupancy is measured by means of mainline detectors situated near the ramp merge with the mainline as shown in Fig. 7.2.

Occupancy data, however, exhibits considerable minute-to-minute variation, particularly when operation is in the transition region between the non-congested flow regime and congested flow. Figure 7.13 shows a portion of the data for 1-min intervals at the same location as for Fig. 7.12. This data encompasses the transition period between uncongested and congested flow as well as a portion of the congested flow period.

Table 7.4 Example of metering rate schedule

Occupancy (%)	Metering rate (vehicles/minute)
≤10	12
11–16	10
17–22	8
23–28	6
29–34	4
>34	3

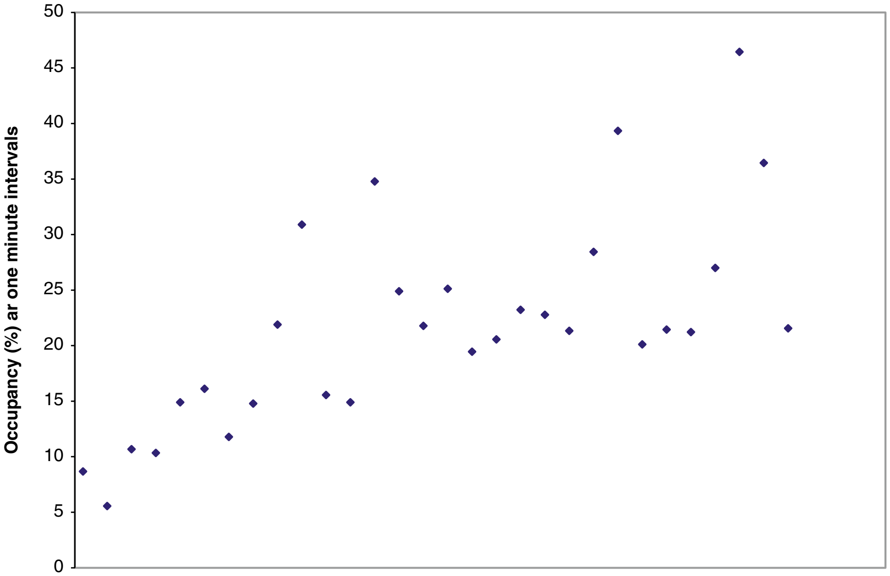


Fig. 7.13 Occupancy data vs. time for 1-min intervals (Developed from Portland Oregon Regional Transportation Archive Listing—PORTAL)

If control were to be implemented using raw data, the current occupancy might be considerably different from the value during the previous interval, i.e. the interval whose data are used to set the parameters for the current interval's metering rate. This would result in considerable variation in the metering rate during successive intervals. In order to mitigate this problem, many ITS use occupancy data that is processed by a filtering or smoothing process. The relationship for a first order linear filter that is commonly used [4] is:

$$\theta_O(j) = \theta_O(j-1) + K \cdot \left(\theta_I(j) - \theta_O(j-1)\right) \tag{7.5}$$

where:

$\theta_O(j)$=Filter output after the jth instant

$\theta_I(j)$=Filter input data value (average value of variable between j−1 and j instants)

K=Filter coefficient in the range 0–1.0; (K=1.0 represents no filtering)

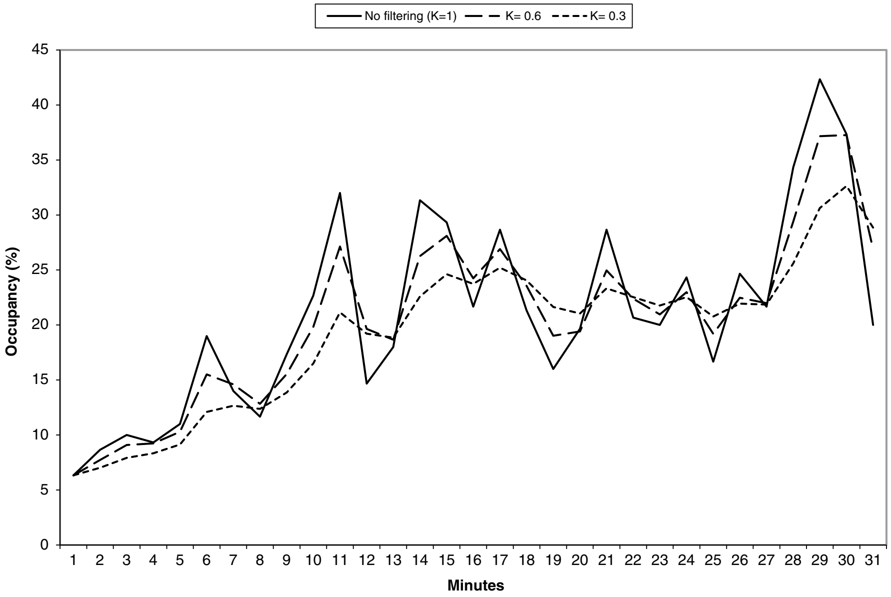


Fig. 7.14 Effect of filter coefficient

Figure 7.14 shows the large minute-to-minute variations in the unfiltered data plot to be considerably reduced as filtering is increased (reduced value of K). However, the time lag in the filtered data increases is the level of filtering is increased. Thus the selection of K is a compromise between the need to reduce the random variation in occupancy, and the requirement to closely track the secular trend.

Similar filtering considerations apply to the other traffic variables (e.g. volume, speed) that may be used for other purposes such as the geographical display of data in the traffic management center, use of data for DMS messages and communication of this information to traffic service providers.

Other data filtering techniques such as Kalman filtering [16] have also been employed in traffic systems. Kalman filters automatically adjust the filter coefficients based on the random variation in the sensed value of occupancy and in the detection error.

7.4.3.3 Closed Loop Control

The technique described in Sect. 7.4.3.2 for scheduling the local metering rate by occupancy measurements does not control the metering rate to achieve a specific objective. Closed loop control systems compare a desired objective function with an estimate of the function derived from measured traffic parameter(s). The metering rate is then adjusted to resolve the discrepancy. ALINEA is a commonly used closed loop control system. The ALINEA strategy controls the metering rate to a desired level

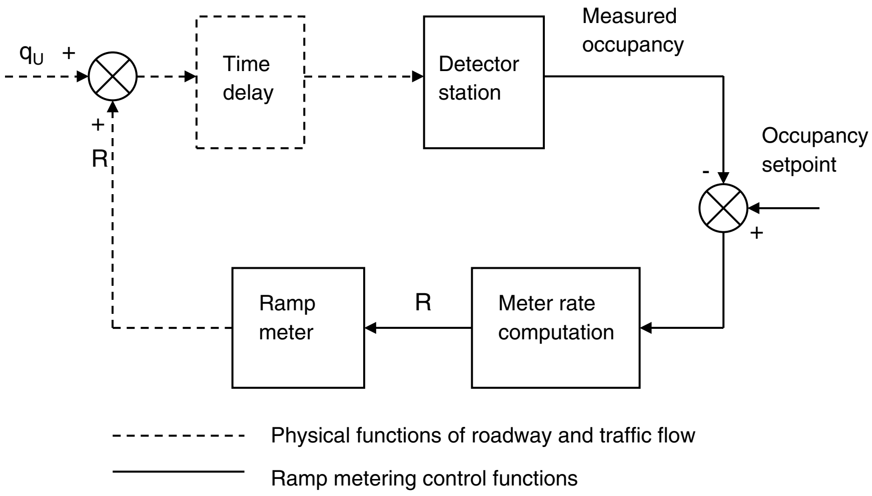


Fig. 7.15 ALINEA model

of occupancy based on the principles of linear control theory [17]. The desired level of occupancy (occupancy set-point) may be established based on capacity or flow breakdown probability. The equation used for the metering rate computation is:

$$R(j) = R(j-1) + K_R \cdot (\theta_S - \theta_M(j)) \tag{7.6}$$

where

$R(j)$ = meter rate (ramp volume) after time j
K_R = adjustable parameter
θ_S = occupancy set-point
$\theta_M(j)$ = occupancy measured by mainline detector (usually somewhat downstream of ramp merge with mainline) between time intervals j–1 and j

Figure 7.15 describes the operation of the control loop. The meter rate is added to the volume upstream of the meter (q_U). The model includes a physical time delay in the merged volume when sensed at the detector. This time delay is equal to the travel time between the ramp meter and the detector station. The detector station sensing this traffic provides the value of occupancy as determined by Eqs. (7.3) and (7.4). As shown in Eq. (7.6), this occupancy θ_M is subtracted from the set-point occupancy value θ_S, and the difference is multiplied by parameter K_R. This product constitutes the *change* in metering rate from the prior computation interval. Because these changes are relatively small for each interval, the filtering of occupancy data as described in the previous section is not required. ALINEA has been deployed at a number of sites in the U.S. and Europe.

SWARM 2 is a set of local traffic responsive algorithms. As described by Chu and Liu [18], SWARM 2a uses a density function to compute local metering rates based on headway theory. Theoretically, it attempts to maintain headway at the detector station upstream of metered ramp by optimizing density to maintain maximum flow. SWARM 2b introduces the concept of storage zone, which starts from the mainline upstream vehicle detector station (VDS) to the next downstream mainline VDS. The number of vehicles stored within this storage zone will be calculated. Then, SWARM 2b computes metering rates to maintain demand such that LOS D is maintained as along as possible. If there are on-ramps and off ramps between the two VDSs, detectors are required to be placed at on-ramps and off ramps for counting traffic volumes. This algorithm depends on accurate loop detector data.

7.4.4 System-Wide Traffic Responsive Restrictive Ramp Metering

System-wide traffic responsive ramp meter strategies adjust the rates of ramp meters as a group to optimize some objective function. A commonly employed objective is to minimize the probability of demand exceeding capacity at any bottleneck location within the controlled section of roadway based on current sensed traffic conditions. This may entail reducing the metering rate at a number of ramps upstream of the bottleneck. Advantages of these strategies include the ability to respond to current changes in traffic demand, and the ability to respond to changes in roadway capacity resulting from weather conditions and incidents. Table 7.5 provides a summary of the key features of these strategies.

In general, these strategies examine detector data in a zone downstream of the meter. Occupancy or density from one or more critical downstream detector locations is compared with criteria (usually at or somewhat less than a value which represents capacity, or the variable's flow breakdown value). In some cases, density is computed by a count-in, count-out process for a zone.

The metering rates of one or more upstream ramp meters are established to adjust the occupancy or density values at the detectors so that the critical value is not exceeded. Many strategies incorporate a local metering algorithm in addition to the system-wide algorithm, and the more restrictive rate computed by these algorithms is implemented.

The ramp is usually instrumented with one or more detector stations upstream of the meter in order to adjust the rates so that the queue does not spill back onto the surface street so as to obstruct traffic flow (this topic is discussed in Sect. 7.4.5.2).

7.4.5 Design Issues

7.4.5.1 Ramp Design Considerations

Metered ramps may be configured in a variety of ways to service signal display, safety and storage requirements. The number of metered lanes and the use of single vehicle metering or platoon metering depends on the maximum metering rate to be

Table 7.5 Examples of system wide traffic responsive ramp metering strategies

Strategy	Example of location used	Reference	Key properties of strategy
Stratified zone metering	Twin Cities, Minnesota	[19]	Freeway divided into zones. Strategy sets metering rate to keep the number of vehicles entering zone less than the number leaving
			Zones are organized into groupings (layers) which serve as the basis for meter rate calculations
			Strong emphasis given to constraint on maximum ramp waiting times. Ramp queues are monitored to assure that waiting time is not exceeded
Fuzzy logic	Seattle, Washington	[20]	See Appendix E
Helper	Denver, Colorado	[21]	Local algorithm initially sets metering rates
			If a ramp is metered at its minimum rate, the rates of upstream ramps are reduced
System wide adaptive ramp metering algorithm (SWARM)	Orange County, California, other locations	[22]	Selects lower of SWARM 1 and SWARM 2
			SWARM 1
			Forecasts density and measures excess density at each detector station
			Calculates target density and required volume reduction at each detector station
			Assigns volume reduction to upstream meters
			SWARM 2 (see Sect. 7.4.3.3)
Metaline	Paris	[23, 24]	Generalizes ALINEA for system wide metering
			Establishes an occupancy setpoint for critical downstream detectors and measures the error between the set-points and the occupancy value
			Provides incremental changes to each meter's metering rate based on weighted downstream occupancy error

employed (see Table 7.2). Where one lane is metered, vehicles may be stored in one lane or in two lanes and merged prior to the meter. In some cases an additional lane may be employed to permit buses or high occupancy vehicles to by-pass the ramp meter. The California Department of Transportation (CALTRANS) provides a ramp meter design manual that recommends design criteria for metered ramps and provides examples of designs [25].

Restrictive ramp metering often requires considerable storage space for vehicles. Caltrans describes a method for computing the ramp storage space required. The process is illustrated in Fig. 7.16 [25]. The figure consists of a grid divided horizontally into 10-min time increments and vertically into 100 vehicle per hour volume increments. The figure is based on an estimate of metering rates such as would be developed for a pre-timed metering schedule. Hourly volumes (in hundreds) are entered into the first row of the table below the figure when the arrival rate exceeds the metering rate. The second row represents the discharge rate which is the metering rate for the period that the queue is present. The third row represents the queue in tens of vehicles, and is computed as the difference between the first row and the second row plus the residual queue remaining from the preceding interval. Thus, in the example in Fig. 7.16, the maximum queue is computed as 60.4 vehicles, and occurs between 40 and 50 min after the demand first exceeds the metering rate as shown by the vertical profile rate. Caltrans recommends that 9 m of ramp lane length be allocated for each vehicle stored, thus the minimum storage requirement is 540 lane meters (60•9) in the example. Caltrans recommends additional storage where there are significant percentages of trucks, buses or recreational vehicles. The website http://www.springer.com/us/book/9783319147673 contains a data free image of this chart as shown in Fig. 7.17 that may be used to assist in establishing ramp meter schedules.

In many cases, the ramps cannot accept or be modified to accept the storage requirement. When this occurs, it may be advisable to consider non-restrictive metering.

7.4.5.2 Control of Ramp Queue Length

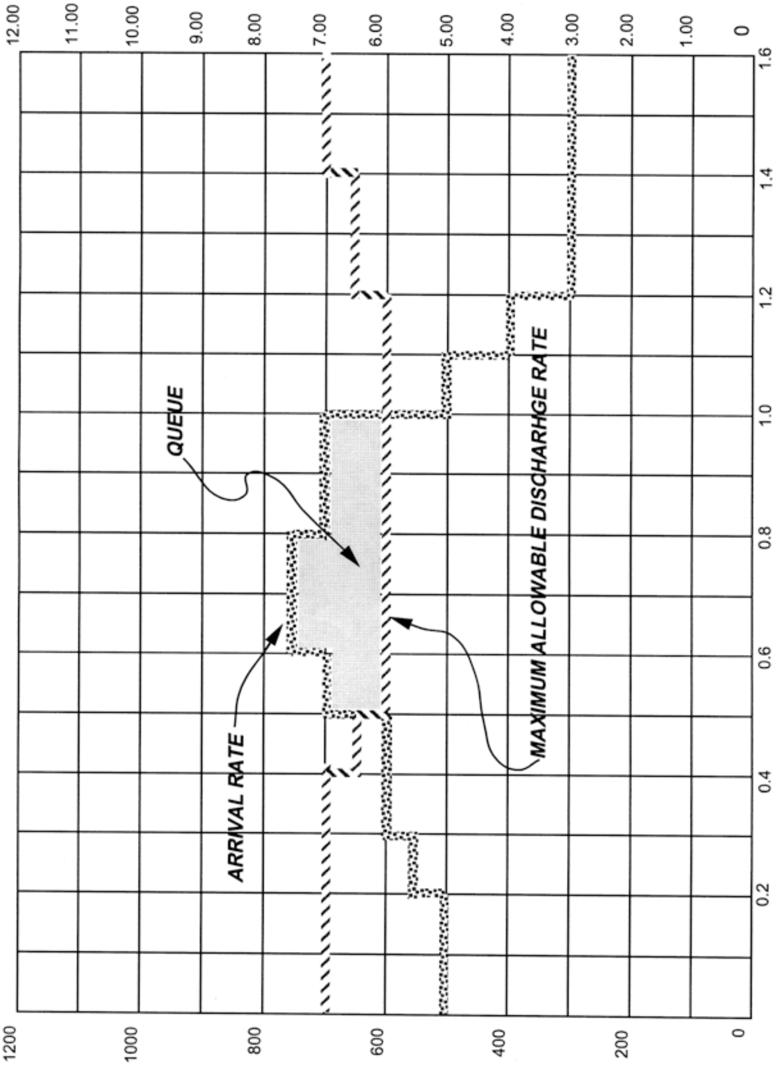
During the course of a control period that uses restrictive ramp metering, the queue will build and wane in the general way shown by the vertical length in the shaded area of Fig. 7.16. Short term variations in this general profile result from random traffic arrivals or by vehicle platoons released by traffic signals upstream of the ramp. Most operating agencies limit the maximum queue length on the ramp for one or both of the following reasons:

- Extending the queue past the physical ramp or past the space set aside for the storage of vehicles destined for the ramp entry will interfere with general surface street traffic operations.
- Some agencies may choose to limit the ramp waiting time (see Sect. 7.5.2).

Thus, most ramp meter controller systems provide a means for limiting the length of the queue, the technique usually utilizing signals from the ramp queue detector shown in Fig. 7.2. The following describes a number of techniques that may be used to control the queue. The first four techniques use the periodic occupancy measurement commonly developed by freeway management systems to determine the presence of the queue over the queue detector. Because the queue continues to build even after the metering control has been changed to compensate for the queue presence over the detector, that detector must be located somewhat

Ramp Meter Design Manual January 2000

ROUTE 10 INTERCHANGE BROWN ROAD RAMP NB - EB
BEGINNING TIME 0630 RAMP COUNT DATE 5/10/92
MAX QUEUE = MAX Δ X 10= 60 (60.4) VEHICLES
TOTAL DELAY = ΣΔ = 26.76 VEHICLE HOURS
TOTAL VEHICLES DELAYED = ΣA X 10 = 480 VEHICLES
AVERAGE DELAY TOTAL DELAY/TOTAL VEH. = 0.05 HOURS



A. Arriv	B. Disch	Δ=ΣA−ΣB
—		
—		
—		
—		
—		
7.00	6.00	1.00
7.52	6.00	2.52
7.52	6.00	4.04
7.00	6.00	5.04
7.00	6.00	6.04
5.00	6.00	5.04
4.00	6.00	3.04
3.00	6.00	0.04

Fig. 7.16 Ramp queue computation chart

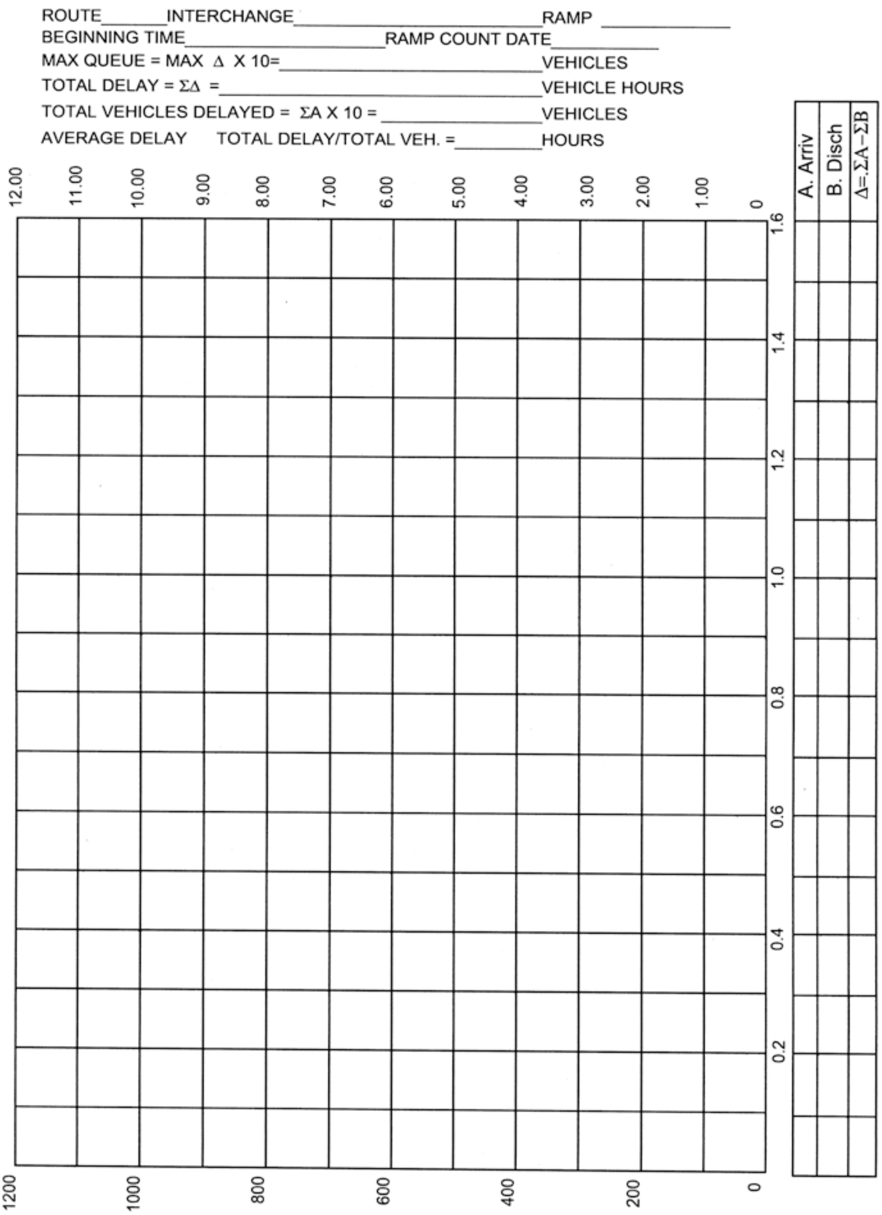


Fig. 7.17 Ramp computation chart (data free)

downstream on the ramp from the maximum expected end of the queue. The fifth technique utilizes additional queue detector data from each vehicle to estimate the end of the queue and control the metering rate accordingly. The sixth technique uses volume and occupancy estimates.

1. Termination of ramp metering when the queue is sensed by a high value of occupancy at the queue detector. Metering is resumed when the queue is no longer over the queue detector This is an early approach that is still sometimes used. It is not recommended because termination of ramp metering has a severe adverse effect on mainline traffic flow.
2. Increase of ramp metering rate to a higher value than the ramp arrival rate when the queue is sensed by a high value of occupancy at the queue detector. The rate may be increased to the maximum ramp metering rate. The planned metering rate is restored when the queue is no longer over the queue detector. This type of control results in a limit cycle (oscillation of the queue) in the vicinity of the queue detector, thus requiring the detector to be placed upstream of the location to be protected from queue spillback. The effect is to reduce the available queue storage space on the ramp.
3. When the queue is sensed by a high value of occupancy at the queue detector the metering rate may be incremented. This incrementation process continues with each sampling period until the queue is no longer over the queue detector, at which time the planned metering rate is restored. This control process, used by many of the ramp meters in California is slower than Method 2, and may lead to instability in controlling the queue [26].
4. In order to minimize the queue buildup after detection, Gordon [27] describes a technique which uses a combination of a faster than conventional sampling period for the occupancy detector (10 s is recommended) in conjunction with a data processing technique that anticipates the presence of the queue at the location of the detector by including the rate of change of occupancy. This technique results in a limit cycle that has a lower amplitude compared with Method 2, resulting in lower queue storage space requirements.
5. Sun and Horowitz [26] describe a technique that is used when the queue is close to the queue detector. At this point it adjusts the metering rate to maintain a prescribed queue length. Queue length is estimated by comparing the speed of each vehicle passing over the detector to a stored profile of vehicle speed vs. distance from the tail of the queue. This profile is developed beforehand based on observed measurements fitted to a curve that represents the vehicle's deceleration profile.
6. Spiliopoulou et al. describe a technique that estimates the number of vehicles in the queue by taking the difference of count measurements at the ramp entry and exit locations. This difference is then calibrated using occupancy measurements taken at the middle of the ramp [28].

7.4.5.3 Freeway-to-Freeway Ramp Metering

Traffic patterns on a freeway in major metropolitan areas are often dominated by traffic merging from another freeway. Often the effect is to create excessive delays to motorists on the first freeway upstream of the merge point. To mitigate these delays, the ramp leading from the merging freeway may be metered to induce some motorists to enter the freeway at a downstream entry ramp. Jacobson and Landsman

Table 7.6 Guidelines for freeway-to-freeway ramp metering [29]

Consider locations where recurrent congestion is a problem or where route diversion should be encouraged
Consider route diversion only where suitable alternative routes exist
Avoid metering twice within a short distance
Avoid metering single lane freeway-to-freeway ramps that feed traffic into an add-lane
Do not install meters on any freeway-to-freeway ramp unless analysis ensures that mainline flow will be improved so that freeway-to-freeway ramp users are rewarded
Install meters on freeway-to-freeway ramps where more than one ramp merges together before feeding onto the mainline, and congestion on the ramp occurs regularly (four or more times a week during the peak period)
If traffic queues that impede mainline traffic develop on the upstream mainline because of a freeway-to-freeway ramp meter, then the metering rate should be increased to minimize the queues on the upstream mainline, or additional storage capacity should be provided
Freeway-to-freeway ramp meters should be monitored and be controllable by the appropriate traffic management center
Whenever possible, install meters at locations on roadways that are level or have a slight downgrade, so that heavy vehicles can easily accelerate. Also, install meters where the sight distance is adequate for drivers approaching the meter to see the queue in time to safety stop

offer guidelines for the selection of appropriate sites [29]. These are summarized in Table 7.6.

Meters on freeway-to-freeway connectors have been extensively deployed on ramps leading to I-210 in California [30].

7.5 Ramp Metering and the Motorist

7.5.1 Motorist Benefits and Disbenefits Resulting from Ramp Metering

A review of ramp metering projects in North America indicates that significant overall benefits in the travel time in the corridor controlled by ramp meters and in the accident rate on the freeways controlled by ramp meters are obtained [10]. However, unlike other ITS treatments that are often characterized by benefits to all users, ramp metering, and especially restrictive ramp metering provides benefits to some motorists and exacts penalties on others.

Beneficiaries of ramp metering generally include motorists whose ramp waiting time is short compared to their trip length on the freeway. In some cases, motorist may enter the freeway upstream of the metered section and experience no waiting time. Other beneficiaries may include transit passengers in buses that utilize a ramp meter by-pass lane. Motorists penalized by ramp metering include the following:

- Motorists whose ramp waiting time is relatively long compared to the travel time on the mainline. These motorists often enter the freeway in the central city closer to the central business district. In other cases, the waiting time is considerably different at different ramps. These *equity* issues have been addressed in the following ways:

  - Metering may be primarily utilized on the suburban ramps rather than in the central city.
  - Queue waits may be limited to an acceptable maximum (Sect. 7.5.2).
  - Metering may be implemented only in the outbound direction.
    Section 3.2.1 discusses the Gini coefficient that may be used as a measure of equity.

- Motorists who divert from the freeway and motorists on the alternate routes whose trips do not utilize the freeway will generally experience longer trip times than they experienced before the freeway was metered. These issues may be mitigated in the following ways:

  - Preplanning by means of simulation or other techniques to provide metering rates that will limit diversion to a level that is acceptable to stakeholders concerned with surface street impacts. For example, when metering was first implemented in Portland, Oregon it was agreed to limit diversion so that surface street volumes would not increase by more than 25 % [1].
  - Detectors in traffic signal systems and CCTV and probe readers on surface streets may be monitored in real time, and metering rates adjusted to assure that an acceptable level of service is maintained on the alternates.

Issues such as these require the stakeholders to agree to the planned ramp metering operations and their estimated impacts. It is recommended that these be included in the Concept of Operations for the system (Sect. 2.1.2).

7.5.2 Public Acceptance of Ramp Metering

When ramps are restrictively metered, motorists waiting in the daily queue rapidly become aware of a delay that they had not previously experienced. The benefits in terms of reduced mainline travel time and more safe merges may not be as easily perceived. The motoring public, political leaders and law enforcement agencies should be made aware of the potential benefits before they experience ramp metering. Public outreach techniques include brochures, use of the print and electronic media and outreach to local leaders and law enforcement officials [1, 2]. In many cases these techniques have resulted in positive public attitudes towards and compliance with ramp meter signals.

As an example of the type of difficulty that acceptance of ramp metering may experience, because of perceived long ramp waiting times, the Minnesota legislature in 1990 required a study to be conducted to assess the benefits of ramp metering at the behest of the public and political leaders. The study involved measuring delay with and without ramp metering, the ramp meters being turned off for a period of approximately 2 months.

The results showed that the ramp meters made considerable improvement in travel time reliability, mainline throughput and in crash reduction. A user survey indicated that while respondents now had an increased appreciation of the role of ramp meters, they felt that there was too much metering under free flow conditions and that there were too many meters in general. The study recommended a new principal for ramp meter operation namely *Balance the efficiency of moving as much traffic during the rush hours as possible*, *consistent with safety concerns and public consensus regarding the queue length at meters* [31].

As a result of the study, ramp metering policy was modified to limit ramp meter wait time to less than 4 min for local ramps and less than 2 min for freeway to freeway connector ramps. Implementation of this plan resulted in system-wide benefits that were better than the no metering situation, but worse that the previously employed ramp metering strategy [32].

7.6 Benefits Model for Ramp Metering

When demand is sufficiently close to capacity, ramp metering can reduce overall corridor delay and provide savings in fuel consumption and emissions in the roadway segment affected. It also reduces the accident rate near metered ramps. Figure 7.18 shows the relationships for a simple benefits model. The model estimates annual delay and accident reduction in a segment of the highway influenced by ramp metering.

The symbols in the model are defined in Table 7.7.

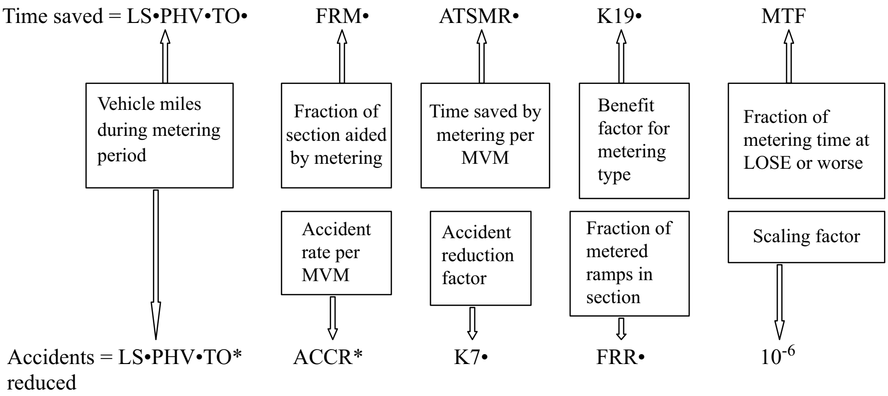


Fig. 7.18 Simple ramp metering benefits model

Table 7.7 Symbols for ramp metering benefits model

Symbol	Definition	Representative default value
LS	Length of roadway segment influenced by ramp metering (miles)	Default not applicable
PHV	Peak hour volume	Default not applicable
TO	Metering hours per year	Default not applicable
FRM	Fraction of roadway segment improved by metering	Default not applicable
ATSMR	Average time per mile per vehicle saved by metering	.00476 h per mile per vehicle
K19	Ramp metering benefit factor	K19 = 1.0 for restrictive metering
		K19 = 0.4 for non-restrictive metering
MTF	Fraction of planned metering period that freeway is at level of service E or worse	Default not applicable
ACCR	Accident rate per million	Default not applicable
K7	Accident reduction factor	0.2
FRR	Fraction of ramps in roadway segment that contain ramp meters	Default not applicable

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Chapter 8
Transportation Management Centers

Abstract This chapter describes the functions of a transportation management center (TMC) and provides examples of the services that TMCs provide. Information flows among stakeholders, how they relate to the Regional ITS Architecture and how they may be implemented are discussed. Statewide TMC architectures and statewide databases are described.

8.1 Transportation Management Center Functions

The control and management of ITS operations is performed in a transportation management center (TMC), sometimes called a traffic management center or traffic operations center. The TMC provides a focal point for implementing the Regional ITS Architecture and the Concept of Operations (CONOPS) [1] developed from the project's systems engineering processes (Sect. 2.1.2). TMCs often house operations for a number of transportation related agencies and emergency service providers.

TMCs provide general management services to support transportation related functions provided by agencies responsible for freeway operations, surface street operations, emergency management and police services. TMCs facilitate inter-agency communication and coordination, implement the provision of traffic information to the media and to the public, coordinate with transit agencies and provide a point of contact for the public and for organizations with special information needs. Major freeway management functions supported by the TMC are described below.

8.1.1 Support of Emergency Management Services

TMCs support emergency management service providers that respond to traffic related incidents. They make available information and traffic conditions to responders and help them identify the need for emergency services while identifying the quickest route for emergency service providers to reach the incident site. Specific information such as CCTV images, lanes affected and the location of the tail of the queue may be afforded in response to requests by emergency service providers. The TMC generates, stores and implements incident management plans and provides the incident support services discussed in Sect. 4.5.2.

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CCTV is a key tool to assist in incident management as it supports the following functions:

- Identifying the types of response services required.
- Assisting responders in finding the quickest route to the incident.
- Assisting responders in managing traffic in the vicinity of the incident and its queue.

CCTV images are often shared with other TMCs, agencies and emergency responders.

8.1.2 Provision of Information to Motorists

The TMC provides information to the agency's field devices such as dynamic message signs (DMS), highway advisory radio, HAR beacons and perhaps kiosks in agency operated locations or in private venues. Traffic information is also offered by private agencies such as independent service providers and the media. The TMC may provide messages requested by other TMCs. Information generated by the TMC typically makes a significant contribution to the information base for the state's 511 motorist information service.

The types of information provided to the motorist by the TMC may include:

- Non-recurrent congestion and related problems such as police activity and roadway surface related problems.
- Recurrent congestion in the form of travel time or travel movement information (depending on the agency's policy).
- Construction scheduling and traffic impact.
- Special event scheduling and traffic impact.
- Major events or incidents on other facilities.
- AMBER alerts.
- Roadway or traffic conditions related to weather events.
- Transit and corridor related information including park-and-ride facility status.
- Default messages related to motorist safety (depending on the agency's policy).

8.1.3 Operation of Ramp Meters

TMCs support the following operations associated with ramp meters:

- Daily operations—Operating personnel select metering modes and may alter metering rates based on observations of mainline traffic flow and ramp queues. Incident management plans and corridor management functions may also require the modification of ramp metering rates.
- Data archiving and mining—Traffic detector data is stored and analyzed by computer programs. These programs provide information showing distribution of

traffic data at a site by time (e.g. Fig. 6.3). Daily profiles showing speed for a section of roadway such as those displayed in Fig. 8.1 [2] and the volume data that accompany them are useful in determining and revising meter rates, schedules and traffic responsive metering parameters. Data archiving and mining also support other TMC functions.

- Revision of metering plans—Meter rates, schedules and traffic responsive metering parameters may be modified based on archived data as described above. Revisions may be facilitated by the use of traffic simulation programs [3].

8.1.4 Operation of Service Patrols

Freeway service patrols, also known as motorist assistance patrols and courtesy patrols may be operated by a highway agency or a private company. The TMC usually coordinates and supervises service patrol operations. Most service patrol vehicles follow pre-established *beats* or routes. Their primary function is to mitigate congestion or potential congestion by clearing minor incidents from travel lanes. They generally provide the following services:

- Assist immobile vehicles by providing fluids, performing minor mechanical repairs and calling towing services. Push bumpers may be used to clear stalled vehicles from travel lanes.
- Clear debris from the moving lanes and from the shoulders.

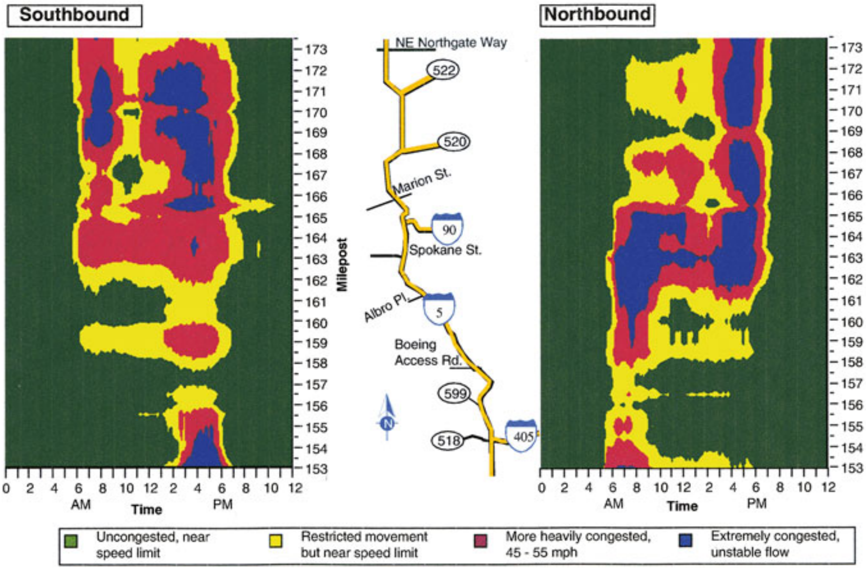

Fig. 8.1 Daily speed profile for roadway section

- Assist police in the tagging and removal of abandoned vehicles.
- Assist response providers in the management of traffic during incidents.

The benefits provided by service patrols to the freeway system include reduction of delay and reduction in secondary accidents by improving the clearance time for incidents. They are popular with the motoring public.

8.1.5 Coordination of Traffic Signal Operation with Freeway and Corridor Requirements

Implementation of traffic diversion plans in the event of incidents may require the TMC to instigate alternative signal timing plans. In some cases, another agency implements the timing plans requested by the freeway TMC. Alternative signal timing plans may be used for the following purposes:

- Diversion along preplanned routes in the event of a freeway incident.
- Support of operations to improve throughput in a transportation corridor.
- Implementation of freeway and surface street traffic plans to support special events.
- Implementation of freeway and surface street traffic plans to support emergency evacuations.

8.1.6 Provision of Weather Information Related to Roadway Conditions

TMCs provide weather information related to roadway conditions. This information may be provided by systems operated by the TMC, or the TMC may receive this information from a statewide system. Roadway weather information systems (RWIS) utilize measurements made at field stations that may include:

- Air temperature, pressure and humidity.
- Wind speed and direction.
- Precipitation type and amount.
- Visibility.
- Pavement and subsurface temperature.
- Pavement condition, e.g. dry, damp, wet, ice, snow, residual salt and water film.

This knowledge is utilized by models that, together with National Weather Service and private weather service data, provide information on visibility and precipitation related conditions. This information warns motorists of hazardous conditions and may influence route selection. The information is also used to deploy snowplows and sanders to the most likely incident prone locations.

8.2 Example of Transportation Management Center in Major Urban Location[1]

Figure 8.2 shows The New York State Department of Transportation's INFORM transportation management center (TMC) which manages traffic on the limited access highways and on a number of surface streets on Long Island. The TMC operates 24-h a day, 365 days a year. A major function of the TMC is to assist emergency responders in the management and clearance of incidents. Figure 8.3 shows a commercial vehicle that illegally entered a Long Island parkway and became trapped under one of the parkway's low overpasses.

Figure 8.4 displays the facility's control room.

Services performed by the INFORM TMC include:

- Notice of traffic conditions on dynamic message signs These DMS provide indications of both recurrent and non-recurrent congestion events.
- Information dissemination to the media, the NYSDOT 511 system and to other transportation agencies.
- Monitoring of roadway conditions via closed circuit television cameras. A number of these cameras are located on surface streets and near special event venues. Public access to the camera displays is available through the INFORM web site [4] as well as others.

Fig. 8.2 INFORM Traffic Management Center. Source: Parsons Brinckerhoff, Inc.

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[1] Much of the information in this section was provided by Messrs. Emilio Sosa of the New York State Department of Transportation and Richard Knowlden of Parsons Brinckerhoff, Inc.

Fig. 8.3 Incident on a Long Island parkway. Source: Parsons Brinckerhoff, Inc.

Fig. 8.4 INFORM control room. Source: Parsons Brinckerhoff, Inc.

- Collection of information from over traffic detectors including inductive loop detectors, video detectors, radar based detectors and acoustic detectors. This information assists in incident management and development of motorist information. The system also operates sites providing weather information.

Fig. 8.5 INFORM ramp meter. Source: Parsons Brinckerhoff, Inc.

- Operation of entry ramp meters. Figure 8.5 shows a typical ramp meter installation. These ramp meters are generally operated in a non-restrictive fashion (Sect. 7.1).
- Dedicated travel time signs at key locations on the Northern State Parkway and state surface street arterials. Travel time is also displayed on the overhead, shared purpose DMS.
- Coordination of traffic signals on surface streets that support the limited access highway network. In the event of incidents or construction on the limited access highways, emergency signal timing plans facilitate diversion to these facilities.
- Motorist assistance during morning and evening peak travel periods.

8.3 Interconnection and Coordination of TMCs

In earlier years, freeway TMCs were primarily stand-alone entities. Coordination with other TMCs and emergency services were primarily telephonic and often informal. Subsequent experience revealed the benefits of intensifying and formalizing the relationships and improving connectivity among freeway TMCs and between freeway TMCs and other agencies. TMCs are important facilities for implementing the Regional ITS Architecture.

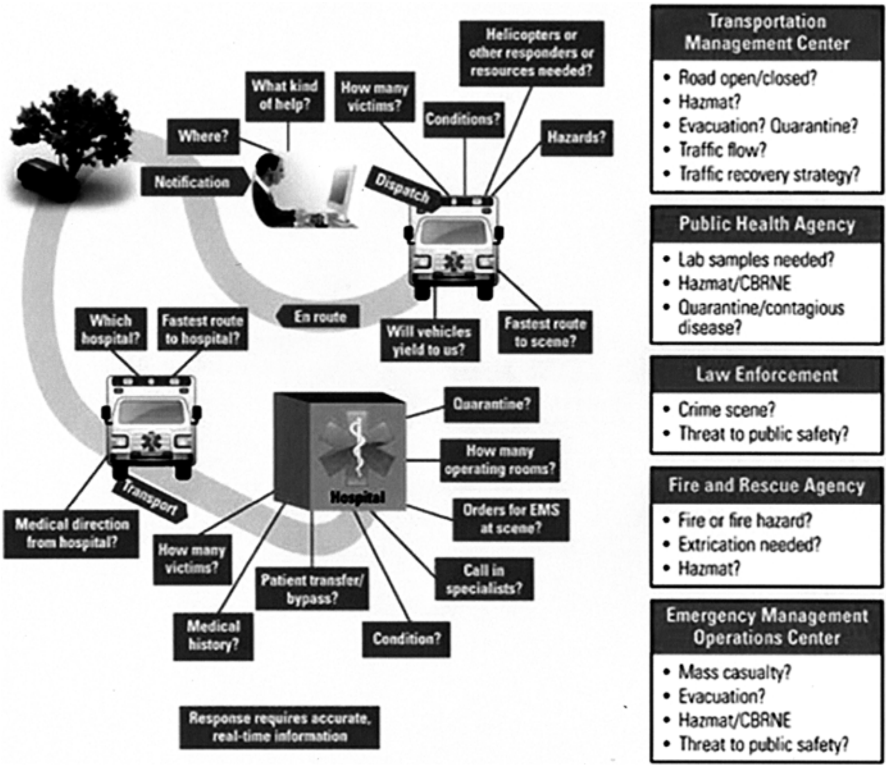


Fig. 8.6 Information flow requirements for emergency response

8.3.1 Regional Coordination

8.3.1.1 Functions of Regional Coordination

The following sections discuss the functions and purposes of coordinating TMCs in a region.

Facilitate Interagency Emergency Response

Agencies responding to emergencies and contributing to clearance of incidents typically operate management centers. Data exchanges among these agencies insure that the most appropriate agencies, equipment, and routes are employed. Interagency emergency response functions may become quite complex as illustrated in Fig. 8.6 [5].

Coordinate Traffic Management Strategies Among Agencies [6]

Management of traffic may require traffic management measures that are required by or implemented by other agencies. These may, for example include:

- Control of traffic signals by other agencies to support coordinated traffic management strategies.
- Coordination of DMS or HAR messages that utilize equipment that is managed by other agencies.
- Responses to weather emergencies and other emergencies.

Support Traveler Mode Choice Decisions

Decisions by motorists to retain or alter their current mode in response to the current situation may require information from other agencies. This information may be displayed on the agency's DMS or on the 511 website. Typical requirements include:

- Information on transit schedules.
- Information on parking availability.
- Information on congestion as a result of special events.
- Significant problems at another location that may cause a traveler to alter the character of his trip.

8.3.1.2 Implementation of Regional Coordination

Regional coordination may be implemented through the following measures.

Regional ITS Architecture

TMCs are key instruments for implementing the Regional ITS Architecture. This section illustrates how the information flows identified in the Regional Architecture may be implemented by TMCs. The Regional ITS Architecture represents a long-range view of the region's ITS needs.

The Regional ITS Architecture emphasizes the use of common communication standards among the stakeholders and management centers. Computer-to-computer data transfers may be performed using ITS protocol families such as NTCIP, TCIP or IEEE 1512 protocol families, or with other standard data transfer protocols.

In contrast, projects that install field equipment or establish or modify TMCs satisfy a subset of these needs. These projects must identify the particular information flows to be incorporated into the project and must define the methodology for accomplishing these information flows. As an example of how this is accomplished, Table 8.1 shows a methodology for implementing information flows for a TMC in Binghamton, NY in conformance with the Regional ITS Architecture.

Table 8.1 Implementation of information links

Source element	Destination element	Flow description	Implementation methodology
NYSDOT Regional TMC	NYSDOT Regional TMC Roadside Equipment	Roadway information system data	DMS NTCIP protocol for controls and message delivery
			HAR voice audio file standard
			HAR beacon control signal
		Signal control data	NYSDOT standard signal system
		Traffic sensor control	NTCIP protocol for data request
		Video surveillance control	NTCIP protocol for camera controls
	Broome County Emergency Management Center	Incident information	NYSDOT TMC workstation, telephone
		Road network conditions	NYSDOT TMC workstation, telephone
	NYSDOT Regional MCO Center	Field equipment status	NYSDOT TMC workstation
		Road network conditions	NYSDOT TMC workstation
		Work plan feedback	Telephone, email
NYSDOT Regional TMC Roadside Equipment	NYSDOT Regional TMC	Freeway control status	DMS Status—NTCIP protocol
			HAR Status—proprietary protocol
			HAR beacon status—simple switch indication
		Traffic flow	Detector data—NTCIP protocol
		Traffic images	CCTV camera images—MPEG standard

Shared Facilities and ITS Equipment

The following general methods of sharing information for incident management and other purposes are utilized:

- Face-to-face information sharing—This usually takes place when facilities are shared by stakeholders. Improvement in operations results when stakeholder management centers are co-located, as co-location provides opportunities for close collaboration in planning operations involving multiple stakeholders. In some cases equipment may be shared among stakeholders. For example, the Regional Traffic Operations Center in the Rochester, NY region (Fig. 8.7) houses

Fig. 8.7 Regional operations center in Rochester, NY

the operations centers for NYSDOT freeway operations, the Monroe County traffic signal system (which operates signals in the City of Rochester, Monroe County and interconnected state signals), and the New York State Police. NYSDOT and Monroe County CCTV cameras are controlled by a single system. Every camera may be accessed by either agency and displayed either on workstations or on shared large screen displays. Similarly, a single system for controlling DMS is shared by both agencies.

Other resource sharing opportunities include the following [6]:

- Sharing of the same computer aided dispatch (CAD) system by emergency responders.
- Text message interfaces between CAD systems and the freeway management system.
- Sharing communication facilities among stakeholders. This may facilitate display of CCTV at stakeholders facilities or in emergency response vehicles.
- Remote voice—Telephones and land mobile radio are examples of this method.
- Electronic text—Examples include paging, facsimile, email and text access to traffic incident-related data systems.
- Other media and advanced systems such as video and traffic management systems.

This type of data transfer may require reprogramming of legacy systems. The modification cost might be significant, particularly for metropolitan areas with limited resources. Alternatively, remote workstations offer a relatively inexpensive way to share information. For example, placing a TMC workstation or workstation software in another management center will enable that center to view road network conditions, equipment status and incident status.

Regional Management

In some locations, a regional data clearing house provides coverage that enables the agency to "see" beyond its geographical or functional operating limits. For example, in the New York Metropolitan Area, TRANSCOM serves as an agency that coordinates transportation data (including transit information) and management of emergency responses.

TRANSCOM [7] was created in 1986 to facilitate construction coordination among agencies throughout the New York, New Jersey, and Connecticut metropolitan region. Subsequently, its role expanded to include multi-agency, regional incident management 24 h a day. In serving its 17 member agencies, TRANSCOM has developed and now operates a number of Intelligent Transportation Systems (ITS). TRANSCOM collects and disseminates up-to-the-minute regional incident, construction, and special events information, 24 h a day, through an extensive notification network. Member agencies contribute traffic condition and incident information, and transit agencies contribute schedule variance information. Each notification is distributed to affected agencies in the tri-state area. Recipients include highway and transit agencies; state, county, and local police departments; and media traffic services. During major incidents, construction, and special events, TRANSCOM helps to marshal regional resources for incident response. These resources include its member agencies' dynamic message signs and highway advisory radio, which get the word out to travelers. Sharing these resources allows information to reach a much wider public.

8.3.2 Statewide Coordination

Many states operate a number of TMCs. Although many were originally designed as stand-alone facilities, a number of states have taken steps to coordinate their design and operation.

8.3.2.1 Functions of Statewide Coordination

The purposes of statewide coordination of operations and facility management among the state DOT's divisions or regions include the following.

Seamless Operation Among Adjacent Divisions or Regions

Incident management and motorist messaging in response to recurrent or non-recurrent congestion that involves more than one TMC must be coordinated. Similarly, requirements for selection of traffic signal timing plans that may cross TMC boundaries must also be coordinated.

Economies of Operation

TMCs that manage smaller regions or those with less intense traffic may be operated by another, larger TMC, particularly during evening hours, thus achieving staffing economies. Implementation requires this requirement to be included during the design or modification of the facilities involved.

Response to Disruption of TMC Operation

Environmental or other events may disrupt TMC service. In some cases, provision may be made for an alternate facility. In other cases, it may be more feasible to conduct operations from another state region or division.

Logistics Economies

Uniform design may lead to economies in personnel and maintenance training and in the maintenance of TMCs. Uniform design also facilitates shared learning and management experience.

8.3.2.2 Implementation of Statewide Coordination

Statewide coordination may be implemented through the following measures.

Statewide ITS Architecture

The statewide ITS architecture provides a vehicle for coordinating both the physical and functional requirements of TMCs. Figure 8.8 [8] shows a depiction of a statewide architecture while Fig. 8.9 [9] shows a small portion of the traffic management responsibilities.

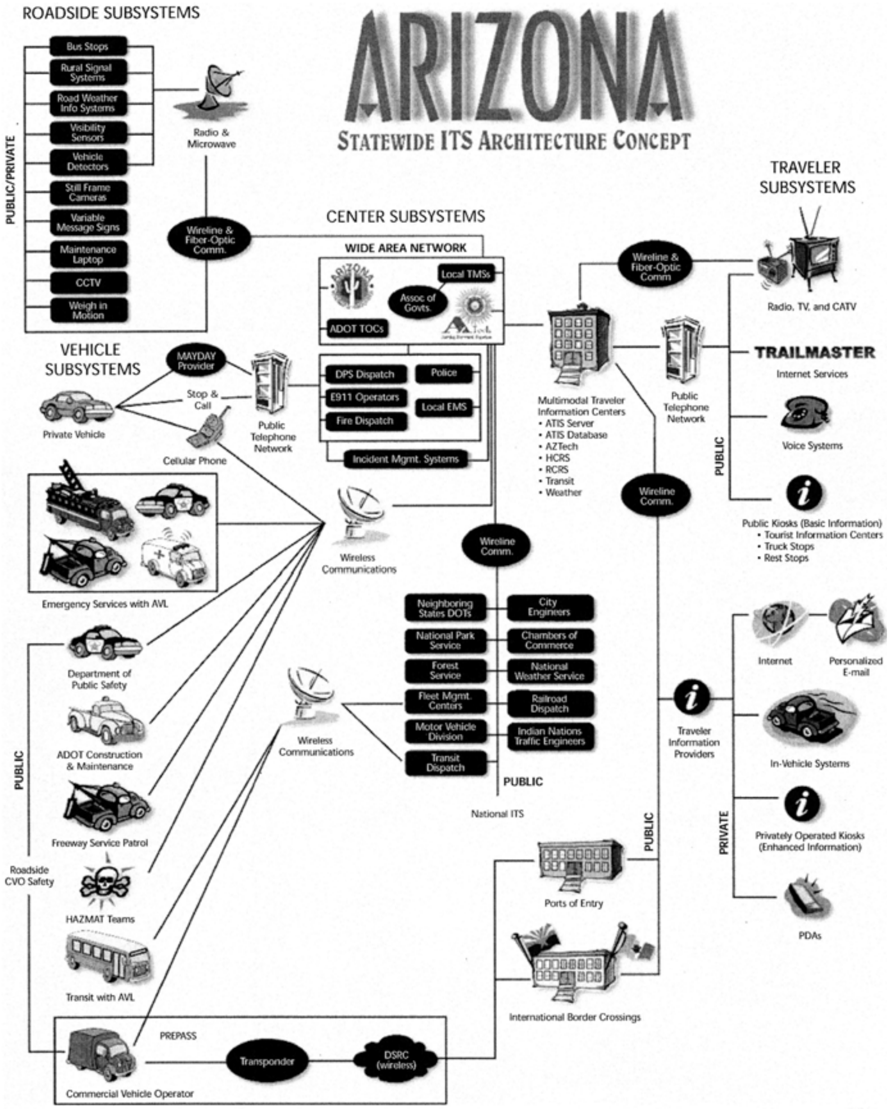
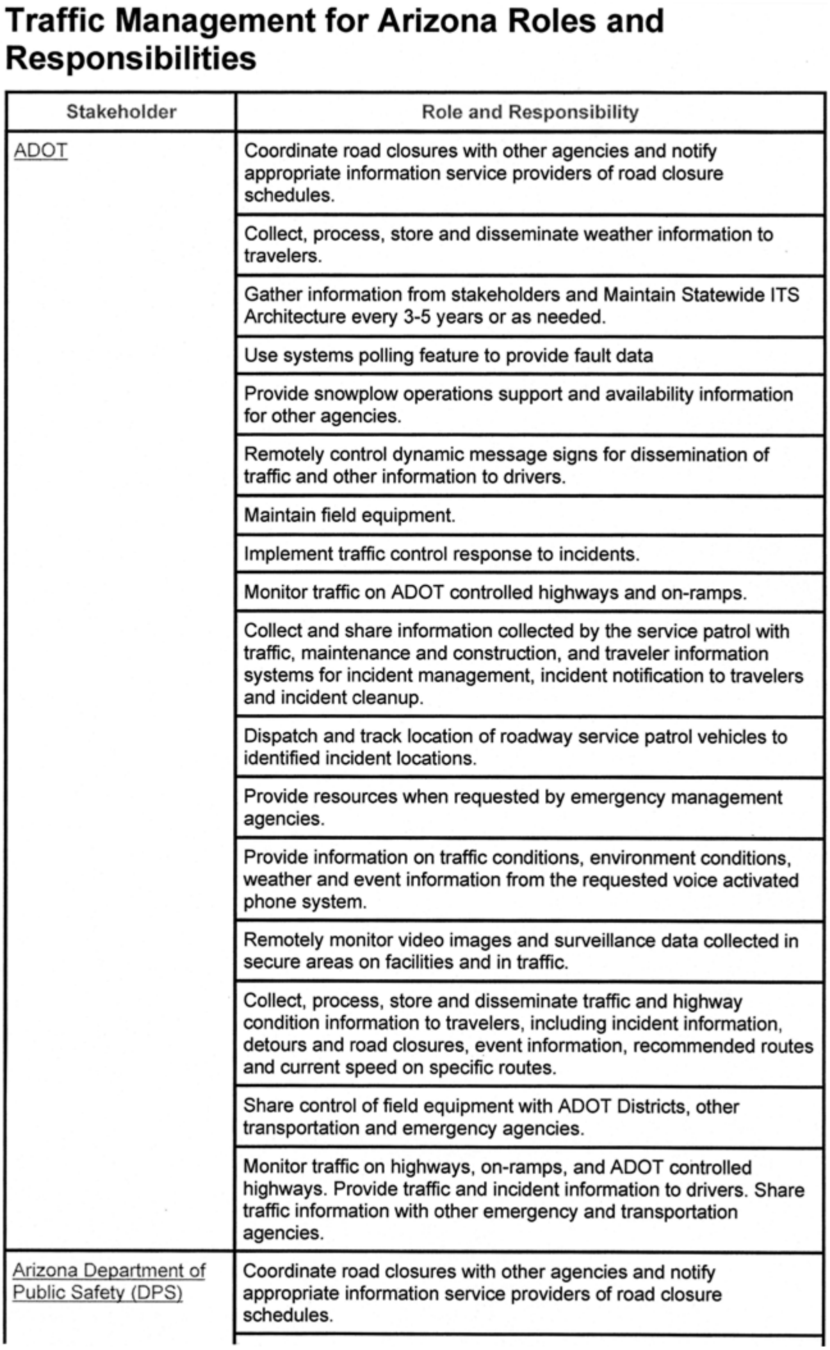


Fig. 8.8 Arizona Statewide ITS Architecture concept

Shared Center-to-Center (C2C) Communications

Some state architectures utilize a highly developed level of center-to-center information sharing. An example of such an architecture is shown in Fig. 8.10 [10].

Figure 8.10 provides an illustration of the interface of several existing component systems via their individual C2C Interface Modules. DMS and CCTV operate through a peer-to-peer approach. For example, when a given jurisdiction desires to



Traffic Management for Arizona Roles and Responsibilities

Stakeholder	Role and Responsibility
ADOT	Coordinate road closures with other agencies and notify appropriate information service providers of road closure schedules.
	Collect, process, store and disseminate weather information to travelers.
	Gather information from stakeholders and Maintain Statewide ITS Architecture every 3-5 years or as needed.
	Use systems polling feature to provide fault data
	Provide snowplow operations support and availability information for other agencies.
	Remotely control dynamic message signs for dissemination of traffic and other information to drivers.
	Maintain field equipment.
	Implement traffic control response to incidents.
	Monitor traffic on ADOT controlled highways and on-ramps.
	Collect and share information collected by the service patrol with traffic, maintenance and construction, and traveler information systems for incident management, incident notification to travelers and incident cleanup.
	Dispatch and track location of roadway service patrol vehicles to identified incident locations.
	Provide resources when requested by emergency management agencies.
	Provide information on traffic conditions, environment conditions, weather and event information from the requested voice activated phone system.
	Remotely monitor video images and surveillance data collected in secure areas on facilities and in traffic.
	Collect, process, store and disseminate traffic and highway condition information to travelers, including incident information, detours and road closures, event information, recommended routes and current speed on specific routes.
	Share control of field equipment with ADOT Districts, other transportation and emergency agencies.
	Monitor traffic on highways, on-ramps, and ADOT controlled highways. Provide traffic and incident information to drivers. Share traffic information with other emergency and transportation agencies.
Arizona Department of Public Safety (DPS)	Coordinate road closures with other agencies and notify appropriate information service providers of road closure schedules.

Fig. 8.9 Portion of Arizona Statewide ITS Architecture

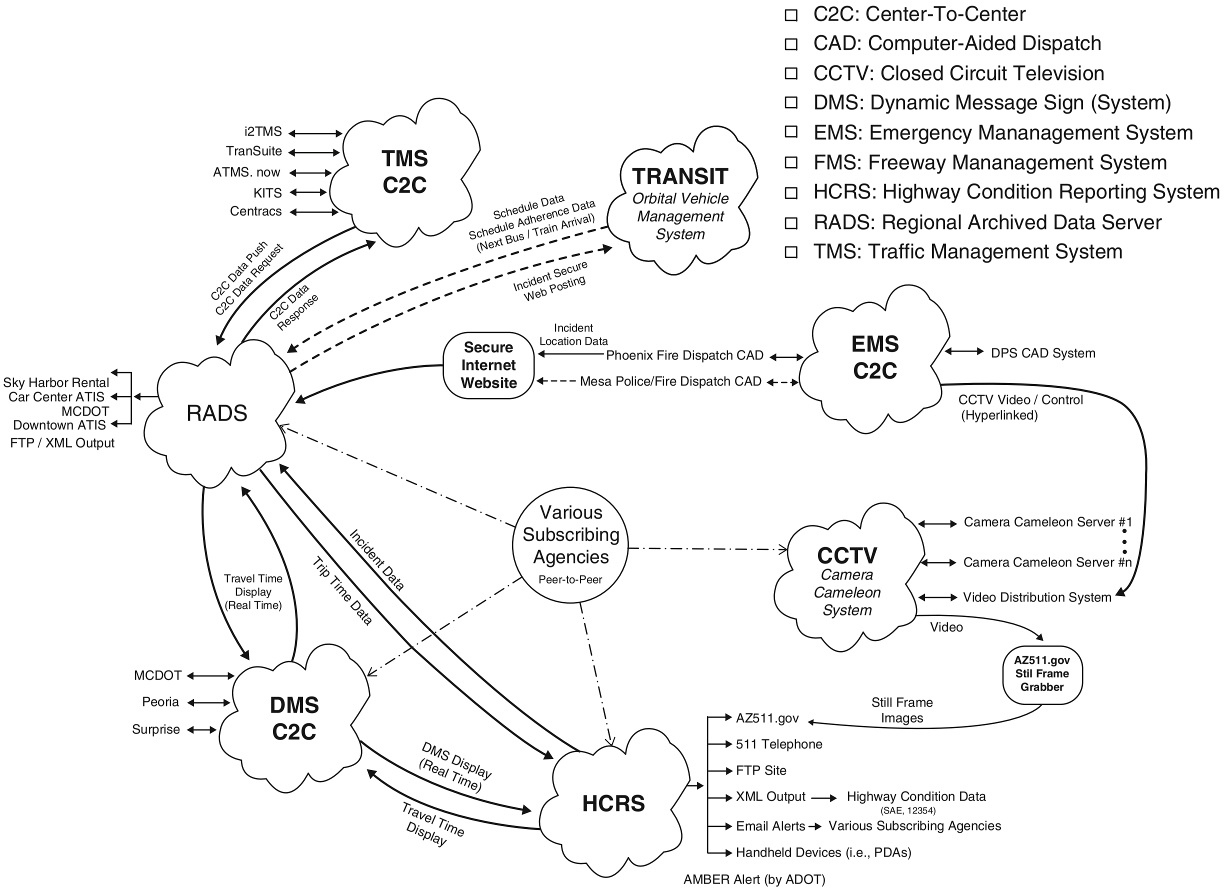


Fig. 8.10 Arizona C2C diagram

place a message on a neighboring jurisdiction's DMS, it places the request through its own software, which is then translated by the C2C Interface Module to the standard protocol. Next, it is passed over the C2C System (through the "cloud"), translated to the neighboring jurisdiction's input format by the receiving C2C Interface Module, and then passed to the receiving system for processing. At no point will an "outside" system have direct control over or communications with that DMS because all inputs and outputs will pass through the local "owning" system. The "owning" system retains the ability to permit or restrict access to any and all users, both internally and externally, and also retains the ability to log all actions by all users [10].

Statewide ITS Standards and Specifications

By including ITS standards in their standard specifications many states ensure that data may be easily transmitted among TMCs. Some of the more commonly employed standards sets are identified in Sect. 8.3.1.2. The National ITS Architecture identifies standards sites that are commonly used [11].

Single Supplier for ITS Management System Software

In the past, many states implemented ITS management software separately for each region or division. The disadvantages of this arrangement include difficulty in migrating data and in coordinating operations between adjacent TMCs, inability to share maintenance and training resources among TMCs and reduced efficiency in sharing "lessons learned". To improve these limitations, a number of states have decided to consolidate TMC software through the use of a single supplier. Because of resource limitations, this process may take some time to complete.

Remote Operation of TMCs

Larger TMCs often are equipped with backup management facilities in the event that circumstances render the primary site inoperative. This approach might not be effective for smaller TMCs. In addition, it may be more efficient, particularly during off hours, to operate smaller TMCs from larger TMCs. The architecture shown in Fig. 8.10 may be adapted to implement this approach. An alternative architecture, shown in Fig. 8.11 may also be employed for this purpose. Using this approach under normal conditions, the local TMC normally manages the operation. In off hours or under emergency conditions, the field devices may be managed by the remote TMC through a communication channel that does not require the local TMC to be available. The use of internet communications protocols facilitates this concept. A link between the TMCs is used to keep the remote TMC up to date on the

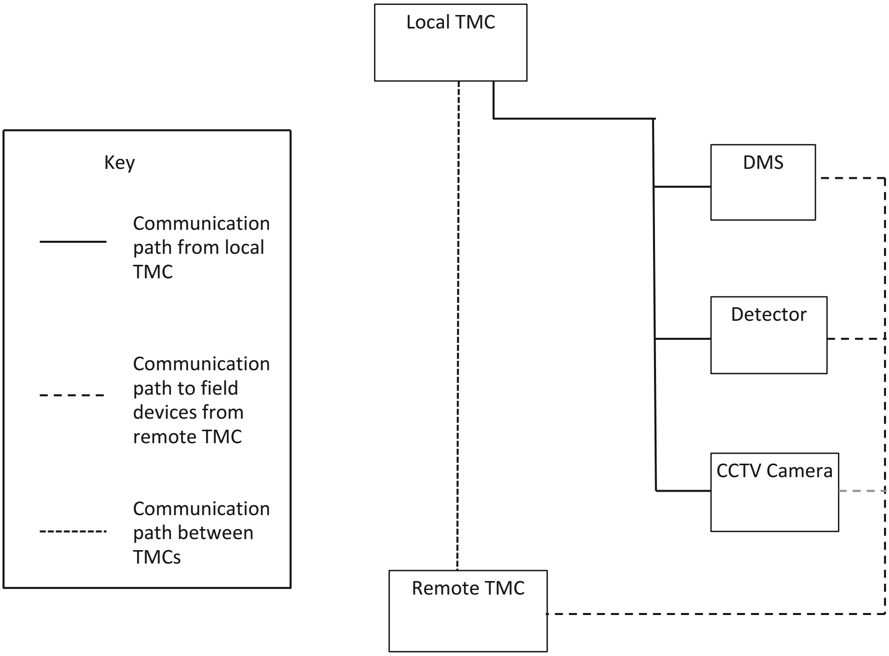


Fig. 8.11 Architecture for remote control of TMC

system status prior to handover, and to assist in the handover and return to local operation. An architecture of this type is being implemented by the New York State Department of Transportation.

Statewide Traffic Databases

An increasing number of states have the capability to collect and archive traffic and incident data in real time and in near real time for such purposes as data exchange among TMCs, use in the development of 911 websites, use by commercial traffic services, researchers and use by motorists. One such system is the Performance Measurement System (PeMS) employed by Caltrans. It is the centralized repository for all of Caltrans' real-time traffic data, enabling easy access to these data that might otherwise be dispersed across multiple districts and more difficult to obtain. PeMS provides a consolidated database of traffic data collected by Caltrans as well as partner agency data sets. The data collected by vehicle detectors are relayed from the field to Caltrans Transportation Management Centers (TMCs) and then sent to PeMS. PeMS is a real-time Archive Data Management System (rt-ADMS) that collects, stores, and processes raw data in real-time. It can be accessed via a standard Internet browser and contains a series of built-in analytical capabilities to support a variety of uses [12]. Figure 8.12 provides an overview of PeMS [12].

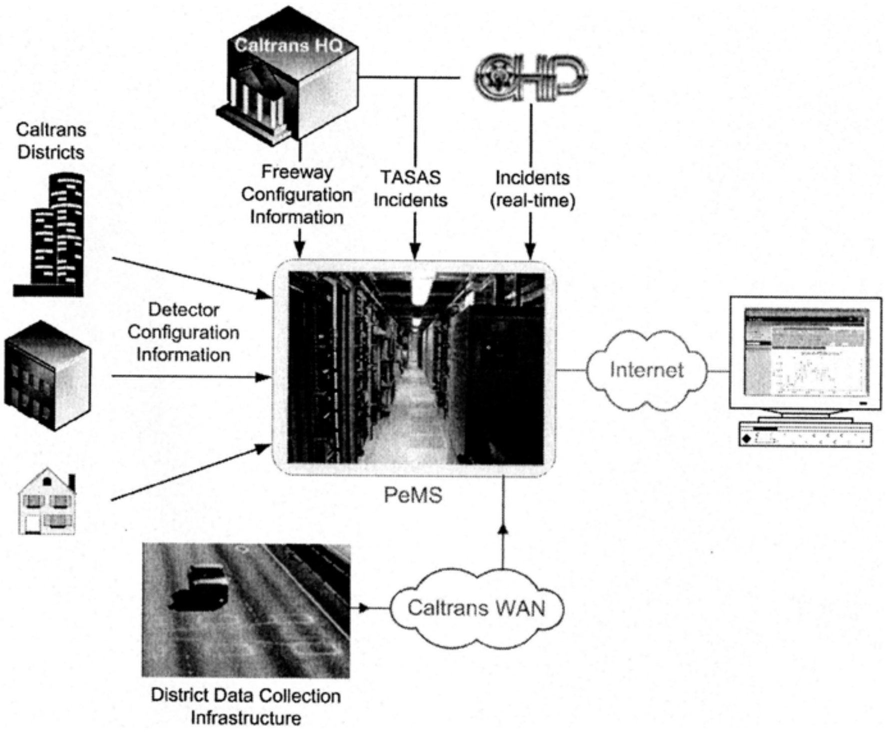


Fig. 8.12 Overview of PeMS

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Chapter 9
Evaluation of System Design and Operation

Abstract Prospective evaluations (evaluations prior to system installation) and retrospective evaluations (evaluations after system operation commences) are necessary to ensure that implemented systems satisfy the stakeholders' requirements upon which they are based. To be effective, these evaluations require methods for performing annualized benefit and cost analyses. Selection of parameters for assessing benefits, and identification of key parameters associated with for benefits estimation are important for these evaluations. These topics along with planning requirements for project evaluations after operation commences are covered. The impact of evaluation requirements on system design are discussed. Methodologies that may be used to implement retrospective evaluations with emphasis on the use of traffic management systems may be used to automatically collect data and compute the measures are included.

9.1 Evaluation of Design Alternatives and Project Feasibility

Prospective evaluations are used to evaluate design alternatives and project feasibility during the project's planning and design phases. These evaluations usually utilize benefit and cost analysis as well as qualitative factors that are important but that do not lend themselves to this type of analysis.

9.1.1 Benefit and Cost Analysis

Benefit and cost analysis has been the principal tool that is traditionally used during the initial project planning and later design phases for highway related projects. As used in prospective assessments, benefit and cost analysis assists with the evaluation of candidate design alternatives and in establishing the feasibility of the project (possibly in relation to other projects that compete for resources). It is also used to establish priorities among projects competing for available funding. As applied to retrospective assessments, benefit and cost analysis assists in evaluating the improvements to system operations, establishing lessons learned, providing inputs to reports to the public, and improving and selecting future designs and projects. The following sections describe the application of benefit and cost analysis to freeway ITS projects.

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9.1.1.1 Methodology for Cost Estimation

A commonly used methodology is an annual cost comparison [1]. This entails converting capital costs to an equivalent annual cost and adding the annual maintenance and operating expenses.

A useful life for the project must be established. For ITS projects it is often considered to be in the range of 20–25 years. Although much equipment will likely be replaced before this period, these replacements may be generally considered as a maintenance expense for the purpose of this analysis.

Several techniques to annualize capital cost are available. The frequently applied capital recovery with a rate-of return method is described below [2]. This approach converts the cost of a design alternative into an equivalent uniform series of annual costs. The salvage value after the project's useful life is generally considered as zero. The conversion is provided by the following equation:

$$\mathrm{R} = \mathrm{PC} \cdot \mathrm{crf} \tag{9.1}$$

where R is the annualized cost with interest, PC the capital equipment cost, and crf is the capital recovery factor.

The capital recovery factor is a function of the interest rate (i) and the project useful life in years (n). It is provided in tables in engineering economics texts and its expression is shown below:

$$\mathrm{crf} = \mathrm{i} \cdot (1+\mathrm{i})^{\mathrm{n}} / \left((1+i)^{\mathrm{n}} - 1\right) \tag{9.2}$$

The annualized life cycle cost is the sum of Eq. (9.1) and the annual maintenance and operating expenses.

9.1.1.2 Implementing Benefit and Cost Analysis

Prospective benefit estimations may be performed by using the RITA ITS data base for benefits [3], by analytical methods such as those described in this book, by ITS evaluation programs or by extension from previous experience. Figure 9.1 shows the results of a benefits analysis for a number of functional design alternatives for a project.

Although the-benefit-to-cost ratio is a commonly used measure of the relative value of a project or of alternative designs, this ratio must be applied in conjunction with other factors, including the ability to achieve project objectives. It is helpful to depict the benefits and costs in a more general way, such as is conceptually shown in Fig. 9.2. The annualized benefits and life cycle costs are shown for alternatives A, B and C. Each of these alternatives has a benefit to cost ratio considerably in excess of 1.0. While Alternative B has the highest benefit-to-cost ratio (depicted in the

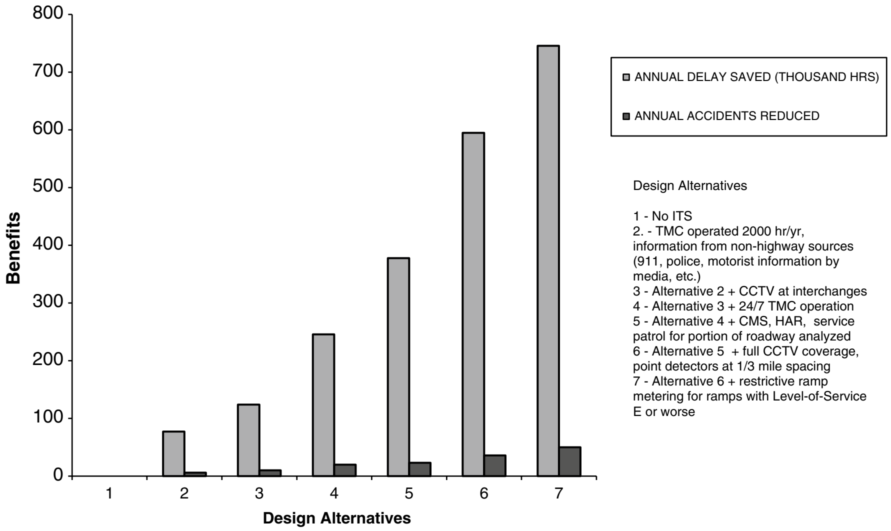

Fig. 9.1 Benefits analysis

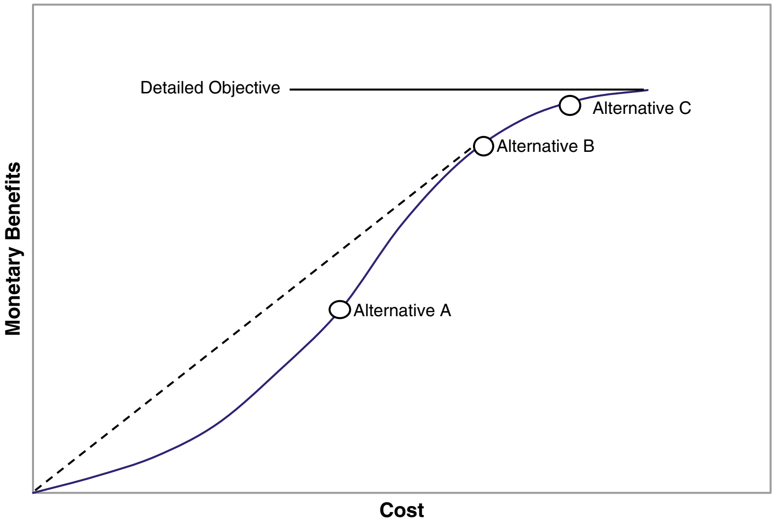

Fig. 9.2 Monetary benefits and costs for design alternatives

figure as the slope of the dashed line), Alternative C more closely approaches the detailed objective.

Selection between Alternatives B and C may be assisted by performing a of marginal benefit to cost analysis as discussed in Sect. 3.2.1. The example shown in that section may be generalized to include all monetary benefits.

Table 9.1 Year that 50 % of total project benefits are achieved

Interest rate (%)	Year after project initiation
4	8.1
6	7.2
8	6.5

9.1.1.3 Selection of Parameters for Estimation of Benefits

As shown in Fig. 4.4, delay is very sensitive to the parameters assumed for the evaluation scenario. In order to improve the credibility of the analysis, it may be constructive to conduct the analysis using a range of volume inputs. The cohort model technique described in Sect. 4.4.1 is a systematic way of selecting volumes for benefits estimation.

To obtain the present worth of future year benefits, each future year benefit must be multiplied by the single payment present worth factor (sppwf) [1]. This is given by Eq. (9.3)

$$\mathrm{sppwf} = 1/\left(1+\mathrm{i}\right)^{\mathrm{n}-0.5} \tag{9.3}$$

where i is the interest rate and n is the year for which the sppwf is computed. Equation (9.3) uses the term n-0.5 instead of the more commonly used n in order to represent the average annual benefit more closely. Although it is more accurate to conduct the analysis by employing each year's volumes to compute the benefits for that year, a commonly applied approximation is to select a single appropriate future year and utilize the volumes for that year.

Because the benefits for the more distant years are more lightly weighted, the appropriate set of volumes to use for the benefits evaluation should be more heavily biased toward the early years for the project. As an aid to selecting the most appropriate year's volumes to employ, Table 9.1 identifies the year that 50 % of the total life cycle benefits are accumulated after operation commences. The table is based on a 20 year project life.

9.1.2 Alternatives Evaluation and Project Feasibility

The development of the Transportation Improvement Plan (TIP)[1] requires the consideration of candidate ITS projects relative to other candidate transportation improvement projects. Similarly, the development of the Regional ITS Architecture and the selection of actual projects to implement the architecture requires

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[1] To qualify for federal aid funding, the project must be included in the Transportation Improvement Plan prepared by the metropolitan planning organization.

consideration of alternative projects. Stakeholders and decision makers are key contributors to the project selection process. The benefit and cost considerations described in Sect. 9.1.1 usually play a significant role in the process, but there are other considerations as well. Section 3.2.1 identifies the following considerations that are common to ITS projects described in this book:

- Economic benefits. For evaluation purposes, delay reduction, safety and fuel consumption are considered in this category.
- Environmental benefits (emissions).
- Mobility. This represents the ease with which people and goods move [4]. Measures may include delay and variation in delay [5].
- Public satisfaction with ITS treatments.

Section 3.2.2 describes multi-attribute utility analysis as an evaluation tool that facilitates the participation of stakeholders and decision makers in the selection of projects and functional alternative project designs.

9.2 Project Evaluation

9.2.1 Role and Function of Evaluation

Project evaluations are retrospective evaluations, i.e. they are implemented after the design of the project. Portions of the evaluation may be conducted prior to or during project installation. The reasons for performing project evaluations include:

- Improvement of operations. Lessons learned during the evaluation may provide the basis for improved operations.
- Reports to the public and to officials responsible for resource planning for the project. Support for ITS is crucial for its continued success. Figures 9.3 and 9.4 show how the Houston TranStar project accomplishes this [6].
- Improvement of future designs.
- Assistance in the selection of future projects [4].

ITS project operations are generally envisioned to continue for an indefinite time period. The evaluation process should therefore be considered as a continuous or at least periodic function, in order to keep the project in tune with evolving objectives, requirements and technologies. This is schematically illustrated in Fig. 9.5 by the addition of an evaluation feedback function to the simplified Vee diagram of Fig. 2.1.

Evaluation planning should be considered during the system design process. If "before" conditions are to be measured in the field, the plan may require data collection prior to project installation. Primary methods of data collection include: field observation, automatic data collection devices, simulations and surveys [5]. It may be useful to use traffic system detectors as a means of collecting volume data, speed data and day-to-day variation in speed. After project operation commences, some

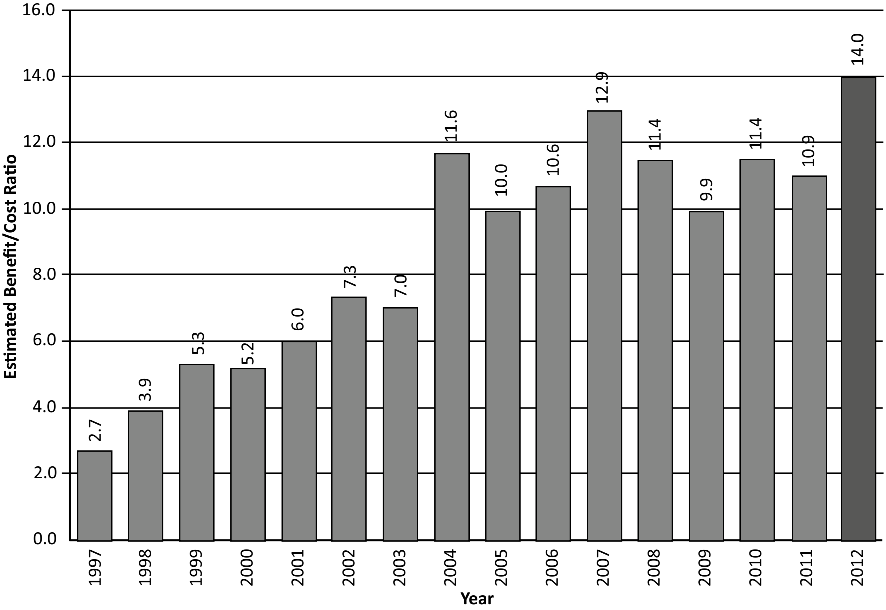

Fig. 9.3 Houston Transtar benefit/cost ratios 1997–2012

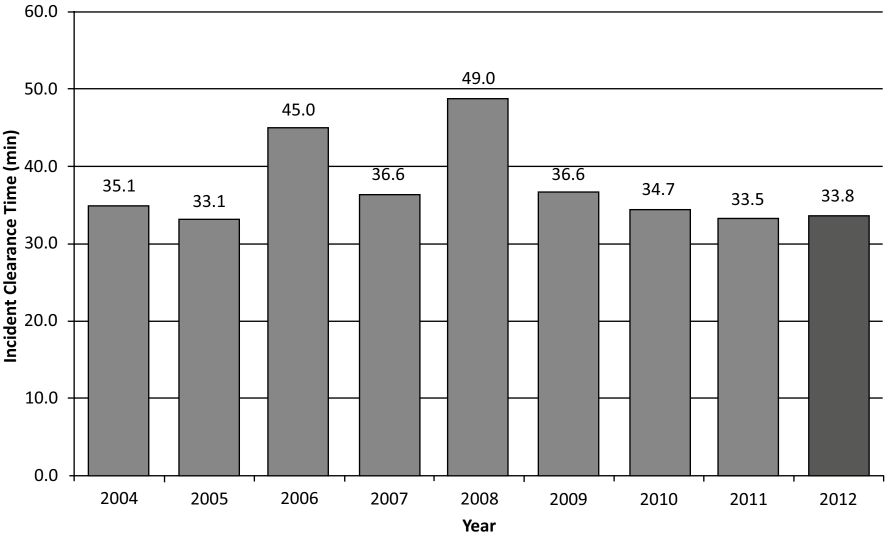

Fig. 9.4 Average annual incident clearance time 2004–2012

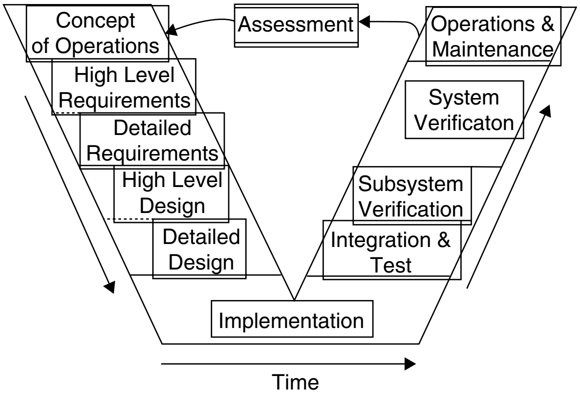

Fig. 9.5 Vee diagram with evaluation feedback

period of time is required for traffic conditions to stabilize. This occurs when the benefits do not change significantly over short periods of time. This time period is usually considerably less than 1 year [5].

Evaluation may be facilitated by including data mining software into the system design. The archived data user service (ADUS) has been incorporated into the National ITS Architecture [7] and guidelines for its use have been developed [8]. For example, the PORTAL ADUS system, developed by Portland State University is extensively used for evaluation in Portland, Oregon [9]. It archives and analyzes inductive loop detector data to create a variety of reports.

9.2.2 *Functions and Measures to Consider for Evaluation*

The material in this section and in the following sections borrows extensively from Ref. [10].

Table 9.2 identifies functions and classes of functions that TMCs that manage freeways commonly provide. A number of references (e.g. [11–13]) describe measures that are useful for the evaluation of ITS functions. Table 9.3 provides a more tightly focused subset of these measures that are further described in this book. The measures shown in the table relate to the *outcomes* of the management measures as sensed by the freeway users. Another class of functions termed *output* functions and associated measures are sometimes used to evaluate the performance of activities that lead to the outcomes. Measures such as incident clearance time and the number of service patrol assists are examples of output measures.

Section 9.2.3 discusses ways that detector data might be structured to facilitate the computation of measures that use this data. Using these data structures, Appendix A provides representative algorithms and computational processes for developing a number of the measures identified in Table 9.3.

Table 9.2 Freeway TMC functions and functional classes

TMC functions and classes of functions
Active traffic and demand management
Speed harmonization
Temporary shoulder use
Queue warning
Dynamic truck restrictions
Dynamic routing
Dynamic lane markings
Incident response
Development of incident management plans
Selection of incident management plan
Assistance to emergency service providers
Motorist information
Management of information for ITS field devices and traffic information service providers
Provision of information to external services
Ramp management and conventional lane management
Ramp metering
Ramp closure
Conventional lane controls
Service patrol
Weather monitoring

9.2.3 Data Structures for Evaluation

Freeway management systems commonly include the following set of data collection, storage and data manipulation capabilities.

- *Collection and storage of traffic flow data*. Data may come from point detector stations (in which case archiving is generally performed at this level), from probe detectors, or from services that provide this data. Point detector data may consist of volume, speed, occupancy, and vehicle classification. Provision is usually made in the freeway management system for the identification and correction of flawed data and missing data. Probe data is comprised of travel time information between physical or virtual probe reading locations.
- *Collection and storage of incident management reports developed by the TMC*. Some states provide this capability on a statewide basis.
- *Link data structures to provide for the agency's TMC functions* (e.g. traffic condition map displays, ramp metering, incident management and motorist information).

Table 9.3 Subset of evaluation measures

Type of measure	Measure
System delay measures	Vehicle system delay
	Private passenger vehicle occupant delay
	Commercial vehicle occupant delay
	Goods inventory delay
	Transit vehicle occupant delay
Safety	Freeway crashes
	Secondary crashes
	Work zone related crashes
	Pedestrian crashes
	Safety performance index
Fuel consumption	Gallons
Throughput	Freeway throughput
Emissions	See Ref. [13]
Service quality/user perceptions	Level of service
	Route travel time
	Route travel time reliability
	User satisfaction
	User satisfaction
Equity	User perception
	Gini coefficient or Lorenz curve
Quality of assistance to motorists	Service patrol assists
	Quality of service—Periods of patrol coverage
	Quality of service—Average motorist waiting time
	Quality of service—Extent of roadway serviced
	Rating by public
Response to weather situations	Response time to provide actionable information to motorists

9.2.3.1 Spatial Data Structures

A data structure concept is required to relate the data sources (e.g., detector data, crash reports, incidents) to a construct that may be used for evaluation purposes. Figure 9.6 shows an example of a data structure based on freeway links that provides this capability. A link represents a section of the mainline between vehicle access or egress points. The concept of a domain is introduced in the figure to relate data from freeway surveillance stations to mainline links. Domains relate links to the roadway locations receiving information from a particular point detector station. As shown in the figure, each domain is related to a particular detector station. Domain boundaries are established at link nodes, at locations where the roadway characteristics may change or where the link is sufficiently long to encompass more than one detector station. In that case (e.g., Link 4) domain boundaries are used to separate the regions for which each detector station will be employed. Note that no detector in Fig. 9.6 lies within the physical boundaries of Domain 4; that domain obtains its information from Detector Station 4.

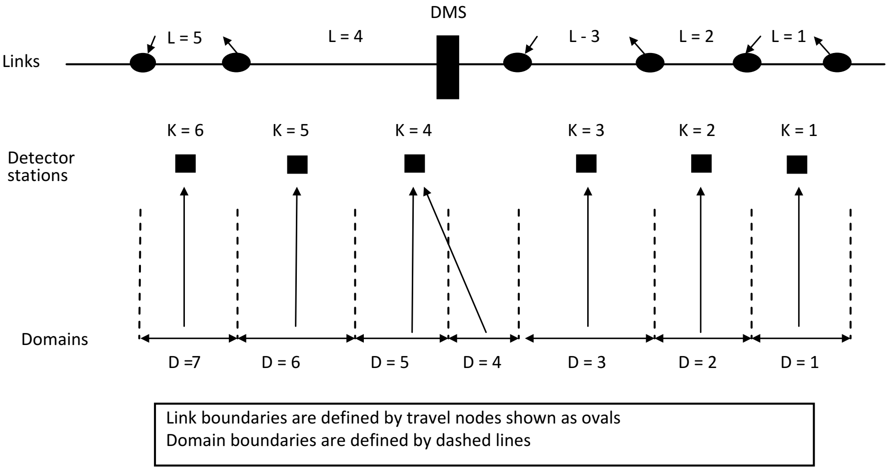

Fig. 9.6 Example of link, domain and detector station relationships

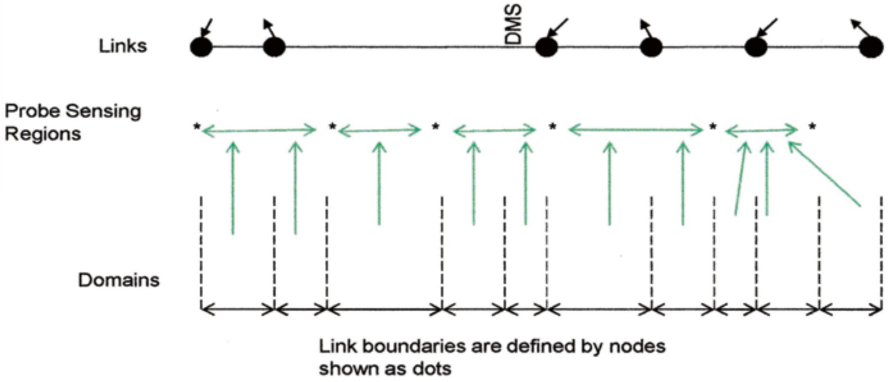

Fig. 9.7 Example of link, domain and probe site relationships

Figure 9.7 shows a similar diagram for probe-based surveillance. The asterisks identify locations for probe travel-time measurements. These boundaries may be established by physical equipment locations (such as toll tag reader locations or locations of Bluetooth readers) or may be virtual boundaries for other types of probe detection systems such as those based on GPS. While it is sometimes possible to co-locate virtual or actual boundaries with link boundaries, this is not always the case. The probe-measured travel times are converted to speeds, and these speeds, in conjunction with link lengths, are used to estimate travel link travel times. Probe-based detection does not provide volume estimates, so supplementing this data with other information is required for certain measures and for benefit-cost analysis. In order to obtain system-wide delay and travel time measures with probe detection, at least one source of volume data per link is required.

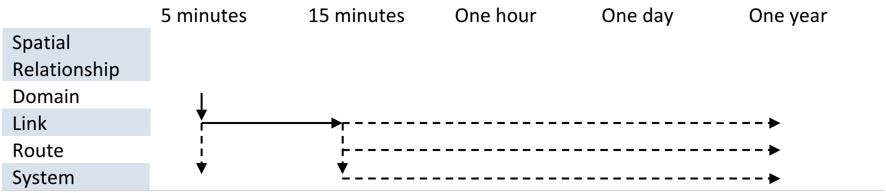

Fig. 9.8 Data accumulation methodology

9.2.3.2 Temporal Data Structures

For archiving purposes, freeway management system volume, speed, and occupancy data from point detectors are often stored at 5-min intervals and aggregated into 15-min and 1-h intervals. The 5 and 15-min intervals provide convenient processing intervals for many of the computations developed from traffic detector data as described in Appendix A and in Sect. 9.2.4. Building on these concepts, a methodology using the spatial/temporal relationship shown in Fig. 9.8 may be used to develop these measures. The methodology uses the domain concept (Figs. 9.6 and 9.7) as the basis for freeway mainline data accumulation.

Detector data is used to obtain these measures at the domain level for 5-min periods and is accumulated at the link level. The 15-min period at the link level is a convenient building block for many of the evaluation measures. The path to computing this level for the 15-min period is shown by the solid trace in Fig. 9.8. The dashed traces show the paths to other spatial levels and time periods. Depending on the particular measure to be computed, and on the purpose (reports, etc.), the 15-min data may be aggregated by time according to the particular spatial relationship required for the purpose. The spatial data structure described in Sect. 9.2.3.1 and the temporal data structure discussed in this section are examples of the types of data structures that may be employed.

9.2.4 Description of Measures

This section describes ways in which a number of the measures in Table 9.4 that are used to identify benefits may be developed. Travel time measures, delay measures route travel time reliability measures and through put measures in the table are discussed in Appendix A. Other measures are discussed in the following sections.

9.2.4.1 Safety

Chapter 4 discusses the management techniques that ITS employs to reduce the number of crashes. A worksheet for use during project design to estimate the potential benefits is provided in Appendix C.

Table 9.4 Relationship of TMC functions to measures of effectiveness

Type of measure	Example of measure	TMC functions					
		Active traffic management	Incident response	Motorist information	Ramp metering and conventional lane management	Weather monitoring	Motorist service patrols
Travel time	1.1. Route travel time (Appendix A, Eq. (A.18))	√	√	√	√	√	√
	1.2. Route travel time reliability (Appendix A, Eqs. (A.21) and (A.22))	√	√	√	√	√	√
System delay	2.1. Vehicle system delay (Appendix A, Eq. (A.7))	√	√	√	√	√	√
	2.2. Private passenger vehicle occupant system delay (Appendix A, Eqs. (A.8), (A.21) and (A.22))	√	√	√	√	√	√
	2.3. Commercial vehicle occupant system delay (Appendix A, Eq. (A.9))	√	√	√	√	√	√
Safety	3.1. Freeway crash rate (Sect. 9.2.4.1)	√	√	√	√	√	√
	3.2. Secondary crash rate (Sect. 9.2.4.1)	√	√	√	√	√	√
Fuel consumption	4. Gallons/year (Sect. 9.2.4.2, Eq. (9.4))	√	√	√	√	√	√
Throughput	5. Vehicle miles during peak hour	√	√	√	√	√	√
User satisfaction	6.1. Measure based on survey	√	√	√	√	√	√
	6.2. Measure based on complaints	√	√	√	√	√	√
Equity	7.1. User perception—Measure based on survey or complaints				√		
	7.2. Gini coefficient (Sect. 3.2.1)				√		
Perceived quality of assistance to motorists	8.1. Hours of coverage per year						√
	8.2. Average motorist waiting time						√
	8.3. Centerline miles of roadway served						√
Emissions	9. Lb. per year for each pollutant	√	√	√	√	√	√

Retrospective evaluations of safety determine whether the project objectives have been realized and enable the results of ongoing operational improvements to be evaluated. The crash rate (crashes per million vehicle miles) is a key measure used by agencies for this purpose. Police accident reports are generally used as the basis for this determination, and the results are generally included in state accident reporting systems. They may be supplemented by data from TMC logs.

ITS motorist communication techniques identify incident locations to motorists to enable them to perform proper lane adjustments prior to entering the incident location, or to avoid the affected route.

Secondary accidents (Sect. 4.1.2) constitute an important problem that ITS functions can significantly address. Moore et al. [14] describe a complex process for identifying them. An alternative approach is to enter secondary accidents as a descriptor in the TMC's incident management log entry classification (Sect. 4.5.1.4).

9.2.4.2 Fuel Consumption

The estimation of fuel consumption under congestion conditions is a complex process that involves a number of variables. Schrank et al. [13] provides a description of this process. The model used is the product of delay time and the excess fuel consumption rate during periods of delay as provided by Eq. (9.4).

$$FE = GE \cdot VSD \tag{9.4}$$

where

FE = Excess fuel consumption (gallons)
GE = Excess fuel consumption rate (gallons/h of congestion delay)
VSD = Vehicle system delay (provided by Appendix A, Eq. (A.7))

Schrank et al. [13] provides statistics for fuel consumption for the metropolitan areas in the U.S. These data may be used to estimate the excess fuel consumption rate. For example, for the 15 largest metropolitan areas in the U.S., the excess fuel consumption rate varies from 0.41 gallons per vehicle hour of congestion delay to 0.57 gallons per hour, with an average of 0.46 gallons per hour.

9.2.4.3 User Satisfaction

User satisfaction may be measured in terms of rating scales associated with user surveys. As an example, Georgia DOT conducted a detailed motorist mail survey [15]. The measure used for this survey was a simple satisfaction scale ranging from 0.0 to 4.0. The survey response rate was approximately 13 %. The survey was detailed and evaluated specific ITS functions as shown in Fig. 9.9.

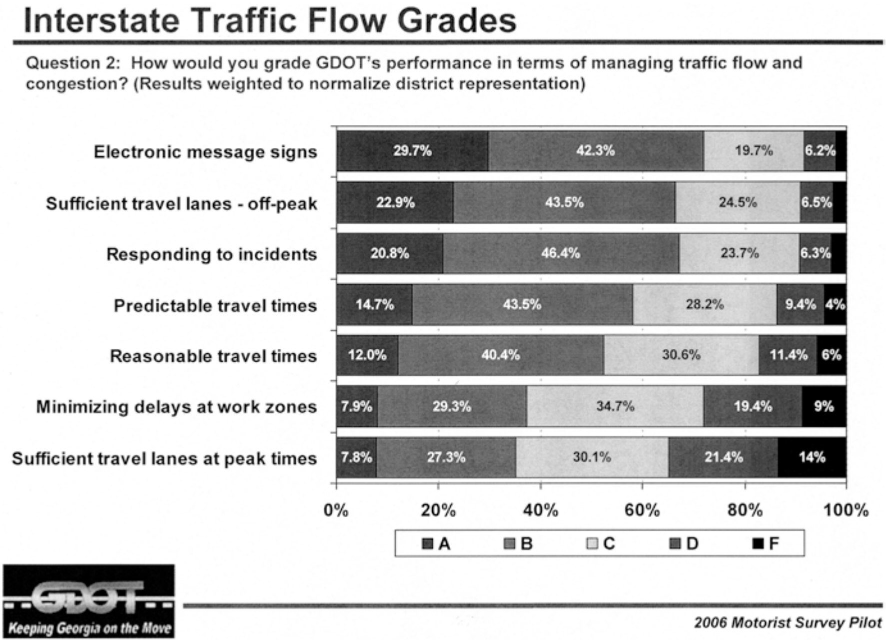

Fig. 9.9 Georgia DOT survey results

The year-over-year trends in the number of complaints provide a basis for determining changes in the quality of ITS management provided by the agency. An unusual number of complaints that focus on a location or an operation at that location may highlight a need for remediation.

9.2.4.4 Equity

While most ITS functions provide benefits to all freeway users, other functions provide benefits to some users and may inconvenience others. Surveys and complaints may provide feedback that may result in modification of the function. Where warranted, quantitative measures of the users benefitted and inconveniences such as the Gini coefficient described in Sect. 3.2.1 may be employed.

9.2.4.5 Quality of Assistance to Motorists

By assisting motorists to resolve vehicle problems or aiding them in getting such assistance, motorist service patrols reduce the congestion that might have resulted from the incident. Several measures identified in Table 3.4 may be used to evaluate the effect of motorist service patrols on the quality and quantity of travel.

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Chapter 10

Active Traffic Management (ATM)

Abstract Active traffic management (ATM) is defined and ATM strategies and their potential benefits are identified. Each of the ATM strategies is described and illustrated. Planning and implementation considerations are summarized.

10.1 Definition and Concept

"Active Traffic and Demand Management (ATDM) is the dynamic management, control, and influence of travel demand, traffic demand, and traffic flow of transportation facilities. Through the use of available tools and assets, traffic flow is managed and traveler behavior is influenced in real-time to achieve operational objectives, such as preventing or delaying breakdown conditions, improving safety, promoting sustainable travel modes, reducing emissions, or maximizing system efficiency. Under an ATDM approach the transportation system is continuously monitored. Using archived data and/or predictive methods, actions are performed in real-time to achieve or maintain system performance" [1]. ATDM actions can be classified into:

- Active Demand Management (ADM). Strategies focused on managing the trip demand on the network.
- Active Traffic Management (ATM). Strategies focused on managing the flow of vehicle traffic on the network.
- Active Parking Management (APM). Strategies focused on managing the parking requirements of vehicles.

This chapter focuses on several ATM strategies. Table 10.1 [2] identifies a class of strategies that are commonly included in ATM. The strategies in the table are often used in combination and several are discussed in the following sections. Although not included in Table 10.1, certain more traditional ITS strategies such as ramp metering are sometimes included as ATM strategies.

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Table 10.1 ATM strategies and potential benefits

Active traffic management strategy	Potential benefits											
	Increased throughput	Increased capacity	Decrease in primary incidents	Decrease in secondary incidents	Decrease in incident severity	More uniform speeds	More uniform driver behavior	Increased trip reliability	Delay onset of freeway breakdown	Reduction in traffic noise	Reduction in Emissions	Reduction in fuel consumption
Speed harmonization	√		√	√	√	√	√	√	√	√	√	√
Temporary shoulder use	√	√						√	√			
Queue warning			√	√	√	√	√	√		√	√	√
Dynamic merge control	√	√	√			√	√	√	√	√	√	√
Dynamic lane markings	√	√						√				
Construction site management	√	√						√		√	√	√
Dynamic truck restrictions	√	√				√	√	√			√	√
Dynamic rerouting and traveler information	√		√	√			√	√			√	√
Automated speed enforcement			√		√	√	√	√			√	√

10.2 Speed Harmonization

The concept of speed harmonization, also called variable speed limits or dynamic speed limits, is already in place in many countries and in several states in the United States. The intent is to minimize the differences among vehicle speeds and to bring the average speed closer to a safe speed for the current conditions. The most common reasons for deploying speed harmonization are for weather related conditions and congestion management under recurrent and non-recurrent congestion conditions. Depending on the goals of the agency, the speed can either be mandatory or advisory [3]. Figure 10.1 [4] shows an example of the speed control signs used on I-5 in the Seattle area in conjunction with a DMS that describes the reason for the speed reduction. As shown in Fig. 10.2 [4], speed harmonization is often used in conjunction with other traffic management techniques such as lane control signals and other ATM measures such as queue warning and shoulder running. The project shown in these figures employs gantries supporting the signs at an approximate spacing of 0.5 miles.

Recommended criteria for the inclusion of speed harmonization include [3]:

- Level of service E or F for a minimum of 3 h for at least one peak period and at least 5 h per day;
- Right of way for overhead gantries and DMS;
- At least one location every 2 miles where queues form and warning is warranted; and
- At least five incidents related to queuing, merging, and/or diverging per week.

The success of speed harmonization is closely linked to the extent to which drivers comply with the signing. The strategy should be success-oriented with a fair and reasonable plan for the majority of users. Speed harmonization should be utilized in response to an issue that is actually present. If users do not believe the system is

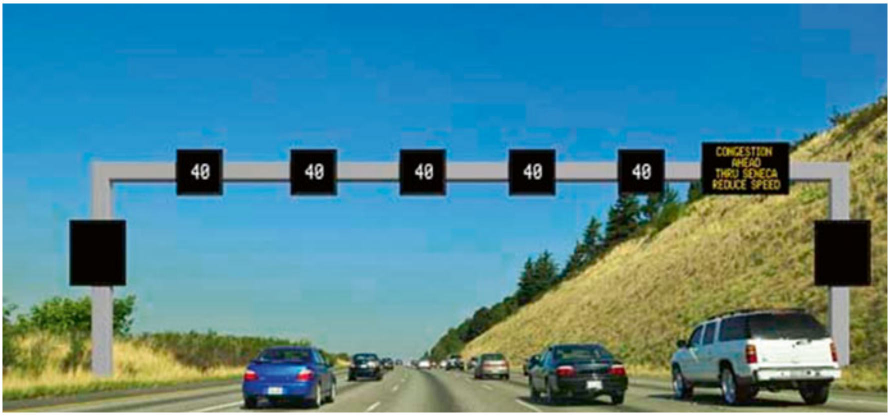


Fig. 10.1 Speed control signs for speed harmonization

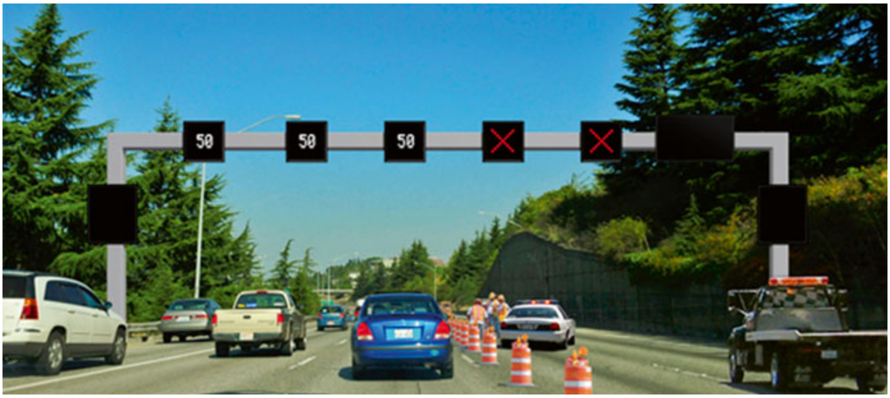


Fig. 10.2 Lane control with speed harmonization

legitimate, compliance rates will be low. Therefore, if the reason for the new speed limit is not apparent, it should be explained through appropriate signing [3].

When speed harmonization is used to manage recurrent congestion, an automatic algorithm to display speed messages is often employed. Measured speed is commonly used as the primary variable. In the Netherlands, the control algorithm reduces the speed as the volume increases. This avoids an abrupt transition into congested flow [5].

Table 10.2 [6] provides spacing characteristics and operating results for a project in the St. Louis area.

One algorithm to control variable speed limit signs (VSLS) examines data from several point detector locations, both upstream and downstream of each VSLS location. The values of measured speed and their variations among locations are used to determine the posted speed [7].

10.3 Temporary Shoulder Use

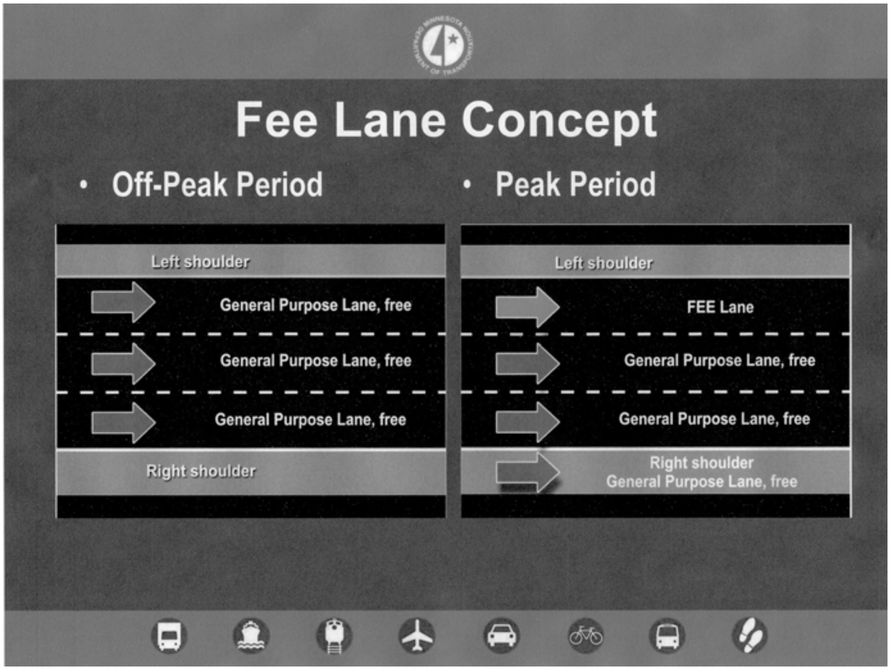
Shoulder use, also known as hard shoulder running (HSR), is a measure designed to temporarily increase the capacity of a facility by opening one or sometimes both shoulders to traffic. Shoulder running may be used for a variety of applications including:

- Use of shoulders for transit buses only. The Minneapolis–St. Paul area uses this approach extensively;
- Use during peak periods to increase capacity;
- Use during peak periods to provide additional storage for exiting vehicles when exit ramp capacity is limited by a traffic signal at the exit ramp intersection;
- Use during peak periods to maintain capacity and permit another lane to be used as a toll lane (Fig. 10.3 [8]); and
- Use as an evacuation route [9].

Table 10.2 Summary of evaluation of side mounted variable speed limit signs in St. Louis

	Segment number			
	1	2	3	4
Number of signs	8	4	7	5
Distance between signs	0.6–1.9 miles	1.3–2.3 miles	1.1–2.9 miles	0.9–2.0 miles
Change in average delay (peak)	Much lower	Much lower	Much lower	Much lower
Change in reliability (peak)	Improvement	Improvement (3–11 %)	Improvement	Improvement
Change in speed standard deviation (peak)	Decreased	Decreased (5.5 %)	No change	Decreased slightly

Change is relative to the pre-VSL (variable speed limit) system
Reliability measured by travel time index, buffer time index, and planning time index
Reduction in standard deviation indicates an increase in speed homogeneity
No conclusive findings on safety due to there being only 1 year of post VSL data



Fee Lane Concept

- Off-Peak Period
- Peak Period

Fig. 10.3 Shoulder use with toll lane

Figure 10.4 shows a display concept for the hard shoulder running lanes and Fig. 10.5 shows a concept for DMS displays upstream of the lane [10].

Shoulder use increases the effective capacity of the freeway and reduces congestion. The essential criteria for considering implementation of shoulder use are [11]:

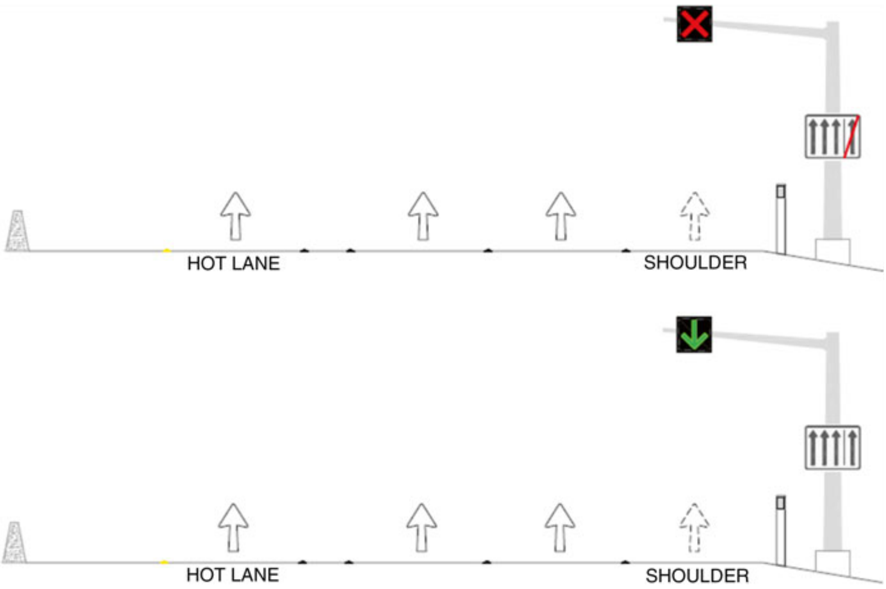


Fig. 10.4 Instrumentation concept for hard shoulder running (inactive and active)

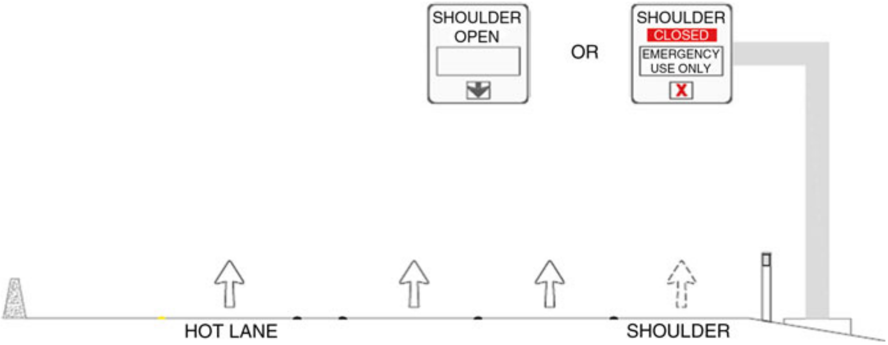


Fig. 10.5 Upstream entrance DMS for hard shoulder running

- Level of service E or F for at least 2 h in at least one peak period; Length of the facility sufficient to alleviate a series of bottlenecks should be at least 3 miles;
- No expected bottleneck downstream of the shoulder use segment;
- Low volume of entering/exiting vehicles if crossing multiple interchanges;
- Minimum shoulder width of 10 ft, with ability to add emergency refuge areas; and
- Pavement strength to accommodate increased traffic load.

Guidelines for consideration of shoulder use that is restricted to transit vehicles include the following [3]

Fig. 10.6 Queue warning system display

- Predictable congestion delays, Level of service D for 2 h per day;
- Minimum 10 ft shoulder width available;
- Sufficient pavement strength to sustain bus load; and
- Minimum service of 50 buses/h (freeway) or 25 buses/h (arterial).

10.4 Queue Warning

Differences in speed often cause vehicle conflicts and increase the potential for crashes. The basic principle of queue warning is to inform travelers of the presence of downstream queues, based on dynamic traffic detection and using warning signs and flashing lights. This strategy allows the traveler to anticipate a requirement for emergency braking and to limit the extent of speed differentials, erratic behavior, and queuing-related collisions. Queue warning can be used on its own with DMS placed on overhead gantries or on roadside mounted DMS that show when a queue is close. It can also be included with speed harmonization and lane control signals to provide incident management capabilities. To improve traffic management under incident conditions, the speed between gantries is measured and incrementally reduced. Traffic is shifted among lanes as appropriate. The system can be automated or controlled by a TMC operator. Work zones also benefit from queue warning with portable DMS units placed upstream of expected queue points [3].

Figure 10.6 shows an example of a dynamic message sign for a stand-alone queue warning system (QWS) in Ontario, Canada [12]. The beacons on the sign flash when a queue is present. Figure 10.7 [12] shows the deployment plan for the major components comprising a portion of the system. Information to develop the message is provided by inductive loop detectors.

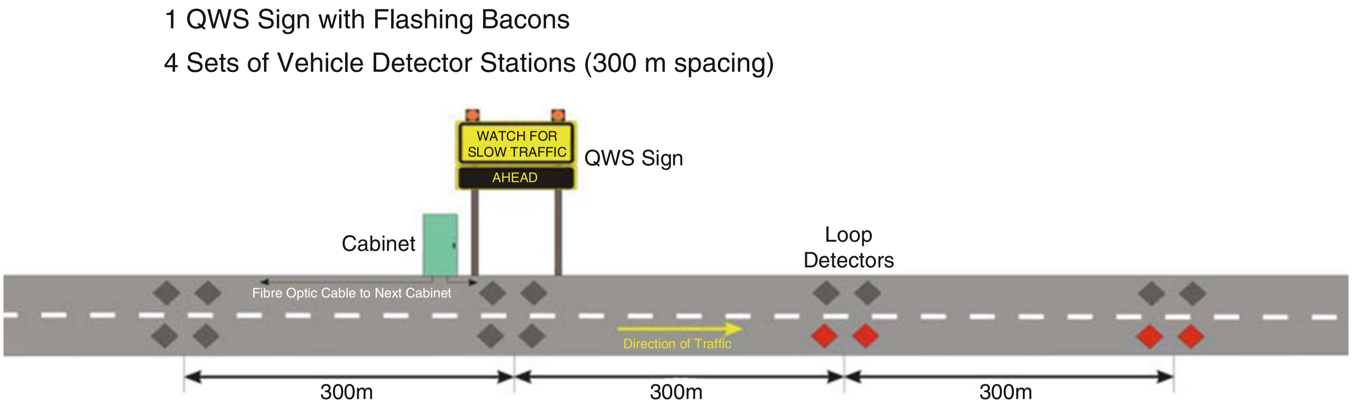


Fig. 10.7 Overview of components

The QWS in Ontario employs the three major traffic parameters that might be sensed by traffic detectors (i.e., volume, speed and occupancy). All admissible traffic patterns are defined in a library. The set of traffic data collected from the detectors is matched to the patterns in the library. The matched pattern determines whether a queue exists in the zone. When a queue has been identified, the system identifies the upstream queue-end location among travelled lanes, and activates the corresponding QWS signs with flashing beacons in a coordinated manner. It automatically chooses the appropriate messages to be displayed on the DMS. The system is close to a border crossing, and the algorithm is designed to detect all types of queue conditions, especially the slow moving traffic and standing truck queues formed near the border [12].

Essential guidelines for the need to implement queue warning include [3]:

- Level of service E or F for at least 2 h per peak period;
- Presence of queues in predictable locations;
- Sight distance restricted by vertical grades, horizontal curves, or inadequate illumination;
- Right of way for overhead gantries and DMS; and
- At least five incidents related to queuing merging and diverging per week.

10.5 Dynamic Merge Control

Dynamic merge control is used to meter or close specific lanes upstream of the interchange to manage access based on current traffic demand. It is an operational treatment that addresses the geometric condition when the sum of both freeway general purpose lanes and merging lanes at an interchange is higher than the number of downstream general purpose lanes. A typical U.S. application of this condition would be a lane drop for one of the outside lanes or a merging of two inside lanes, both of which are static solutions. The intent is to provide dynamic priority access to the higher traffic stream. It is a practical approach to handling varying demand on the mainline lanes and the merging lanes to effectively utilize existing capacity. This concept is implemented by lane control signals and is illustrated in Fig. 10.8 [3].

Essential criteria for dynamic merge control include the following [3]:

- Significant merging volumes (>900 vph);
- Available capacity on general purpose lanes upstream of the interchange that can be borrowed with no worse than LOS E after implementation; and
- Non-simultaneous peak traffic upstream on the general purpose lanes and merging lanes.

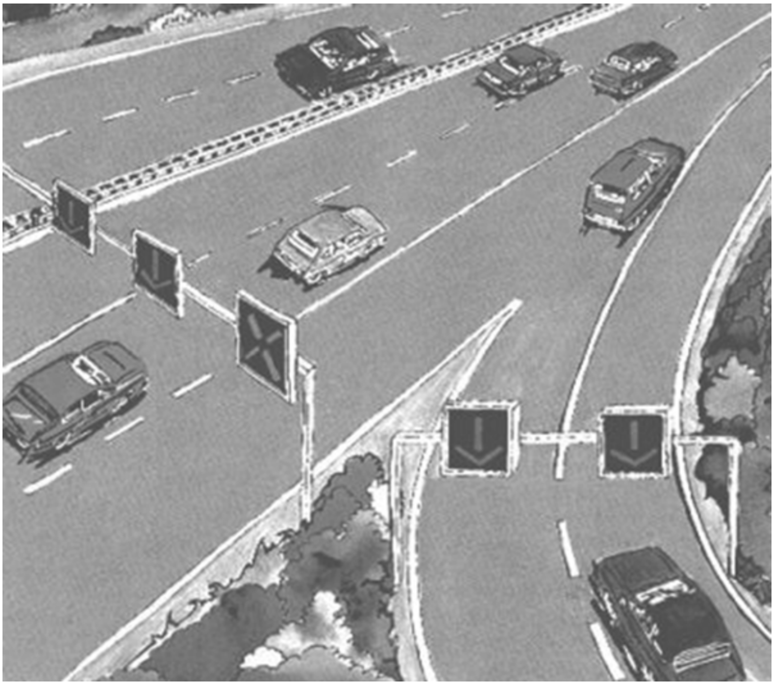


Fig. 10.8 Dynamic merge control concept

10.6 Dynamic Lane Markings

Dynamic lane markings may be used to assist in implementing strategies such as shown in Fig. 10.8. They may also be used to manage lane use for other functions. In Minnesota, a lane may sometimes be used to implement a priced dynamic shoulder lane (PDSL) as shown in Fig. 10.9 [8]. Lane marking changes are used to highlight the use requirement as shown in Fig. 10.10 [8].

10.7 Implementation Considerations

Lane control signals such as shown in Fig. 10.2 may display a variety of characters and symbols. A set of options employed in Minnesota is shown in Fig. 10.11 [8]. These signals are used to support incident management, speed harmonization and the priced dynamic shoulder lane. They are spaced at half mile intervals.

Motorist displays for lane use and lane speed vary with time and with distance along the roadway. Measurements of speed, occupancy and volume are usually

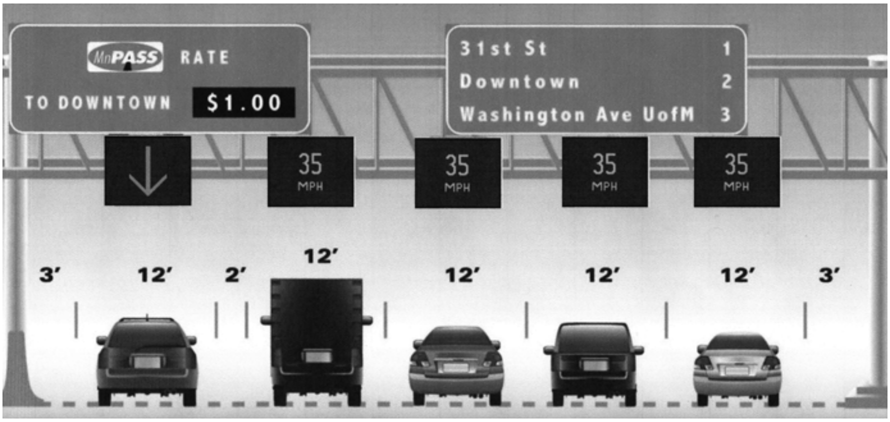


Fig. 10.9 Priced dynamic shoulder lane

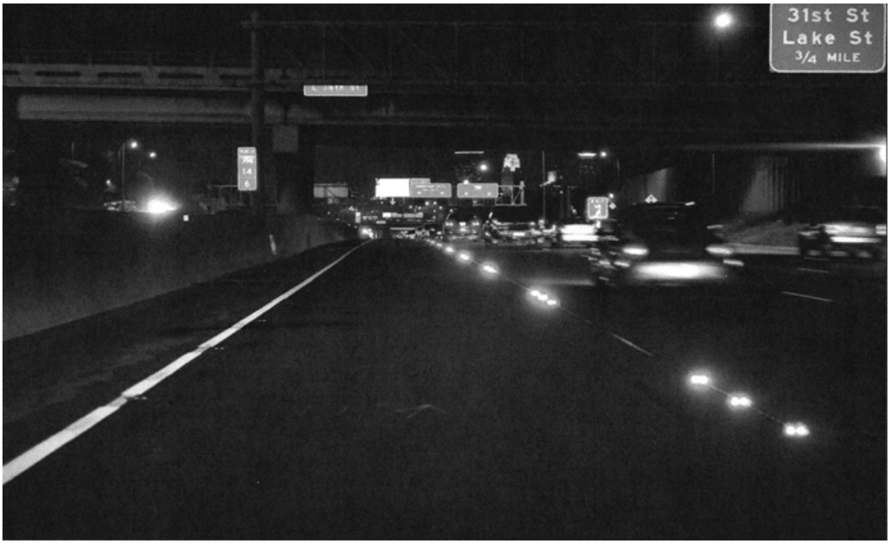


Fig. 10.10 In pavement lighting when priced dynamic shoulder lane is open

provided by point detectors that are located in each roadway section that is separated by overhead lane control displays.

Equipment deployment plans for ATM installations are influenced by the following:

- Roadway geometrics including entry and exit ramps, lane additions and drops, sight distance problems resulting from rapid changes in roadway alignment.
- The presence of existing ITS equipment. Since ATM is often employed for roadway sections that experience volumes that approach or exceed roadway capacity,

Fig. 10.11 Options for intelligent lane control signals in Minnesota

in many cases these sections are equipped with freeway management systems and ATM strategies provide more precise control at the lane management level. Existing equipment should be considered for use when applicable.

- Legislation and public attitudes on automatic speed limit enforcement.

10.8 Planning for Active Traffic Management

ATM strategies generally provide for more intensive speed and lane management treatments than do conventional ITS designs. They are often installed in locations that are equipped with conventional ITS. The existing ITS, however, often provides considerable underlying infrastructure support in the form of communications, traffic surveillance and motorist information systems thus facilitating ATM implementation. ATM is also often introduced concurrently with a major highway facility upgrade or change in the roadway's use characteristics.

Refs. [3, 13] provide descriptions of ATM strategies and concepts. Ref. [14] is an interactive guide to assist in the selection of ATM strategies to address traffic management objectives.

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Chapter 11
Corridor Management

Abstract Management strategies for traffic corridors consisting of coordinated freeways and arterials (CFA) are described. The USDOT Integrated Corridor Management (ICM) program and its inclusion of other than private vehicle based modes is described. The chapter discusses the strategies and approaches employed in the San Diego and Dallas ICM corridors. Special corridors that address issues that are unique to particular locations are described and an example is discussed.

11.1 Coordinated Freeway and Arterial Operation

Prior chapters discuss many of the components employed for freeway management including ramp metering, incident management and motorist information technology and diversion strategies. This chapter discusses the integration of those strategies with arterials and with other components of the transportation system, and the operations required to implement this integration. Figure 11.1 [1] depicts a managed corridor.

Freeway corridors are often defined in terms of a freeway and the connecting and parallel arterials that serve to move traffic in the same direction. The arterials may serve as an alternative to the freeway. Coordinated freeways and arterials (CFA) operations is the implementation of policies, strategies, plans, procedures, and technologies that enable traffic on freeway and adjacent arterials to be managed jointly as a single corridor and not as individual, separate facilities. These policies, strategies, etc. should have an end goal of improving the mobility, safety, and environment of the overall corridor as well as traffic on individual facilities [2]. This implies a proactive mindset to corridor management that emphasizes planning and operational cooperation and coordination among the agencies involved.

Urbanik et al. [2] identifies the following sources of congestion that may be managed by the CFA approach.

- Traffic incident management
- Work zone management
- Planned special event management
- Day-to-day or recurring operations

Goals and objectives are similar to those for the management of freeways, but with extension to the corridor.

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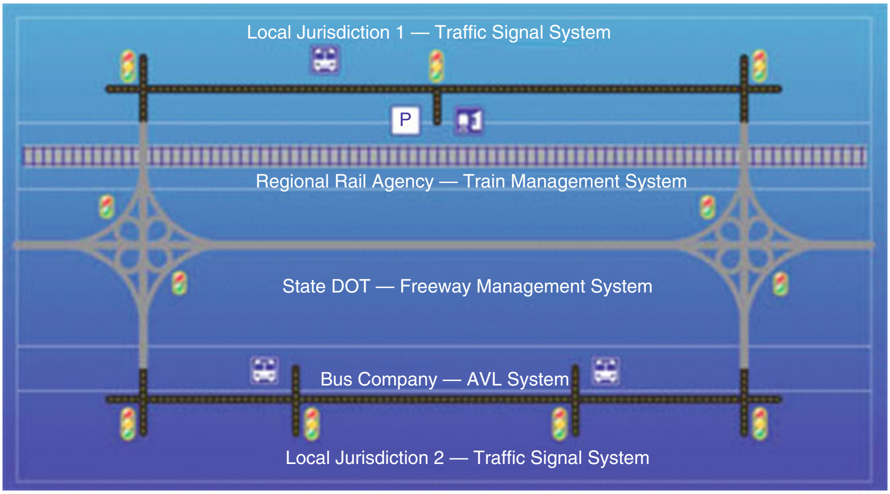


Fig. 11.1 Example of development of corridor operations plans

11.1.1 Management Strategies

The strategies employed for CFA management are generally adaptations of freeway and surface street arterial ITS strategies, but with the emphasis on optimizing operation for the corridor. Strategies for coordinated operation are shown in Table 11.1.

11.1.2 Operational Plans and Procedures for Coordinating Freeways and Arterials

CFA operation requires a single coordinated management approach to be employed by the agencies involved. One approach for managing incidents is illustrated in Fig. 11.2 [2]. It employs the following steps:

- Definition of *background scenarios* (the set of normal traffic conditions that may be expected).
- Use of an *activation matrix*, the relationship between the lane blockage and incident clearance activity and criteria such as traffic flow characteristics that may help to differentiate response requirements.
- Selection of *operations plans* based on *corridor operating strategies*. Examples of these strategies include:
  - DMS messages and arterial DMS messages
  - Use of alternative signal timing plans
  - Lane use strategies
  - Function related real time communication requirements among agencies

Table 11.1 Examples of management strategies for coordinated corridors

Category	Strategies	Real time strategy	Every-day strategy
Traffic management and control			
Freeway management	Ramp metering	Traffic responsive metering	Pretimed metering
	HOV bypass at metered ramps	Not applicable	Encourage HOV use
	Active traffic management	See Chap. 10	Not applicable
	Ramp closure	For incident management	Certain ramps may be closed to improve safety and mobility
Arterial management	Changeable lane use	Active lane controls	Pretimed lane controls
	Road closures	For incident management	Time of day controls
	On-street parking restrictions	For incident or special events management	Permanent or time of day
	Trailblazers	Dynamic trailblazers	Static trailblazers
	Parking management systems	Reduces circulating traffic	Not applicable
	Arterial dynamic message signs	Incident and congestion management	Not applicable
Intersection traffic control	Traffic signal timing and coordination	Traffic responsive and traffic adaptive,	Pretimed signal control
		Operator selection of diversion timing plan	
		Transit vehicle signal priority	
		Preemption for emergency vehicles	
	Access and turn restrictions	Only if safety considerations permit	Improves safety and mobility
Traveler information			
Pretrip traveler information	Provision of information by public agencies (e.g. 511 services), provision by internet, smartphone and the media	Real time traffic conditions, incidents, weather	Construction information
		Trip reliability	Transit schedules
		Transit vehicle arrival time	
	Provision of information by private organizations, provision by internet, smartphone and the media	Real time traffic conditions and incidents, construction, route planning	Not applicable

(continued)

Table 11.1 (continued)

Category	Strategies	Real time strategy	Every-day strategy
En route traveler information	Provision of information by public agencies	Incident, congestion and travel time provided by DMS, arterial DMS, portable DMS, HAR, 511 services	Static signing
		Provision of incident and congestion information to private services and to the media	
	Provision of information by private organizations. Provision of information by smartphone and by in-vehicle displays	Traffic information obtained from public sources and by private agencies. Provision of traffic conditions, routing information, lane and speed advisory information, anticipatory traffic signal signal display information	Not applicable
Incident management and safety initiatives			
Traffic and incident surveillance, incident management	Surveillance with CCTV, traffic detectors, 911 reports, police reports	Find shortest route for emergency responders to incidents, help to manage traffic and locate tail of queue, implement traffic management incident response plans, provide information to media and traffic service providers	Not applicable
	Motorist service patrols	Expedite clearance of minor incidents	Not applicable
Connected vehicle techniques (emerging)	In vehicle safety messages and vehicle controls	Provision of corridor information using in-vehicle displays	Not applicable

Figure 11.3 [2] shows the procedures that are required by this approach to transform the operations plans into *action steps*.

11.2 Integrated Corridor Management

The concepts described in Sect. 11.1 have been broadened by the USDOT Incident Corridor Management (ICM) program [3] to emphasize the employment of additional assets and strong corridor management initiatives to enhance corridor mobility. The listing below identifies these corridor assets.

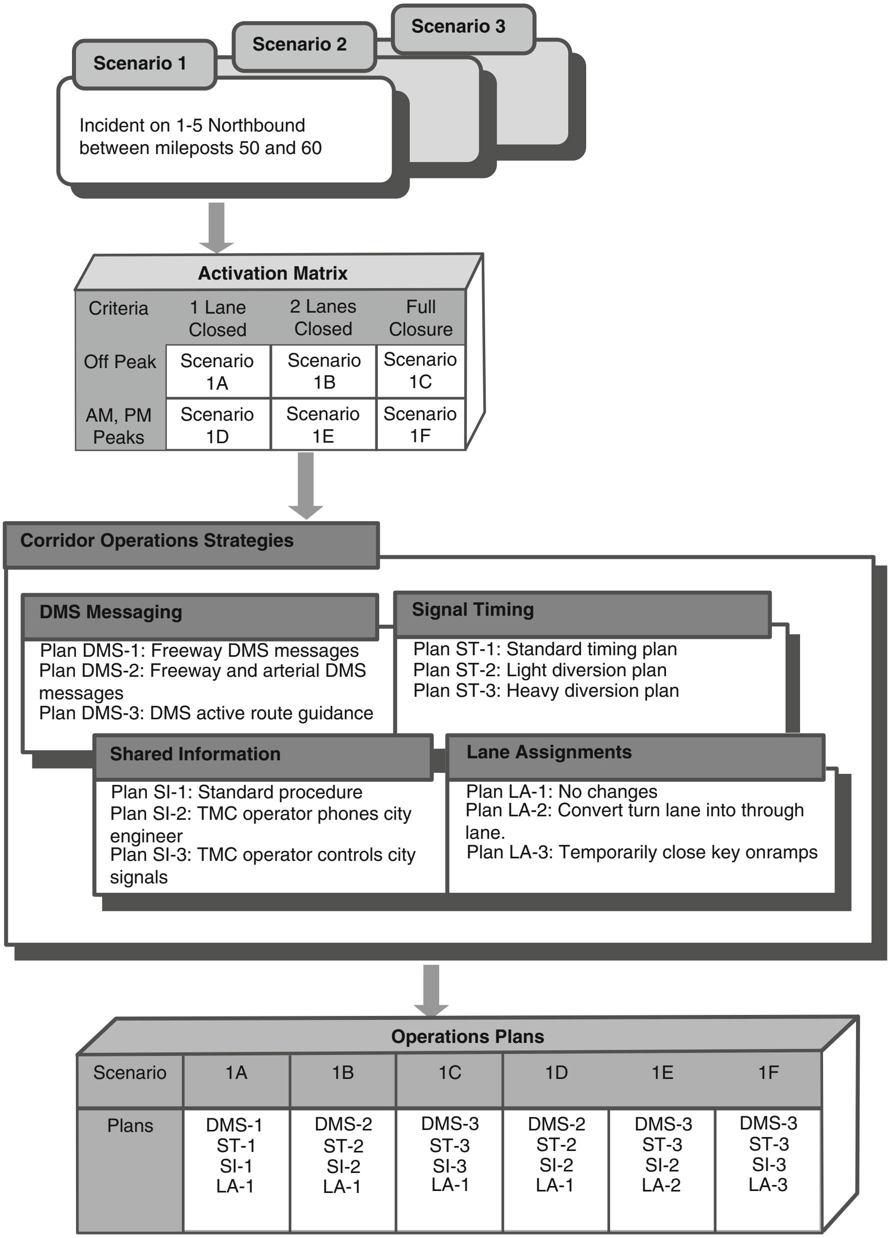
- Freeways
- HOV
- Tolling
- Value pricing
- Arterials
- Real time control
- Bus
- Fixed route
- Express bus
- Bus rapid transit
- Rail
- Commuter rail
- Light rail
- Subway/heavy rail

A USDOT project established Dallas, TX and San Diego, CA as sites to demonstrate ICM principles. In order to efficiently use corridor resources and assets these sites incorporate decision support systems (DSS). The San Diego site's rule based DSS concept is shown in Fig. 11.4 [4] (redrawn) with examples of the rules for various conditions. Stakeholders defined a high-level decision support framework for ICM as part of their concept of operations. They organized their response plans, their "Response Posture," around a combination of demand conditions on the network ('X' axis), i.e., "light," "moderate," or "heavy;" and predicted 'event impact' ('Y' axis), assessed as "low," "medium," or "high." Within this framework (organized as a matrix), they then determined whether they would be likely to take "conservative," "moderate," or "aggressive," measures to manage the impacts. They then coded their joint response plans accordingly, and associating finely-tuned response actions with a host of scenarios.

Highlights of the Integrated Corridor Management system for the US 75 Corridor in Dallas include the following concepts [5]:

- Congestion is monitored along I-75 and travel time is monitored on key surface streets using Bluetooth readers.
- A predictive model determining corridor response is employed to assist in selecting corridor management strategies.
- For minor incidents (one lane and shoulder blocked with less than a 2 mile queue) traffic is diverted to the Frontage Road.
- For major incidents (two or more lanes blocked or a 2–4 mile queue) traffic is diverted to the Frontage Road, Greenville Ave and to the Red Line LRT.
- Travel time assists in the selection of the appropriate signal timing plan are provided for appropriate surface streets in the corridor.
- Parking availability is monitored for five park and ride lots for the Red Line LRT and messages are provided on the DMS.

Table 11.2 provides an overview of US 75 ICM strategies [6].



Incident on 1-5 Northbound between mileposts 50 and 60

Activation Matrix

Criteria	1 Lane Closed	2 Lanes Closed	Full Closure
Off Peak	Scenario 1A	Scenario 1B	Scenario 1C
AM, PM Peaks	Scenario 1D	Scenario 1E	Scenario 1F

Corridor Operations Strategies

DMS Messaging

Plan DMS-1: Freeway DMS messages
Plan DMS-2: Freeway and arterial DMS messages
Plan DMS-3: DMS active route guidance

Signal Timing

Plan ST-1: Standard timing plan
Plan ST-2: Light diversion plan
Plan ST-3: Heavy diversion plan

Shared Information

Plan SI-1: Standard procedure
Plan SI-2: TMC operator phones city engineer
Plan SI-3: TMC operator controls city signals

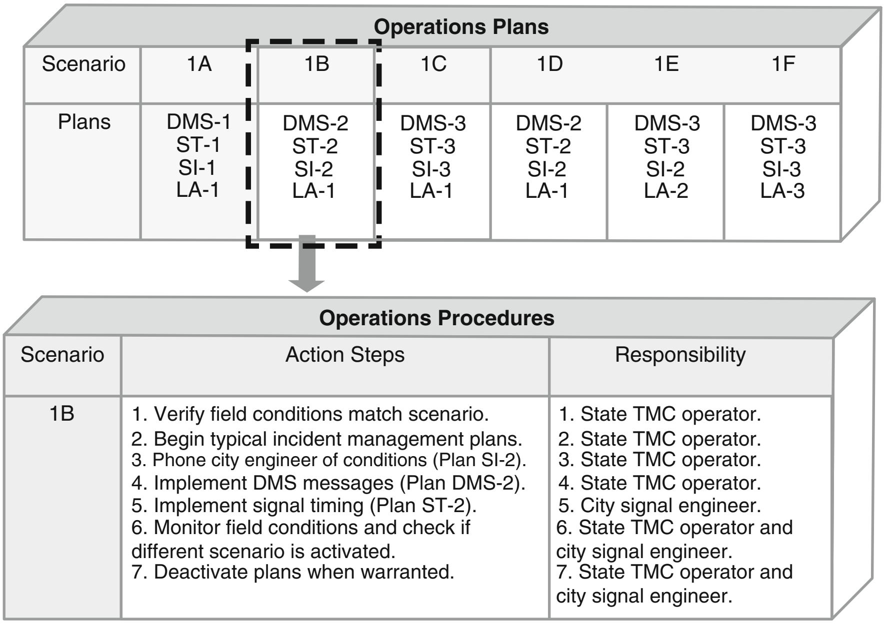
Lane Assignments

Plan LA-1: No changes
Plan LA-2: Convert turn lane into through lane.
Plan LA-3: Temporarily close key onramps

Operations Plans

Scenario	1A	1B	1C	1D	1E	1F
Plans	DMS-1 ST-1 SI-1 LA-1	DMS-2 ST-2 SI-2 LA-1	DMS-3 ST-3 SI-3 LA-1	DMS-2 ST-2 SI-2 LA-1	DMS-3 ST-3 SI-2 LA-2	DMS-3 ST-3 SI-3 LA-3

Fig. 11.2 Example of development of corridor operations procedures



Operations Plans

Scenario	1A	1B	1C	1D	1E	1F
Plans	DMS-1 ST-1 SI-1 LA-1	DMS-2 ST-2 SI-2 LA-1	DMS-3 ST-3 SI-3 LA-1	DMS-2 ST-2 SI-2 LA-1	DMS-3 ST-3 SI-2 LA-2	DMS-3 ST-3 SI-3 LA-3

Operations Procedures

Scenario	Action Steps	Responsibility
1B	1. Verify field conditions match scenario. 2. Begin typical incident management plans. 3. Phone city engineer of conditions (Plan SI-2). 4. Implement DMS messages (Plan DMS-2). 5. Implement signal timing (Plan ST-2). 6. Monitor field conditions and check if different scenario is activated. 7. Deactivate plans when warranted.	1. State TMC operator. 2. State TMC operator. 3. State TMC operator. 4. State TMC operator. 5. City signal engineer. 6. State TMC operator and city signal engineer. 7. State TMC operator and city signal engineer.

Fig. 11.3 Example of integrated managed corridor

Table 11.2 Overview of US 75 ICM strategies

Strategies	Scenarios						
	Daily operations—no incident		Minor incident		Major incident		
Demand	Med	High	Med	High	Low	Med	High
Traveler information							
Comparative, multi-modal travel time information (pre-trip and en-route)	●	●	●	●	●	●	●
Traffic management							
Incident signal retiming plans for frontage roads			●	●	●	●	●
Incident signal retiming plans for arterials			●	●	●	●	●
HOV lane[a]	○	○	○	○	○	○	○
HOT lane (congesting pricing)	●	●					
Express toll lane (congestion pricing)	●	●					
Light rail transit management							
Smart parking system						●	●
Red line capacity increase						●	●
Station parking expansion (private parking)						●	●
Station parking expansion (valet parking)						●	●

[a] HOV lane 2+ is currently in operation, thus is not considered an ICM strategy but is part of all scenarios

11.3 Special Corridors

11.3.1 Types of Special Corridors

The coordinated freeway and arterial corridors (Sect. 11.1) and the integrated corridors (Sect. 11.2) address issues that are common to many major urban areas. Many urban areas require special consideration of issues that are unique to a particular traffic corridor. Examples of special corridors include:

- Long term construction causing significant traffic congestion. Section 11.3.2 provides an example of a corridor of this type.
- Emergency evacuations. ITS may assist police in providing support to such measures as reversing lanes, closing access points, and providing additional capacity on supporting alternate routes.
- Special events. Lane management techniques, permanent or portable DMS and management messages on existing DMS in conjunction with intensive parking management techniques may be employed.
- Limited access highways with no shoulders or sub-standard shoulders. While these problems may be addressed by the more intensive incident management operations commonly employed by bridge and tunnel operators, active traffic and demand management strategies (Chap. 10) may also be employed to address these deficiencies.

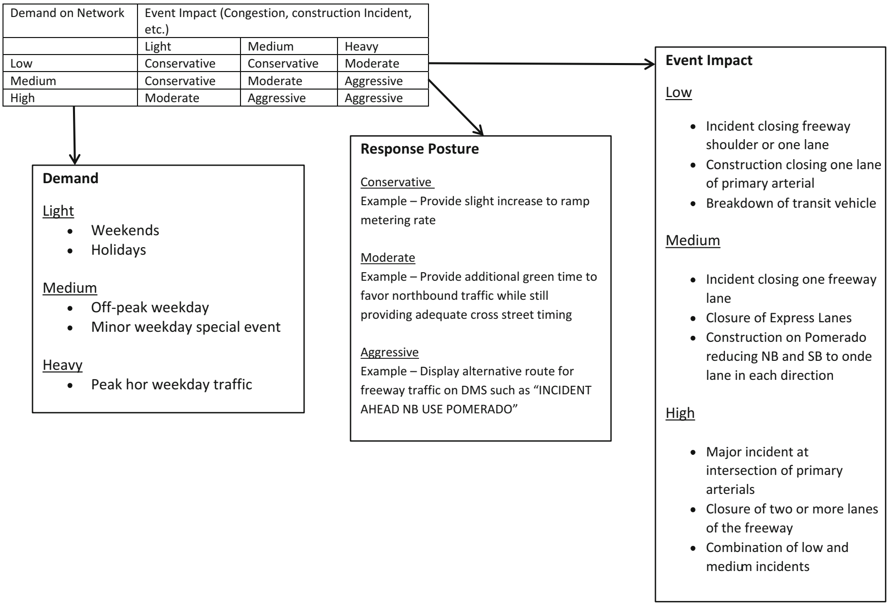
The concept of operations for projects containing special corridors should emphasize the unique issues involved and how the management concepts address these issues.

11.3.2 Example of Special Corridor [7]

Construction on ramps connecting the Betsy Ross Bridge to I-95 and Aramingo Ave. (a major surface street arterial) in Philadelphia will develop congestion for extended periods of time on I-95 and on Aramingo Ave. from Bridge St. to Allegheny Ave. The special corridor shown in Fig. 11.5 was defined to address this need.

The special corridor is a portion of the I-95 Corridor in Philadelphia. It is managed by the Pennsylvania Department of Transportation (PennDOT). Key ITS assets in the special corridor prior to any improvement include:

- CCTV and point detectors on I-95.
- CCTV and Bluetooth probe detectors on Aramingo Ave.
- DMS on I-95. Arterial DMS (ADMS) on certain surface street locations in and near the corridor.
- Interconnected signals on Aramingo Ave. Signals are controlled by the Philadelphia Department of Streets during working hours and by PennDOT at other times.
- Extensive fiber optics communications cable on I-95 and on key surface streets.



Demand on Network	Event Impact (Congestion, construction Incident, etc.)		
	Light	Medium	Heavy
Low	Conservative	Conservative	Moderate
Medium	Conservative	Moderate	Aggressive
High	Moderate	Aggressive	Aggressive

Demand

Light
- Weekends
- Holidays

Medium
- Off-peak weekday
- Minor weekday special event

Heavy
- Peak hor weekday traffic

Response Posture

Conservative
Example – Provide slight increase to ramp metering rate

Moderate
Example – Provide additional green time to favor northbound traffic while still providing adequate cross street timing

Aggressive
Example – Display alternative route for freeway traffic on DMS such as "INCIDENT AHEAD NB USE POMERADO"

Event Impact

Low
- Incident closing freeway shoulder or one lane
- Construction closing one lane of primary arterial
- Breakdown of transit vehicle

Medium
- Incident closing one freeway lane
- Closure of Express Lanes
- Construction on Pomerado reducing NB and SB to onde lane in each direction

High
- Major incident at intersection of primary arterials
- Closure of two or more lanes of the freeway
- Combination of low and medium incidents

Fig. 11.4 Decision support logic for San Diego ICM project

A series of major reconstruction projects in the region encompassed by Fig. 11.5 is planned. The objective of the special corridor is to improve response to construction related congestion or incidents in the special corridor. In addition to a more rapid response to incidents it will provide detailed motorist information on congestion avoidance in the special corridor. A managed roadway network for the special corridor was defined (Fig. 11.6) and is consistent with the emergency detour routes developed under a prior project.

Requirements for managing the special corridor include the following:

- Enhancement of incident detection and management capability by additional CCTV cameras at key locations.
- Retention of currently employed motorist information messaging when no incidents or construction related delays are present in the special corridor.
- Provision of detailed motorist information when incidents or construction related delays are detected in the special corridor. A decision support system (Appendix H) assists TMC operators to select detailed messages to be provided on DMS on arterial I-95 and on arterial ADMS at special corridor entry points, denoted as A, B, C, D and E in Fig. 11.7. Additional ADMS will be provided at these points as necessary. Figure 11.8 shows an example of a message to be provided on a northbound DMS on I-95 prior to corridor entry. The DMS indicates conditions on both I-95 and on the Aramingo Ave. alternate.

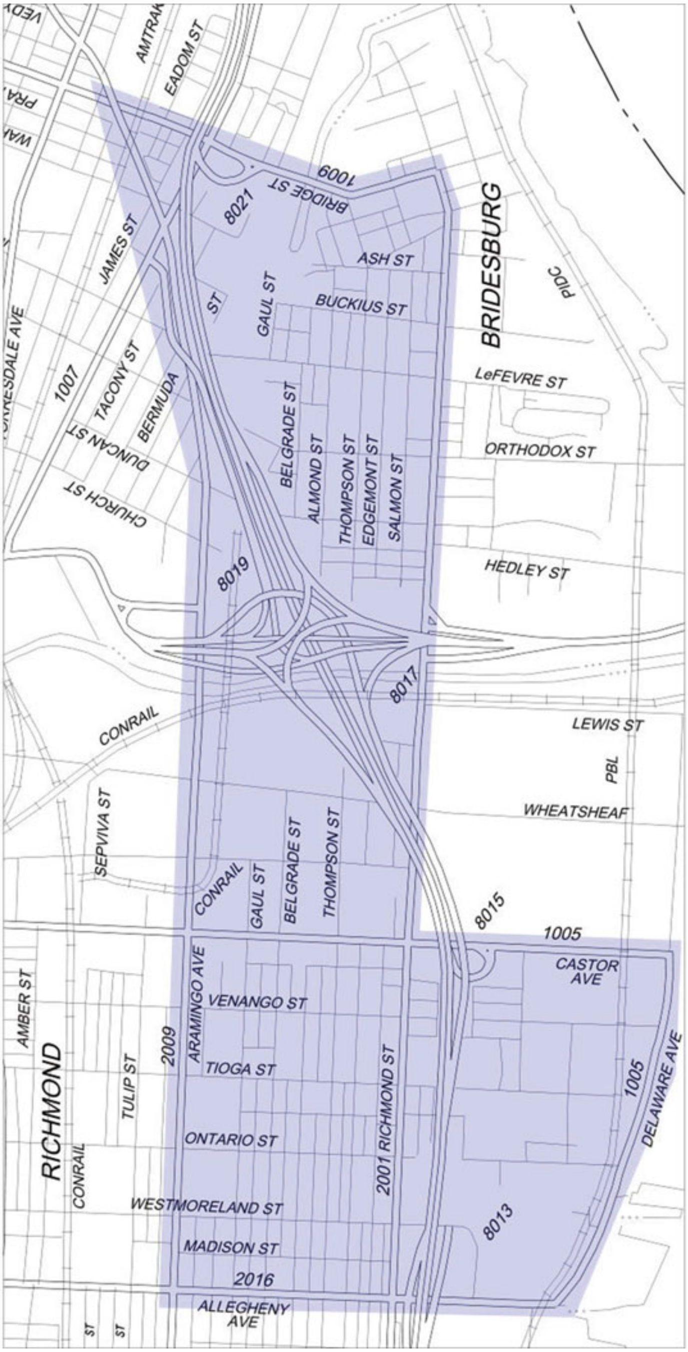


Fig. 11.5 Special corridor in Philadelphia

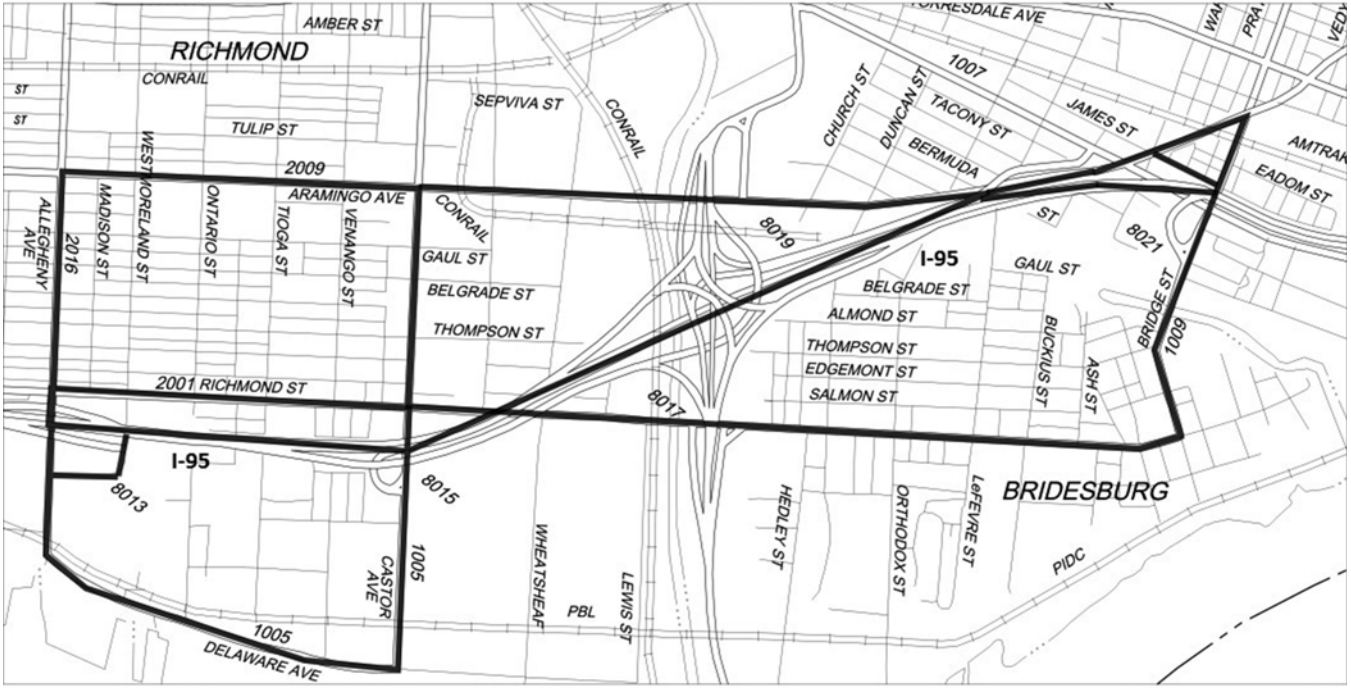


Fig. 11.6 Managed roadway network in special corridor

Fig. 11.7 Corridor entry points

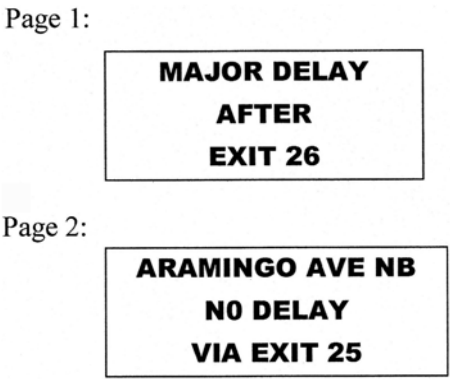


Fig. 11.8 Example of detailed DMS message

- Interconnection and coordination of signals other than those on Aramingo Ave. (which are currently coordinated). Provision of signal timing plans to support the diversion introduced by the detailed motorist messaging.
- Addition of fiber optics communication cable to support the additional ITS devices and signal coordination.

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Chapter 12
Website Support

Abstract This chapter provides short descriptions of the files on the website that support this book (http://www.springer.com/us/book/9783319147673). The files implement models that are described in more detail in earlier chapters.

12.1 Introduction

In order to facilitate the reader's use of several of the models described in the text, several worksheets are provided in the form of Microsoft® Excel workbook files and a Microsoft® Word file on the website. The contents of these files are described in the following sections. In order to facilitate modifications or adaptations that the reader deems appropriate, the Excel workbook files are not protected and are populated with data to illustrate the type of data needed. Readers must substitute their own data to obtain results specific to their applications.

Because the Excel files are provided as "read only" files, the user must copy these files to a suitable folder and rename them prior to use.

12.2 System Delay per Incident

Since incidents may occur under a variety of traffic conditions, the model offers a methodology to apportion the appropriate fraction of daily volume to the capacity conditions that apply and to then compute the resulting delay. Two worksheets are used to estimate the delay resulting from an incident on a roadway section with three lanes in one direction.

As described in Sect. 4.4.1 and illustrated in Fig. 4.12, the first worksheet (CD Excel file *Cohort Factors 3 Lane*) Titled "COMPUTATION OF COHORT FRACTIONS (THREE LANE ROADWAY)" generates fractions for the relative occurrence of incidents for groups of volume-to-capacity ratios (cohorts). This file is applicable where the roadway section under analysis consists of three lanes in one direction. The user must supply appropriate hourly volumes in columns 2 and 3, appropriate roadway section titles and an appropriate capacity. The data from the file are utilized as input to the Excel file *Average delay resulting from incident*. Figure 4.13 illustrates the worksheet and Sect. 4.4.2 describes the inputs to the file.

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12.3 Relative Effectiveness of CCTV Coverage

Section 4.5.1.2 describes the considerations for providing CCTV coverage. Appendix B presents a model for the effectiveness of this coverage. The measure, RTV represents the probable capability of CCTV to observe an incident on a section of roadway. Figure 4.28 shows an application of this model to a particular case. The Excel file *RTV* on the website provides one data point for this figure. The shaded cells require data input by the analyst.

12.4 Incident Management Effectiveness Potential

A model for assessing the effectiveness of ITS in enhancing the management of the response to incidents is described in Sect. 4.6.3.2. Figure C.1 in Appendix C illustrates an application of the model to evaluate candidate system design alternatives. Computations for this figure are shown in Fig. C.2. The Excel file *Inc mgt effectiveness potential* was used to compute the data for the 3 camera, 5 detector alternative for Fig. C.1. The value of RTV was obtained from Fig. 4.28.

12.5 Delay Reduced on Freeway Due to Queue Reduction Resulting from Diversion

Section 5.1.5 describes a model that provides approximate values for the reduction of freeway delay resulting from diversion. Figure 5.9 shows the results of the Excel worksheet file *Delay improvement on freeway*. The shaded cells in the workbook represent required data entries. The non-shaded cells perform the worksheet calculations.

12.6 Probability that the Motorist Encounters DMS Prior to Incident (P34)

Section 5.2.2.2 illustrates the computation of the parameter P34 when origin-destination data is not available. This parameter represents the probability that the motorist encounters a DMS prior to the section containing the incident, thus providing the capability for diversion. The worksheet shown in Fig. 5.15 was computed by the Excel file *Computation of P34*.

12.7 Queue Storage Requirement for Ramp Meter

Section 7.4.5.1 describes Caltrans' approach to estimating the storage space required for metered ramps. Figure 7.16 illustrates a typical computation chart [1]. The reference also provides a chart that is not populated with data (Fig. 7.17). For convenient use, that chart is reproduced in the jpeg file *Ramp storage empty computation chart*.

Reference

1. Ramp meter design manual (2000) Traffic operations program. California Department of Transportation, Sacramento, CA

Chapter 13
ITS and the Connected Vehicle

Abstract Section 13.1 describes one view of a connected vehicle architecture that encompasses both the USDOT connected vehicle architecture and non-government entities and Sect. 13.2 covers the components of this architecture. Section 13.3 covers cellular telephone based techniques and Sect. 13.4 describes in-vehicle displays. Section 13.5 considers a key ITS operational issue related to connected vehicles and Sect. 13.6 discusses the USDOT connected vehicle program.

13.1 The Connected Vehicle

A connected vehicle is defined as any vehicle connected to an external network. At this writing, connected vehicle technology is evolving quite rapidly in both the private and public sectors. As the technology is rapidly changing, this chapter provides an overview of the status in 2015, and subsequent developments that may reasonably be foreseen. Private sector technology includes "infotainment", a category that includes vehicle and driver functions (the focus of this chapter) as well as others. While unsafe cellular telephone techniques are often employed to deliver this information, this chapter focuses on the current and emerging safe methodologies that may be employed.

Traditional methodologies for providing the motorist with ITS information include freeway based dynamic message signs (DMS), lane control signals (LCS) and variable speed limit signs (VSLS). In-vehicle display methodologies may be used to advantage to present this information.

Vehicle provided displays may reduce the future need for non-regulatory roadway information devices such as DMS. For example, A. Prasad, Secretary of Florida DOT, states "Ten years ago, VMS[1] made sense because the space was empty and there was a need for traveler information. State DOTs were the only ones providing this. Now there's so much information out there, we are starting to question whether we as a DOT, still need to provide traveler information…They probably make sense for the next few years, but long term we need to seriously think about whether this is something we should be investing in". Prasad envisages DOTs collecting data,

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[1] VMS (variable message sign) is an alternative acronym for dynamic message signs (DMS).

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entering into public–private partnerships to share the publicly and privately collected data, and to provide that data to the public [1]. Reduced emphasis on DMS is also anticipated by Hendrickson et al. [2]. With the emphasis on motorist information shifting to the private sector, the role of transportation management centers in providing motorist information is changing.

13.2 Connected Vehicle Data Links

Figure 13.1 shows one perspective of the types of data links that may be used for connected vehicles.

The figure includes the following data link types:

- Conventional ITS communication links—These links typically connect the traffic management center (TMC) with field equipment such as vehicle detector stations and roadway motorist information displays such as dynamic message signs (DMS), These connections typically use fiber optic cable, cellular connections or owned wireless equipment. Communications with other centers are typically implemented by cellular telephone service, often over virtual private networks (VPNs).
- Cellular/internet telephone based services—Cellular/internet telephone based service connects most of the currently available public and private applications to the vehicle. The figure shows an architecture that facilitates a safe and convenient methodology for smartphone based services. From the user's smartphone, a physical or Wi-fi connection is established to an appropriately adapted vehicle infotainment system (IVI). The IVI may be supplied by the vehicle manufacturer or by an aftermarket supplier. This architecture is further discussed in Sect. 13.3.
- USDOT connected vehicle architecture links—Fig. 13.1 includes a simplified overview of the USDOT connected vehicle communication links. The connected vehicle architecture and its applications are discussed in Sect. 13.6. Vehicles exchange basic safety messages (BSMs) through their on-board units (OBUs) and provide these messages to roadside units (RSUs) as well. RSUs are provided at certain freeway locations and at certain traffic signal controllers. Communication among OBUs and between OBUs and RSUs is provided by dedicated short range wireless communications (DSRC) in the 5.9 GHz band. Information from central sources such as traffic management centers may be sent to RSUs for transmission to vehicles.
- Proprietary communication channels—These channels may carry special services provided in cooperation with vehicle manufacturers or aftermarket equipment suppliers. An example of a proprietary communication service is Sirius XM radio. Using satellite communications in the S band (2.32–2.345 MHz), this service provides traffic and weather information in addition to entertainment channels. Proprietary connection capability using smartphones is also employed.
- Conventional ITS roadway displays and AM/FM radio. Dynamic message signs, lane controls, highway advisory radio and conventional radio traffic information reports are examples of currently available ITS applications.

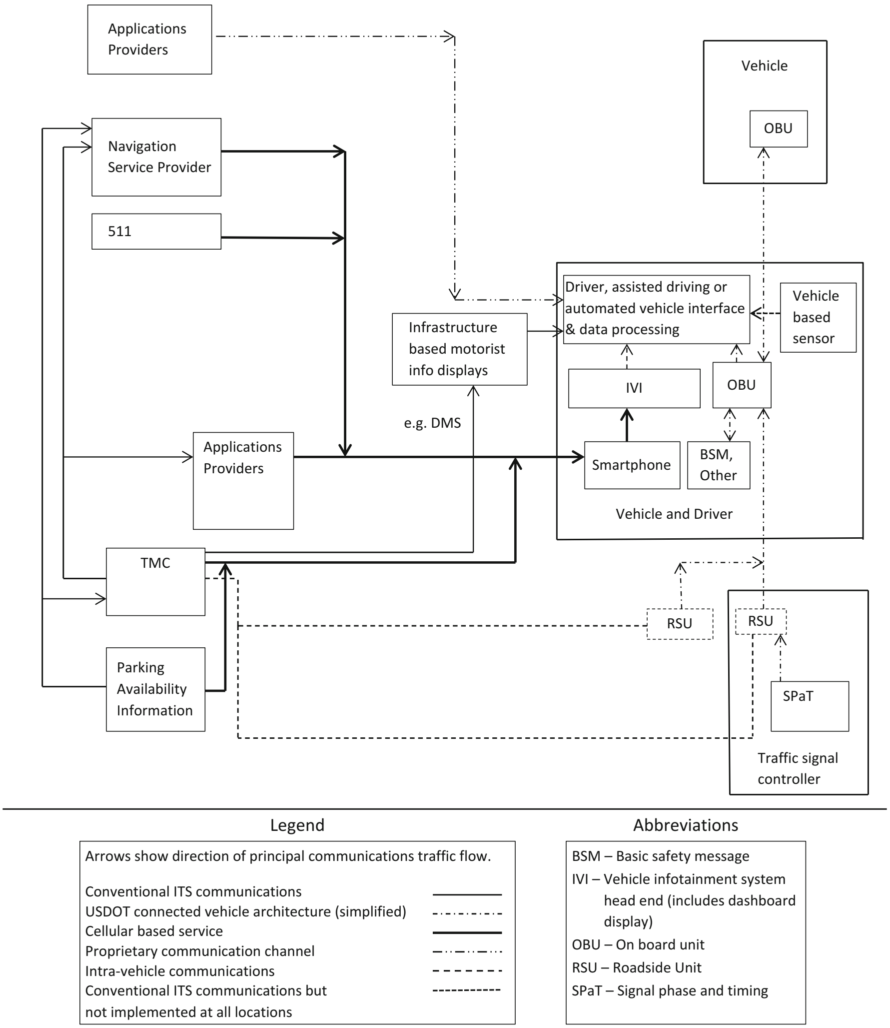
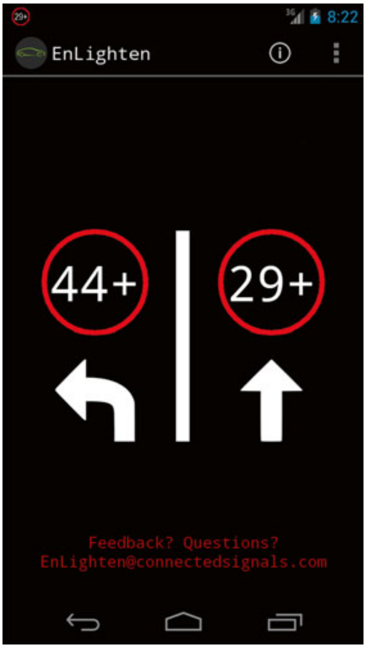


Fig. 13.1 Data links for connected vehicles

13.3 Cellular/Internet Based Services

Most of the connected vehicle applications provided to date utilize this approach. Section 13.4 describes techniques for safely providing this information to motorists. A wide variety of mapping, route finding and navigation services are currently available with no subscription cost to the motorist. Information may be delivered in text, map and oral formats. In some cases, the information may be downloaded directly from the internet. In other cases, an application program must first be



Feedback? Questions?
EnLighten@connectedsignals.com

Fig 13.2 Traffic signal state display

installed in the cell phone. Major limitations of cellular/internet information delivery include:

- Latency limitations—Latency is a measure of the communications response time. It is usually defined as the average time to transmit a message and receive a response. Rapid response requirements for certain safety related messages may prevent the use of this approach for those applications.
- Cellular telephone charges. Continuous connection requirements may result in charges that are unacceptable to the driver.

Travel related functions commonly provided by cellular/internet technology include:

- Traffic information and navigation
- State 511 systems
- Parking availability
- Specialized services. One specialized service is the provision of traffic signal state countdown information. A system implemented by Connected Signals Technology provides displays such as that shown in Fig. 13.2 in certain locations.

The information must be provided to the motorist in a safe and convenient manner, and at this writing, vehicular technology is moving rapidly in this direction.

Currently, internet/cellular information may be provided in three ways:

1. *Vehicle manufacturer supplied equipment and software*. The Ford Sync system is an example of this technique. The interface with the smartphone is through a Bluetooth connection. The screen can be controlled by voice activated commands as well as by screens. Travel related functions such as those described above may be accessed. In addition other internet provided infotainment functions are available as well as vehicle supplier functions such as vehicle health reports.
2. *Cellular telephone providers*. Major providers of cellular telephone operating systems have developed interfaces to head units similar to those described above. Android Auto and Apple CarPlay are examples of this approach. Selected applications are supported. Travel related features are generally similar to those described above.
3. *Non-proprietary standards*. The Car Connectivity Consortium comprised of a number of auto and electronics manufacturers has established an industry standard for certifying applications and devices that are both safe and useful for drivers called MirrorLink [4]. It displays the smartphone screen from a number of mobile operating systems. It is available for both vehicle manufacturers and aftermarket suppliers.

13.4 In-Vehicle Displays

Typical in-vehicle components include the cellular telephone and the infotainment system head unit including the visual display and a method of control. Controls may consist of a touch screen integrated with the dashboard display or alternatively a head-up display (HUD) may be employed. Head-up augmented reality displays have been introduced. In one implementation, the head unit connects to the cellular phone with a cable or wireless connection. The screen of the head unit essentially replicates the cell phone display. Voice replication and voice command capability are also provided. Commands on the screen and by voice provide for the selection of all infotainment systems.

Traffic information, roadway conditions and regulatory information may be presented in a variety of display techniques and provided by vehicle suppliers or by aftermarket suppliers. HUDs may result in less driver distraction than dashboard displays.

NHTSA has developed guidelines for avoiding driver distraction [5]. These guidelines recommend that glances away from the roadway should be completed in two seconds or less and that the cumulative time spent in glancing away from the roadway should be 12 seconds or less.

13.5 The Traffic Management Dilemma

As the provision of motorist information becomes increasingly privatized, a consequence is that the capability of government agencies to provide the traditional traffic management and assignment functions may become significantly impacted. Privatized traffic assignment is ad hoc, does not conform either to theoretical traffic assignment principles or to traffic assignment practices desired by the TMC. This may result in unfavorable impacts on traffic distribution. Although private firms do not explicitly try to manage traffic on an area-wide basis, their messages, in effect and at least in part, perform this function. While private firms have the advantage of access to both private and publicly available traffic information, their ability to properly manage traffic is limited by:

- The inability to provide CCTV based traffic information as well as the personal supervision and judgement such as provided by TMC managers and operators.
- The business models of private firms focus on providing automated information to individual motorists. Turn-by-turn route guidance information is the most popular form of presentation. These firms generally have no mandate or motivation to implement corridor-wide or area-wide traffic management strategies, nor to inject human supervision. The individual strategies for responding to non-recurrent congestion may prove counter-positive from a system-wide viewpoint.
- The route optimization models of private firms may contrast with the traffic assignment emphasis and constraints employed by public agencies.

Possible techniques to address these issues include:

- Provision of traffic information such as that presented on state 511 websites and their mobile applications to enable safe, in-vehicle presentation of corridor management information.
- Provision of detailed traffic conditions and traffic management messaging to private traffic services.

13.6 USDOT Connected Vehicle Program

This is a very large scale program whose basic objectives are the improvement of safety, mobility and the environment by the use of connected vehicle technology. USDOT indicates that connected vehicles have the potential to address approximately 80 % of vehicle crash scenarios involving unimpaired drivers [6]. The

```
-- Part I, sent at all times
msgID DSRCmsgID, -- App ID value, 1 byte
msgCnt MsgCount, -- 1 byte
id TemporaryID, -- 4 bytes
secMark DSecond, -- 2 bytes
-- pos PositionLocal3D,
lat Latitude, -- 4 bytes
long Longitude, -- 4 bytes
elev Elevation, -- 2 bytes
accuracy PositionalAccuracy, -- 4 bytes
-- motion Motion,
speed TransmissionAndSpeed, -- 2 bytes
heading Heading, -- 2 bytes
angle SteeringWheelAngle, -- 1 bytes
accelSet AccelerationSet4Way, -- 7 bytes
-- control Control,
brakes BrakeSystemStatus, -- 2 bytes
-- basic VehicleBasic,
size VehicleSize, -- 3 bytes
```

Fig. 13.3 Basic safety message descriptors

fundamental premise of the connected vehicle initiative is that enabling wireless connectivity among vehicles, the infrastructure, and mobile devices will bring about transformative changes in safety, mobility, and the environmental impacts in the transportation system [7]. Key elements of the program include:

- Vehicle to vehicle (V2V) communication. In 2014 NHTSA published an advanced notice of proposed rulemaking (ANPRM) that would require light motor vehicles to contain a vehicle to vehicle short-range communication (DSRC) capability in the 5.9 GHz band [8]. The communications and data formatting are provided by an on board unit (OBU).
- NHTSA's study recommended transmission of a basic safety message (BSM). The contents of the BSM are shown in Fig. 13.3 [9]. Position and motion messages are broadcast at a rate of ten times per second. The ANPRM cites the following applications that would significantly improve safety:
    - Intersection Movement Assist (IMA)
    - Left Turn Assist (LTA)

  The safety applications using this technology would be developed by industry.
- Vehicle to infrastructure (V2I) communication. Roadside units (RSU) communicate with vehicle OBUs in the 5.9 GHz band and may exchange information with information sources such as TMCs as shown in Fig. 13.1. They may also provide information from intersection traffic controllers to vehicles. Since USDOT does not currently plan to mandate installation of RSUs, their availability is not

assured. A key application envisioned by USDOT is the signal phase and timing (SPaT) message which identifies the current traffic signal state. This message is transmitted by an RSU in a traffic signal controller cabinet to vehicle OBUs. Software in the vehicle may use this data, in conjunction with information from the vehicle's own sensors to determine whether additional action is required to enable the vehicle to obey the signal. This type of information, when coupled with BSM information from other vehicles may possibly be used to determine whether additional action is required to avoid a crash with another vehicle that is not going to slow or stop when required.

The USDOT Connected Vehicle Program is engaged in research covering a large number of applications. While some of these applications are unique to connected vehicles, others are modifications of existing ITS or non-USDOT based connected vehicle services.

The Connected Vehicle Reference Implementation Architecture (CVRIA) is being developed as the basis for identifying the key interfaces across the connected vehicle environment that will support further analysis to identify and prioritize standards development activities. CVRIA will also support policy considerations for certification, standards, core system implementation, and other elements of the connected vehicle environment [10]. CVRIA is developed in four viewpoints:

- Enterprise—The relationships between organizations and the roles those organizations play within the connected vehicle environment.
- Functional—Abstract functional elements (processes) and their logical interactions (data flows) that satisfy the system requirements.
- Physical—Physical objects (systems and devices) and their application objects as well as the high-level interfaces between those physical objects.
- Communications—The layered sets of communications protocols that are required to support communications among the physical objects that participate in the connected vehicle environment.

A key standard included in the CVRIA is the SAE J 2735 Standard [10]. This standard essentially provides the message sets used for V2V and V2I communications. Table 13.1 shows proposed message priorities based on safety impacts and latency (urgency) for applications [10]. Higher priority numbers represent greater safety impacts.

Table 13.1 Message priorities (proposed values) and latency

Importance level from FCC policy description	Description (when to apply a specific urgency level)	Example(s)	Reception latency (urgency) (ms)
1 = Safety of Life Those Messages and Message Sets requiring immediate or urgent transmission	Emergency impact mitigation and injury avoidance/mitigation	Crash-Pending Notification	<10
	Emergency potential-event impact and/or injury mitigation and avoidance	Pre-Crash	<10
	Urgent Warning Events (using Event Flags)	Hard-Brake (Collision Warning, EEBL, Anti-Lock, etc.) and Control Loss	<10
	Urgent warning of impending local situation	Emergency Vehicle Approaching	10–20
	Situation-based status information of uninvolved local interest	Situation Ahead (e.g., Emergency Vehicle, Accident)	10–20
	Situation-based status information of uninvolved local interest	Situation Ahead (e.g., Emergency Vehicle, Accident)	10–20
	Potential-situation information of uninvolved local interest	Probable-situation (e.g., Rapidly deteriorating dangerous conditions)	10–20
	Possible-situation information of uninvolved high-latency local interest	Possible-situation (e.g., Deteriorating dangerous conditions)	>20

(continued)

Table 13.1 (continued)

Importance level from FCC policy description	Description (when to apply a specific urgency level)	Example(s)	Reception latency (urgency) (ms)
2 = Public Safety (Safety not in 1) Roadside Units (RSUs) and On-Board Units (OBUs) operated by state or local governmental entities that are presumptively engaged in public safety priority communications (Includes Mobility and Traffic Management Features)	Urgent public safety downloads (Intersection Information)	SPAT (Signal Phase and Timing)	<10
	Urgent public safety data transactions, exchanges	Electronic Toll Collection	<10
	Periodic public safety status information	Heartbeat message	<10
	Public safety geospatial context information	GID message (Geospatial Context)	<10
	Semi-urgent public safety link establishment	Lane Coordination; Cooperative ACC	<10
	Public safety GPS correction information	GPSC message (GPS Correction)	<10
	Periodic less frequent public safety status information	Heartbeat (at lower frequency)	<10
	Semi-urgent public safety system enabler	Localized Geometric Intersection Definition Download	10–20
	Semi-urgent public safety data and application enabler	Services Table, Digital Map Download	>20
	Important Traffic Management status information enabler	Highway Closed Ahead	>20
	Important Announcement of Services	WSA message (Wave Service Announcement)	>20
	Semi-important Traffic Management enabler	General Traffic Information Download	>20
	Non-urgent Traffic Management Foundational Data	Probe Messages, Localized warning zones update	>20
3 = Non-Priority Communications (not in 1 or 2) Fleet Management of Traveler Information Services and Convenience or Private Systems	Urgent, private mobility message	Off-Board Navigation Reroute Instructions	<10
	Urgent, private and commercial electronic transactions	Electronic Payments	<10
	Semi-urgent, private mobility data exchange	Private mobility applications (e.g., GPS based driving instructions)	10–20
	Semi-urgent, private and commercial electronic transactions	Commerciai and private e-commerce applications	10–20
	Important, private and commercial electronic transactions	Large commercial transactions (E-Commerce)	10–20
	Important, private mobility data exchange	Commercial and private offers, directions	10–20
	Background, private mobility data exchange	Area map download or upgrade	>20
	Background, private data downloads and upgrades	Database download	>20

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Appendix A
Travel Time, Delay and Travel Time Reliability Measures

This appendix describes the techniques and algorithms that may be used to compute a number of the measures described in Table 9.3. This appendix provides the computations for obtaining the 5 min and 15 min values for travel time, delay and travel time reliability (see Fig. 9.8). The 15 min values must be further aggregated by the user to obtain the specific time period desired for the measure. This appendix is largely based on Gordon [1]. Table A.1 summarizes the notation employed in the appendix.

Freeway Delay and Travel Time

Many freeway management systems are equipped with point-based, and in some cases probe-based, traffic detectors to perform normal traffic management functions. Since these detectors provide a basis for automatic data collection for performance evaluation purposes, the manual effort to obtain measures based on speed and travel time is minimal.

Several measures in Table 9.3 require the computation of travel time and delay. *System delay* is the sum of freeway mainline delay and freeway ramp delay for all vehicles. *System travel time* has a similar relationship. *Vehicle travel time*, *delay* and *travel time reliability* consider these quantities on an individual trip basis.

The relationships provided below describe the requirements for obtaining freeway mainline data.

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Table A.1 List of symbols, variables and parameters for Appendix A

a, b denote domain end points for link level computations
D = System mainline delay for measurement interval (vehicle hours)
DO = Domain ID
FC = Commercial vehicle fraction of traffic volume
FD = Freeway system delay
FP = Private passenger vehicle fraction of traffic volume
K_1 = Average number of travelers in private passenger vehicle
K_2 = Average number of occupants in commercial vehicle
L = Link ID
L1 = Start of link range under evaluation
LE = Length of link, domain or probe sensing region (mi)
LN = Last link in range under evaluation
LPP = Traveler system delay in private passenger vehicles (person hours)
LPT = Occupant delay in commercial vehicles (person hours)
LV = Link volume
M = Mean travel time of a set of sample trips for the period
N = number of sample trips
N15 = 15-min evaluation period index number
N5 = 5-min evaluation period index number
NF = Freeway evaluation time period index number (used for freeway and entry ramps)
P = 15-min period index
PHT = Peak hour throughput
PR = Probe sensing region ID
RI = Link on start of selected route
RO = Link on end of selected route
ROD = Freeway route delay (hours)
RRT = Reference ramp travel time
RTT = Route travel time (hours)
s = Standard deviation
SD = Domain speed (mph)
SP = Probe sensing region speed (mph)
SR = Reference speed (reference speed for delay) (mph)
T = Time measurement interval (hours)
  T15 = 15 min (.25 h) for intersection signals and surface streets
  T5 = 5 min (.06777 h) for mainline and ramps
T_j = Travel time of jth trip on a specific route
TP = Travel time as sensed by probe vehicles (hours)
TT = System mainline travel time (veh h)
V = Roadway volume (vph)
VD = Vehicle delay (hours)
VSD = Vehicle system delay (hours)
VT = Vehicle travel time (hours)
x denotes the number of vehicles in 5- or 15-min probe vehicle sample

Mainline Delay and Travel Time Evaluation for Point Detectors

The values for these measures are built up using the structure and relationships shown in Figs. 9.6, 9.7, and 9.8. The domain is the basic spatial structure for the computation scheme. Its boundaries are determined by the following:

- Freeway entry and exit locations
- Location of DMS and other traffic management and control devices
- Detector locations

Domain System Travel Time

Equation (A.1) computes domain travel time for all vehicles in a domain in a 5 min period.

$$TT(DO,N5) = T5 \cdot V(DO,N5) \cdot LE(DO) / SD(DO,N5) \tag{A.1}$$

where

TT = System mainline travel time (veh h)
DO = Domain ID
N5 = 5-min evaluation period index number
T5 = 5 min (.06777 h) for mainline and ramps
V = Roadway volume (vph)
LE = Length of link, domain or probe sensing region (mi)
SD = Domain speed (mph)

In some systems traffic management systems SD represents weighted speed [2]. Since speeds and volumes are different in different lanes, weighted speed is the product of lane volume and lane speed divided by total volume.

Domain System Delay

Domain system delay removes the vehicle hours of vehicles travelling at or above a reference speed which is considered to be an acceptable value.

$$\begin{aligned} &If\left(TT(DO,N5) - T5 \cdot V(DO,N5) \cdot LE(DO) / SR(DO)\right) > 0 \;\; then \;\; D(DO,N5) \\ &\quad = \left(TT(DO,N5) - T5 \cdot V(DO,N5) \cdot LE(DO) / SR(DO)\right) \;\; else D(DO,N5) = 0 \end{aligned} \tag{A.2}$$

where

D = System mainline delay for measurement interval (vehicle hours)
SR = Reference speed (reference speed for delay) (mph)

Link System Travel Time

Travel links (distance between each freeway exit or entry location and the next downstream location) are commonly used to provide the geographical structure for expressing measures. Equation (A.3) sums the system travel times for the domains in a link.

$$TT\left(L,N5\right)=\sum_{DO=a}^{b}TT\left(DO,N5\right) \tag{A.3}$$

where

L = Link ID
a = domain that begins link
b = domain that terminates link

Link System Travel Time for 15-Min Periods

Equation (A.4) aggregates the 5-min period link travel time to 15 min.

$$TT\left(L,P\right)=\sum_{NF}^{NF+3}TT\left(L,N5\right) \tag{A.4}$$

where

P = 15-min period index
NF = NF 5-min index at the beginning of the 15-min period

Link System Delay

$$D\left(L,N5\right)=\sum_{DO=a}^{b}D\left(DO,N5\right) \tag{A.5}$$

System Delay for 15-Min Periods

$$D\left(L,P\right)=\sum_{N5=NF}^{NF+3}D\left(L,N5\right) \tag{A.6}$$

Vehicle System Delay

Equation (A.7) sums Eq. (A.6) over a daily period and over the set of links under evaluation (for example, a freeway or the entire freeway system)

$$VSD = \sum_{L=L1}^{LN} \sum_{P=1}^{96} D(L,P) \tag{A.7}$$

where

L1 = the start of start of the link range under evaluation
LN = the last link in the link range under evaluation
VSD is vehicle system delay

By modifying Eq. (A.7), Eqs. (A.8) and (A.9) provide values for private passenger vehicle occupant system delay and commercial vehicle occupancy system delay.

Private Passenger Occupancy System Delay

$$LPP(L,P) = K1 \cdot \sum_{L=L1}^{LN} \sum_{P=1}^{96} D(L,P) \cdot FP(L,P) \tag{A.8}$$

where

K1 = Average number of travelers in private passenger vehicles
FP = Private passenger vehicle fraction of traffic volume

Commercial Vehicle Occupant System Delay

$$LPT(L,P) = K2 \cdot \sum_{L=L1}^{LN} \sum_{P=1}^{96} D(L,P) \cdot FD(L,P) \tag{A.9}$$

where

K_2 = Average number of occupants in commercial vehicle
FC = Commercial vehicle fraction of traffic volume
LPT = Occupant delay in commercial vehicles (person hours)

Domain Vehicle Travel Time

Equation (A.10) provides the travel time for an individual vehicle in a domain computed for each 5-min interval.

$$VT(DO,N5) = T5 \cdot LE(DO) / SD(DO,N5) \tag{A.10}$$

where

VT = Vehicle travel time (hours)

Domain Vehicle Delay

$$\begin{aligned} &\mathit{If}\left(VT\left(DO,N5\right)-T5\cdot LE\left(DO\right)/SR\left(DO\right)>0\right)\ \mathit{then}\ \ VD\left(DO,N5\right) \\ &\quad=\left(VT\left(DO,N5\right)-T5\cdot LE\left(DO\right)/SR\left(DO\right)\right)\ \mathit{else}\ \ VD\left(DO,N5\right)=0 \end{aligned} \tag{A.11}$$

where

VD = Vehicle delay (hours)

Link Vehicle Travel Time

$$VT\left(L,N5\right)=\sum_{DO=a}^{b}VT\left(DO,N5\right) \tag{A.12}$$

Link Vehicle Travel Time for Each 15-Min Period

$$VT\left(L,P\right)=\sum_{N5+NF}^{NF+3}VT\left(L,N5\right) \tag{A.13}$$

Link Vehicle Delay

$$VD\left(L,NF\right)=\sum_{DO=a}^{b}VD\left(DO,N5\right) \tag{A.14}$$

Link Vehicle Delay for Each 15-Min Period

$$VD\left(L,P\right)=\sum_{N5+NF}^{NF+3}VD\left(L,N5\right) \tag{A.15}$$

Mainline Delay and Travel Time Evaluation for Probe Detectors

Probe detectors provide the basis for developing link delay and link travel time. Because the boundaries of probe sensing regions may not directly correspond to link boundaries, a domain structure, such as shown in Fig. 9.7, or an equivalent relationship is required. The basic concept requires determining the speed in the set of domains included in the probe sensing region by dividing the region's length by the travel time measured by the probe vehicles, as shown in Eqs. (A.16) and (A.17). This speed (SP) represents the speed for all domains encompassed by the probe-sensing region and is employed to compute domain and link vehicle travel time and delay in Eqs. (A.8)–(A.13) at the 5-min level. It is used for probe detection in place of SD in Eqs. (A.1) and (A.10).

$$TP\left(PR,T5\right)=\frac{1}{x}\cdot\sum_{i=1}^{x}TP\left(i\right) \tag{A.16}$$

$$SP\left(PR\right)=LE\left(PR\right)/\,TP\left(PR,T5\right) \tag{A.17}$$

where

TP = Travel time as sensed by probe vehicles (hours)
PR = Probe sensing region ID
x denotes the number of vehicles in 5 or 15 min probe vehicle sample
SP = Probe sensing region speed (mph)
LE = Length of probe sensing region

In order to develop system delay and system travel time measures, the volume variable required by Eqs. (A.1) and (A.2) must be obtained. A source of link volume data such as a point-detector station is required. Only one volume data source per link is required.

Route Travel Time, Route Travel Time Reliability and Throughput

Route Travel Time

Route travel time is commonly provided to the motorist by DMS on the freeway mainline as well as by web sites. Designated routes are often provided for this purpose, and these routes are convenient to use for evaluation [3].

Route travel time is the sum of route link travel times (VT) and may be computed as follows.

$$RTT=\sum_{L=RI}^{RO}VT\left(L,N5\right) \tag{A.18}$$

where

RTT = Route travel time (hours)
RI = Link on start of selected route
RO = Link on end of selected route

If the trip starts at 7 AM, the travel time for the first link on the route (designated as RI) becomes VT for the time period starting at 7 AM. N5 for the first link in this case is 73 (12 5-min periods for the period from midnight until 7 AM plus the current evaluation period). It is designated as NSTART.

Recognizing that the links on the route might be traveled during different time periods, and consequently at different speeds, a laddered concept for computing route travel times (RTT) is discussed by Ishimaru and Hallenbeck [3]. Route travel time is the sum of route link travel times (VT) and is computed for the appropriate time period for that link as follows.

If VT for this link < 5 min, then the travel time for the next link uses the same 5-min time period. If VT ≥ 5 min, then the travel time for the next link uses the subsequent 5-min time period. Higatani et al. [4] indicate that this approach is more accurate than the summation of link travel times computed for a single time period. Figure A.1 depicts a flow chart that implements this concept.

Similarly, freeway route delay (ROD) may be computed as follows.

$$ROD = RTT - \sum_{L=RI}^{RO} LE(L)/SR(L) \tag{A.19}$$

Route Travel Time Reliability

Travel time reliability measures the extent of this unexpected delay. A formal definition for travel time reliability is: *the consistency or dependability in travel times, as measured from day-to-day and/or across different times of the day* [5].

Travel time variability may be measured by comparing travel times for a specified route for a given time period (for example for a peak hour starting at 7 AM). Shaw [6] recommends a minimum data collection period of 4 weeks at 15 min intervals. Coupling this criterion with the previous discussion of route travel time, if a "trip" is considered to be a calculation of three 5-min travel times for each 15-min period in a weekday peak hour, eliminating holidays and other non-representative days, a 1 month data collection cycle provides a sufficiently representative data cycle.

The basis for travel time variability and the measures that are used to express it is the standard deviation of the travel time measurements. This is given by Martin and Wu [7] as:

$$s^2 = \frac{\sum \left(T_j - M\right)^2}{n-1} \tag{A.20}$$

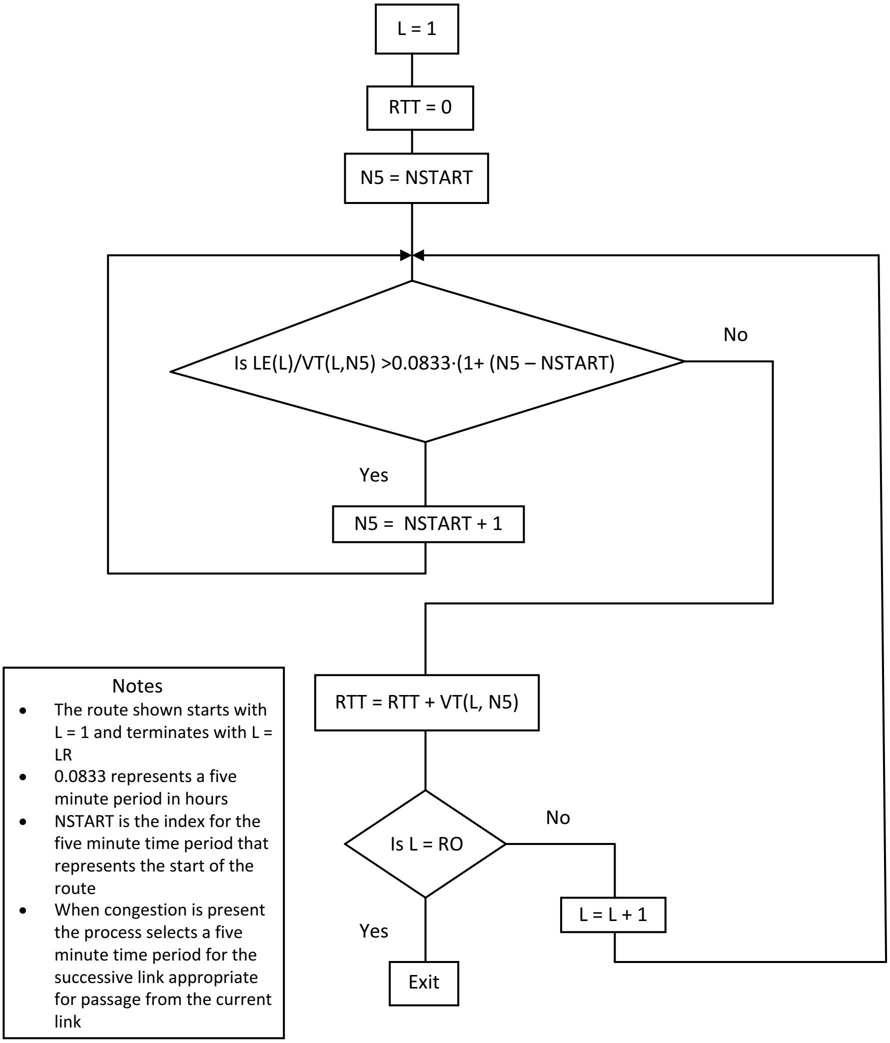

Fig. A.1 Time periods for travel time computation

where

s = estimate of travel time standard deviation
Tj = the travel time of the jith trip on a specific route
M = the mean travel time of a set of sample trips for the period (e.g. 15 min)
n = the number of sample trips

Commonly used measures of route travel time reliability are the completion of 90 % or 95 % of the trips within a given time. Statistical tables indicate that the relationship between the sample of travel times and the mean are as follows:

A 90 % reliability corresponds to 1.28 standard deviations
A 95 % reliability corresponds to 1.64 standard deviation

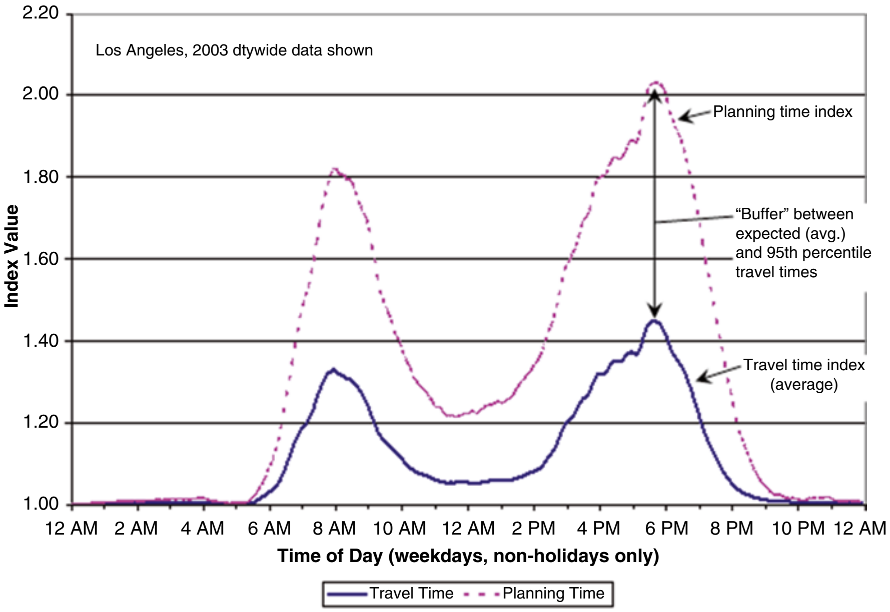

Fig. A.2 Relationships among travel time reliability measures

Measures that are commonly used [5] include:

Buffer time—The extra time required (i.e., calculated as the difference between the 95th percentile travel time and the average travel time) as provided by Eq. (A.21).

$$Buffer\,time = 1.64 \cdot s \tag{A.21}$$

Planning time—The total travel time, which includes buffer time (i.e., calculated as the 95th percentile travel time).

$$Planning\,time = RouteTravelTime + Buffer\,time \tag{A.22}$$

Planning time index—How much larger the total travel time is than the ideal or free-flow travel time calculated as the ratio of the planning time to the ideal.

Buffer index—The size of the buffer time as a percentage of the average route travel time calculated as the planning time minus the average, divided by the average route travel time.

The relationship among these measures is shown in Fig. A.2 [5].

The basis for all of the reliability measures is route or point-to-point travel times. There are four basic ways in which these travel times can be developed [7]:

1. Directly calculated from continuous probe vehicle data;
2. Estimated from continuous point-based detector data;

3. Collected in periodic special studies (e.g., floating car runs); and,
4. Estimated using computer simulation, sketch planning, or demand forecasting models.

List et al. [8] provide a detailed discussion travel time reliability along with examples of deployments.

Throughput

One measure of throughput is the vehicle miles for a link for the peak hour. For each 5 min of the peak hour identify the lowest volume for each domain in the link (LV). Peak hour throughput (PHT) is provided by Eq. (A.23)

$$PHT(L) = \sum_{N5=\textit{five minute period identifier for peak hour start}}^{N5+12} T5 \cdot LE(L) \cdot LV(L, N5) \tag{A.23}$$

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Appendix B
Relative Effectiveness of CCTV Coverage

Most of the accidents on urban and suburban freeways occur in the vicinity of interchanges. These accidents often take longer to clear than non-accident-related incidents. Thus, ITS designs that do not provide for complete or near-complete CCTV coverage usually place most of the cameras in the vicinity of the interchanges. The incident-hours covered by these cameras provide a larger fraction than would be experienced if the accidents were distributed evenly along the roadway (non-accident-related incidents are assumed to be evenly distributed along the roadway). This appendix describes a measure (RTV) for evaluating the relative coverage of incidents by CCTV. RTV approximately represents the fraction of incident periods in the section that is observable by the CCTV cameras.

Figure B.1 provides the physical layout for the RTV computation. The section shown in the figure represents one direction of the roadway between two interchanges. For convenience, half the distance within the interchange is attributed to the section (the other half is assigned to the adjacent section).

The following parameters are used for the computation of RTV:

ACR	Accident rate for section
ARI	Accident rate in interchange area
ARNI	Accident rate in non-interchange area
IDI	Duration of incidents and accidents in interchange areas
IDN	Duration of incidents and accidents in non-interchange areas
LS	Section length
L1	Distance in the section in the vicinity of the upstream interchange for the section midpoint of the interchange that encompasses most of the accidents
L2	Distance in the section in the vicinity of the downstream interchange; the values L1 and L2 represent half the distance centered at the midpoint of the interchange that encompasses the highest accident rate portion of the section
NAIR	Non-accident incident rate
TVI	Fraction of roadway visible to CCTV at interchanges
TVN	Fraction of roadway visible to CCTV away from interchanges
TNA	Test for presence of non-interchange area in section
WE	Ratio of accident rate in interchange area to accident rate in non-interchange area

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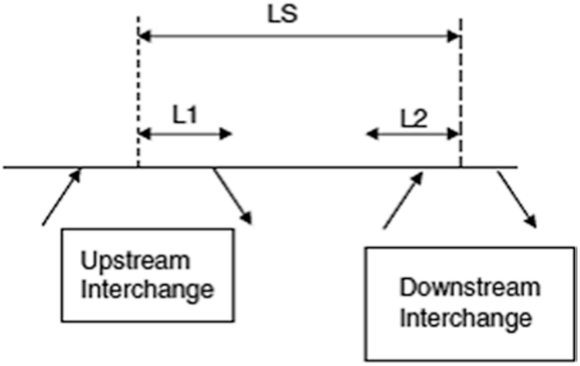


Fig. B.1 Physical relationship for RTV equation

Accident data may be available in the following ways:

- Accident rate summary for the section.
- Detailed accident rate data may be available by milepost (usually 0.1 mile intervals) or by geodetic reference.

Accident rate data for the section (identified above as ACR) may be disaggregated into the high accident rate portion near the interchanges (ARI) and the lower accident portion away from the interchanges (ARNI). The model expresses the approximate relationship.

$$\mathrm{ARI} = \mathrm{WE} \cdot \mathrm{ARNI} \tag{B.1}$$

An estimated value for WE is required. The total number of annual accidents (TA) in the section may be expressed as

$$\mathrm{TA} = \mathrm{ACR} \cdot \mathrm{LS} = (\mathrm{L1} + \mathrm{L2}) \cdot \mathrm{ARI} + (\mathrm{LS} - \mathrm{L1} - \mathrm{L2}) \cdot \mathrm{ARNI} \tag{B.2}$$

Substituting (B.1) into (B.2) yields

$$\mathrm{TA} = \mathrm{ACR} \cdot \mathrm{LS} = (\mathrm{L1} + \mathrm{L2}) \cdot \mathrm{WE} \cdot \mathrm{ARNI} + (\mathrm{LS} - \mathrm{L1} - \mathrm{L2}) \cdot \mathrm{ARNI} \tag{B.3}$$

Simplifying (B.3) yields

$$\mathrm{ARNI} / \mathrm{ACR} = \mathrm{LS} / \big(\mathrm{LS} + (\mathrm{L1} + \mathrm{L2}) \cdot (\mathrm{WE} - 1)\big) \tag{B.4}$$

In some cases detailed accident data at tenth of mile intervals is available, thus providing WE directly from (B.1).

The computations for the relative coverage of incidents by CCTV are as follows:

$$\mathrm{IDI} = (\mathrm{ARNI} \cdot \mathrm{WE} + \mathrm{NAIR}) \cdot (\mathrm{L1} + \mathrm{L2}) \tag{B.5}$$

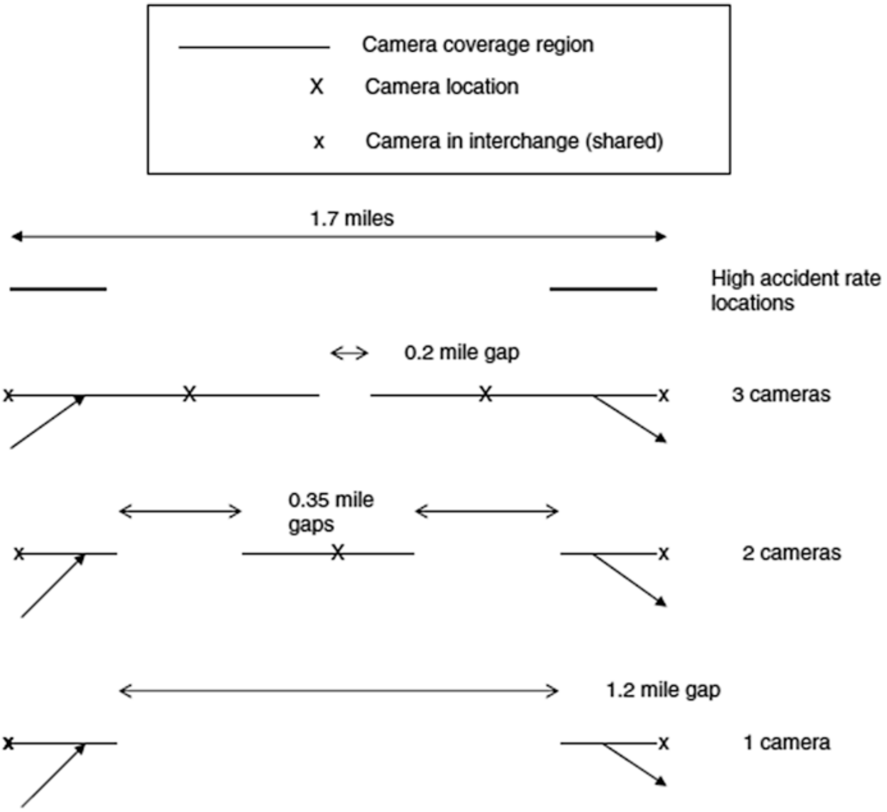
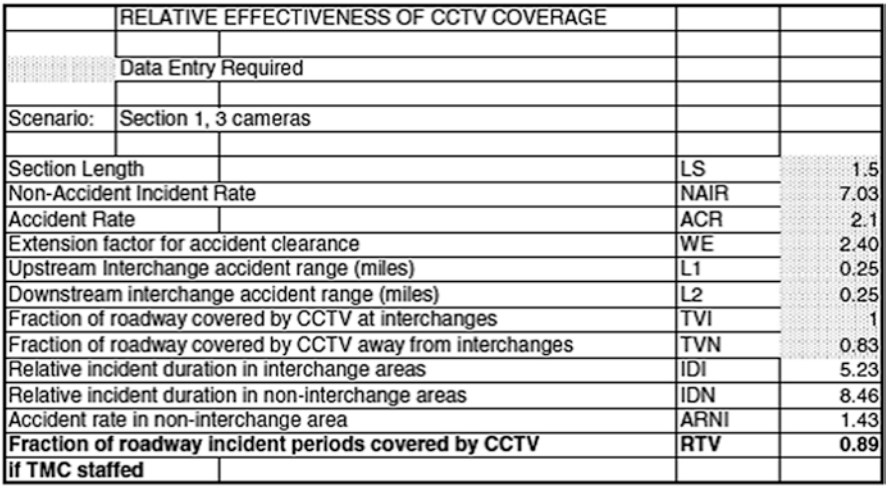


Fig. B.2 CCTV coverage for camera development alternatives

$$\mathrm{IDN} = \left(\mathrm{LS} - \left(\mathrm{L1} + \mathrm{L2}\right)\right) \cdot \left(\mathrm{ARNI} + \mathrm{NAIR}\right) \tag{B.6}$$

$$\mathrm{RTV} = \left(\mathrm{TVI} \cdot \mathrm{IDI} + \mathrm{TVN} \cdot \mathrm{IDN}\right) / \left(\mathrm{IDI} + \mathrm{IDN}\right) \tag{B.7}$$

Figure B.2 illustrates a simplified case study for evaluating RTV. Here each CCTV camera is assumed to cover one half mile of roadway. A distance of one half mile centered at the midpoint of the interchange is also assumed to represent the accident clustering region. The boundaries for the section under evaluation extend from the midpoint of the upstream interchange to the midpoint of the downstream interchange. Three alternate deployments providing less than 100 % CCTV coverage are shown in Fig. B.2, along with the CCTV camera count. The cameras at the interchanges are each counted as one half of a camera because 50 % of their



	RELATIVE EFFECTIVENESS OF CCTV COVERAGE		
▨	Data Entry Required		
Scenario:	Section 1, 3 cameras		
Section Length		LS	1.5
Non-Accident Incident Rate		NAIR	7.03
Accident Rate		ACR	2.1
Extension factor for accident clearance		WE	2.40
Upstream Interchange accident range (miles)		L1	0.25
Downstream interchange accident range (miles)		L2	0.25
Fraction of roadway covered by CCTV at interchanges		TVI	1
Fraction of roadway covered by CCTV away from interchanges		TVN	0.83
Relative incident duration in interchange areas		IDI	5.23
Relative incident duration in non-interchange areas		IDN	8.46
Accident rate in non-interchange area		ARNI	1.43
Fraction of roadway incident periods covered by CCTV		**RTV**	**0.89**
if TMC staffed			

Fig. B.3 Relative effectiveness of CCTV coverage

coverage extends into another section. Other parameters for the case study example include the following:

- Non-accident incident rate = 7.03 incidents per mile per year
- Accident rate for section = 2.1 accidents per mile per year
- Ratio of accidents in interchange area to accidents in non-interchange area = 2.4

The worksheet *RTV* on the website http://www.springer.com/us/book/9783319147673 and shown in Fig. B.3 was used to compute the values shown in Fig. 4.28. If the milepost based accident data is available, the value WE may be computed from this data (B.1) and entered into the worksheet. If only section summary accident rate data is available, the default value of WE = 2.4 may be retained or another value may be substituted.

Appendix C
Example of Benefits for Incident Management

This appendix provides an example of an alternatives analysis for the computation of the reduction in vehicle delay and accidents for ITS support of incident management.

The traffic parameters in the travel direction for the example are described in Table C.1, The parameters for the ITS treatments are shown in Table C.2. Two alternatives are considered for CCTV camera placements and two alternatives for detector deployment are examined in the example.

Equations (4.13)–(4.17) were applied to the parameters described above for the example for alternatives ac, ad, bc and bd. Figure C.1 shows a plot of the results for the alternatives shown in Table C.2 as well as the alternative of no detectors and no CCTV camera. The *Inc mgt effectiveness potential* worksheet on the website http://www.springer.com/us/book/9783319147673 (shown in Fig. C.2) was used to develop the data for the three camera and five detector alternative designs in Fig. C.1.

Table C.1 Traffic parameters for example

Symbol	Definition	Value	Comments
	Number of lanes	3	
AADT	Average annual daily traffic (vehicles/day)	75,000	
ACCR	Accident rate (accidents per million vehicle miles)	2.1	Based on New York State average for freeway accidents
CS	Capacity (vehicles/h)	6,300	
IR	Capacity reducing incidents in incidents per million vehicle miles	9.01	Based on data for upstate New York metropolitan areas
LS	Section length (miles)	1.7	
MVMPY	Million vehicle miles per year	46.54	Based on $MVMPY = AADT \cdot LS \cdot 365/1{,}000{,}000$
PHV	Peak hour volume (vehicles/h)	6,000	
TSI	Time reduced per incident in vehicle miles for high level of ITS deployment and intensive incident management by the TMC	271.8	Table 4.3 for three lanes and traffic condition level 3
K35	Correction factor for level of service	1.0	See Appendix F for further details

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Table C.2 ITS parameters for example

Technology or operation	Alternative	Deployment	Comments
911/PSAP information availability		Included in project	
Police operations		Included in project	
CCTV	a	3 cameras	RTV = 0.89 (example in Appendix B and Fig. 4.28)
	b	2 cameras	RTV = 0.62 (example in Appendix B and Fig. 4.28)
Motorist service patrols		Not included	
Electronic traffic detection	c	5 detector stations	Average spacing = 1.7/5 = 0.34 miles/ detector
			B1 = 0.9 (see Sect. 4.5.1.3)
	d	None	No detectors
			B1 = 0 (see Sect. 4.5.1.3)
TMC operational support		TMC assists in incident management	P10 = 1.0 K5 = 0.1 (see Table 4.13)
		TMC staffed around the clock	P21 = 1.0

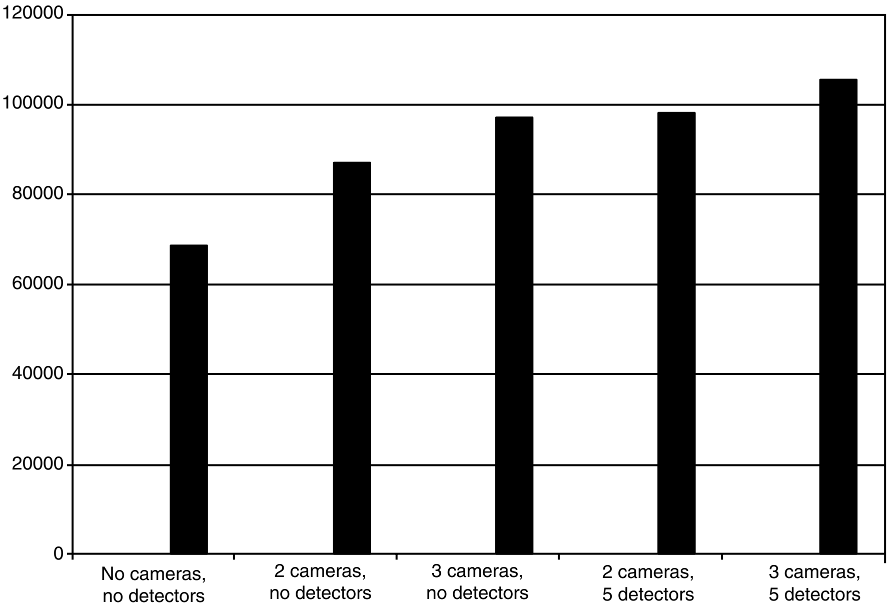

Fig. C.1 Reduction in vehicle hours of delay per year for design alternatives

INCIDENT MANAGEMENT EFFECTIVENESS POTENTIAL						
▨	Must enter data to obtain results following data entry					
░	May be optionally entered or changed by user					
Alterfnative:		0 CCTV cameras in section, 0 detector stations in				
section, no service patrols						
RTV =	0.89					
K40 =	1					
K41 =	1					
B1 =	0.9					
		V_{1g}	V_{2g}	V_{3g}	V_{4g}	V_{5g}
Functions (g)						
1		0.6	0.3	0.9	0.5	0.4
2		0.3	0.6	0.9	0.5	0.2
3		0	0.9	0.8	0.5	0.2
4		0	0.1	0.5	0.2	0.8
	Cumulative Probability for Each Function (H_g)					
Functions	Symbol					
1	H1 =	0.982				
2	H2 =	0.977				
3	H3 =	0.988				
4	H4 =	0.888				
Fraction of benefits obtained by assistance in clearing incident						
Y =	0.8					
Incident Management Effectiveness Potential						
H =	**0.929**					
IR	9.01					
P10	1					
P21	1					
TSI	271.8					
MVMPY	46.54					
ACCR	2.1					
K5	0.1					
Vehicle hours and accidents reduced						
Vehicle hours of delay reduced			**105902**	**per year**		
Accidents reduced			**9.1**	**per year**		

Fig. C.2 Inc mgt effectiveness potential example

Appendix D
Message Display Software for Southern State Parkway

This appendix describes the DMS semi-automatic control software employed in the freeway management system for the Southern State Parkway on Long Island in New York State [1].

The software performs the following functions:

- Provides DMS messages that display congestion conditions measured by system point detectors. Messages for several levels of congestion may be displayed.
- When congestion conditions are present on different sections of the roadway, the software prioritizes the messages to be displayed by location and severity condition. The priority scheme enables the limited messaging capability of the DMS to provide the most relevant information to the largest number of motorists.
- Provides the capability for the operator to alter the message.

Relationships Involving Geometry. Travel Time and Delay

The message generation technique is based on travel time and delay between certain key locations. Travel time is obtained from estimated speed from detector stations on the mainline of the freeway. A set of definitions and geometrical relationships to support the computation was defined and is discussed below.

As shown in Fig. D.1, a link represents a section of the mainline between vehicle access or egress points. The concept of a domain, discussed in Sect. 9.2.3.1 and illustrated in Fig. 9.6 is employed to relate data from freeway surveillance stations to mainline links. Domains relate links and DMS to the roadway locations receiving speed information from a particular detector station. Speed information from detector stations is filtered to remove short term fluctuations. In some cases the detector station may not physically be in the domain. As shown in the figure, each domain is assigned to a particular detector station.

Figure D.2 introduces the geometry and definitions used by the technique. In urban areas, DMS are often deployed at spatial intervals that encompass more than

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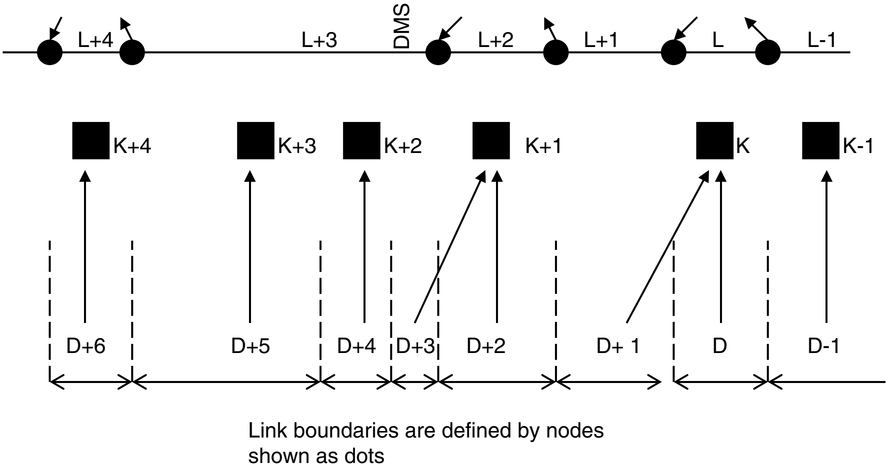
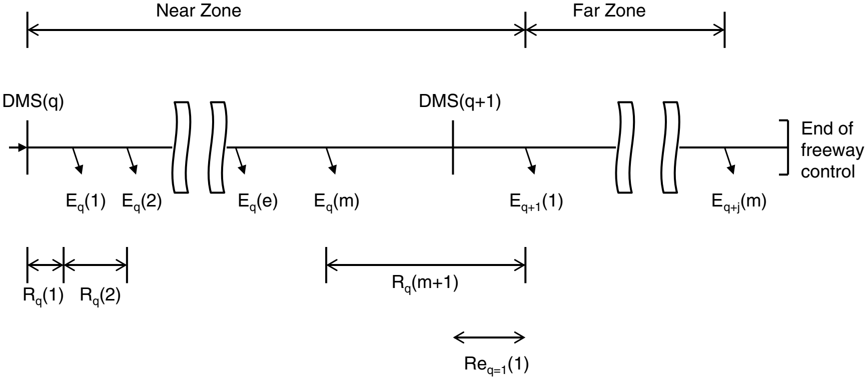


Fig. D.1 Link, domain and detector station relationships [1]



DMS	DMS locations
E	Exit ramps
R	Length of mainline roadway CMS control elements
q	Subscript for parameter definitions for near zone q
j	Subscript indicating end of far zone
m+1	Index for last element in near zone when there is at least one CMS in far zone
e	Index for element

Fig. D.2 Definitions for dynamic message sign software [1] one exit ramp. Thus, a “near zone” is defined in Fig. D.2 as the distance from the DMS to the exit ramp just downstream of the subsequent DMS. This distance is serviced by one or more exit ramps $E_q(e)$. The “far zone”, which is user defined, may encompass a number of subsequent DMS. A near zone and far zone is established for each DMS. As described later, the software develops different messages for the two zones.

Figure D.2 defines another data type, the “element” which is the distance between exit ramps. Each element includes one or more of the domains shown in Fig. D.1. Travel time for each domain is the quotient of domain length ($R_q(e)$) and the speed provided by the detector station associated with each domain. Element travel time is the sum of the domain travel times within the element.

The system operator must establish a nominal travel time for each element. Element delay, the difference between element travel time and nominal travel time is the basic component used for building the message.

Message Development

The following describes the message development capability of the software. The software provides two levels of congestion messages (delay and long delay) and a default message. For each element, the operator defines a delay threshold value that may trigger the message. Similarly, a long delay threshold value is also defined. A tentative delay indication or tentative long delay indication is declared for the element where prescribed thresholds are exceeded. The message is confirmed by the software if the declaration is valid for several computation intervals.

If the last element in the near zone (element $m+1$ in Fig. D.2) exceeds the delay criterion for that zone, it is possible that the next downstream element is also congested. In this case the software modifies the near zone boundary downstream to encompass those adjacent elements that experience delays.

Candidate Message Set Identification and Message Selection

Each candidate message is characterized by two factors:

- Intensity of delay (delay or long delay message classes).
- Freeway exits for which the delay condition applies.

When the appropriate delay or long delay thresholds are exceeded, a set of candidate congestion messages is developed for each zone. Each candidate message identifies a contiguous group of elements experiencing congestion.

Because the DMS are limited in their message display capability, more candidate messages may be developed than can actually be displayed. Table D.1 identifies the

Table D.1 Message priority classes

	Near zone	Far zone
Long delay message set	a	c
Delay message set	b	d

priority classes for each DMS. The system operator may select the priorities. A commonly used priority order is a, b, c, d.

Within each priority class the messages are ordered geographically, the first message being closest to the motorist. DMS on the freeway mainline commonly display three or four lines of information. The software provides messages according to the priority selected within the DMS display constraints.

Reference

1. Southern State Parkway ITS Early Implementation Project, Nassau County and Suffolk County (1997) New York State Department of Transportation

Appendix E
Washington State Fuzzy Logic Ramp Metering Algorithm

Fuzzy logic has the ability to address multiple objectives (by weighing the rules that implement these objectives) and to implement the tuning process in a more user-friendly fashion (by the use of linguistic variables rather than numerical variables). This algorithm employs fuzzy logic to provide ramp metering rates.

There are six inputs to the fuzzy logic controller (FLC). These include:

- Speed and occupancy from the mainline detector station located just upstream of the on-ramp merge
- Occupancy and speed from a downstream detector station. The station selected exhibits the maximum occupancy of selected downstream stations that have historically exhibited high flow breakdown rates
- Occupancy from a ramp queue detector typically located halfway between the ramp metering stop bar and the end of ramp storage
- Occupancy from the advanced queue occupancy detector at the upstream end of the ramp storage location

"Fuzzification" translates each numerical input into a set of fuzzy classes. For local occupancy and local speed, the fuzzy classes used are very small (VS), small (S), medium (M), big (B), and very big (VB). The degree of activation indicates how true that class is on a scale of 0 to 1. For example, if the local occupancy is 20 %, the medium class would be true to a degree of 0.3, and the big class would be true to a degree of 0.8, while the remaining classes would be zero (Fig. E.1). The downstream occupancy only uses the very big class, which begins activating at 11 %, and reaches full activation at 25 % (Fig. E.2). The downstream speed uses the very small class, which begins activating at 64.4 km/h and reaches full activation at 88.5 km/h. The queue occupancy and advance queue occupancy use the very big class. For ramps with proper placement of ramp detectors, the parameter defaults are for activation to begin at 12 %, and reach full activation at 30 %. The dynamic range, distribution and shape of these fuzzy classes can be tuned for each input at each location.

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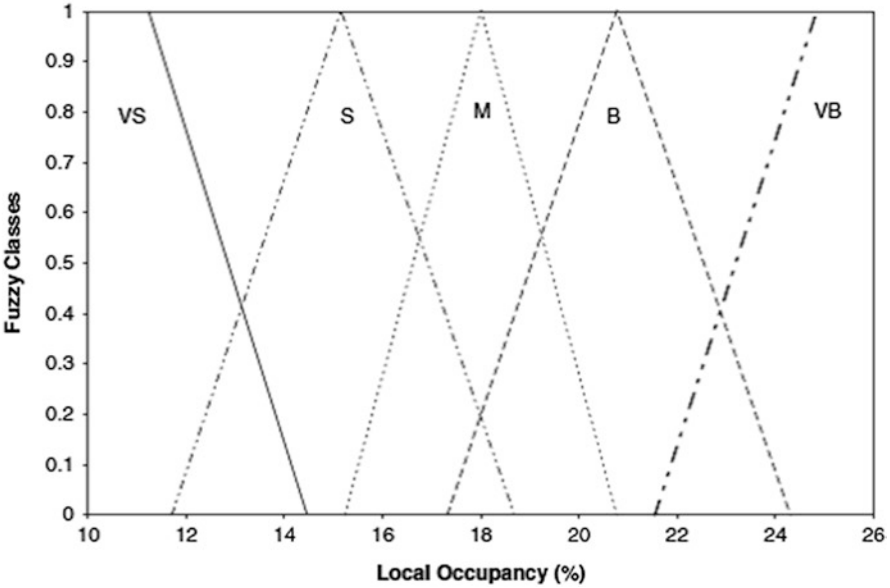

Fig. E.1 Fuzzy classes for local occupancy, redrawn. Presented at the 79th annual meeting of the Transportation Research Board, January 11, 2000, Washington, DC. Reproduced with permission of the Transportation Research Board

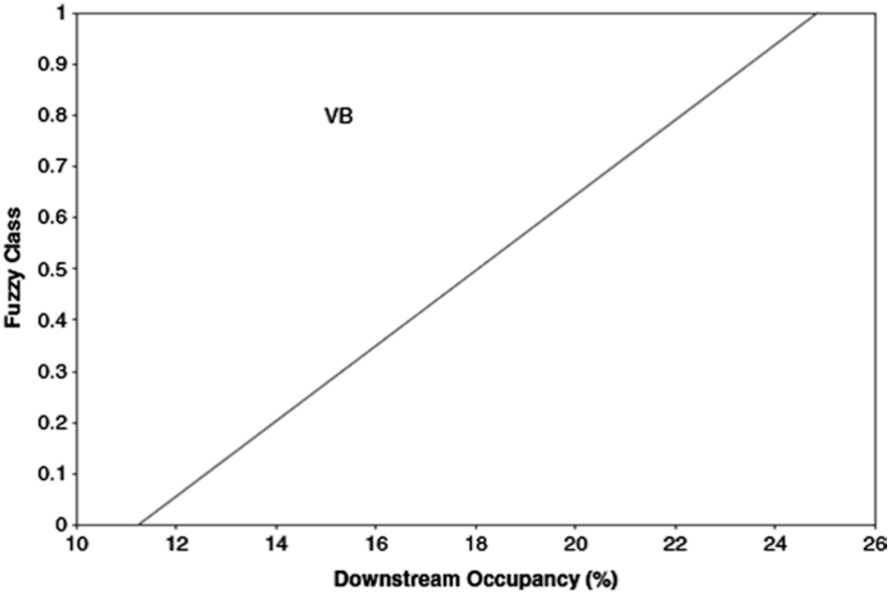

Fig. E.2 Fuzzy class for downstream occupancy [1], redrawn. Presented at the 79th annual meeting of the Transportation Research Board, January 11, 2000, Washington, DC. Reproduced with permission of the Transportation Research Board

Table E.1 Examples of fuzzy logic rules in the Washington state algorithm [1]

Rule	Default rule weight	Rule premise	Rule outcome
6	3.0	If local speed is VS AND local occupancy is VB	Metering rate is VS
10	4.0	If downstream speed is VS AND downstream occupancy is VB	Metering rate is VS
12	4.0	If advance queue occupancy is VB	Metering rate is VB

The last step, called *defuzzification*, generates a single valued numerical metering rate based on the rule outcomes and the degree of activation.

After the fuzzy states have been developed, weighted rules are then applied to develop the metering rate. Examples of weighted rules are shown in Table E.1.

References

1. Taylor C et al (2000) Results of the on-line implementation and testing of a fuzzy logic ramp metering algorithm. In: 79th annual meeting of the Transportation Research Board, Washington, DC
2. Neudorff LG et al (2003) Freeway management and operations handbook. Report FHWA-0P-04-003. Federal Highway Administration, Washington, DC
3. Klein LA (2001) Sensor technologies and data requirements fror ITS. Artech, Boston, MA

Appendix F
Benefits Model for Motorist Assistance Patrols

A possible model for delay reduction for motorist assistance patrols is provided by the following expression:

$$\mathrm{TS} = \mathrm{K12} \cdot \mathrm{K17} \cdot \mathrm{K35} \cdot \mathrm{K40} \cdot \mathrm{MTSSV} \cdot \mathrm{LS}$$

TS = Motorist time saved
K12 = Annual service patrol stops per directional mile. The default value of 119 is based on INFORM ITS data and is based on an annual service patrol period of 2,600 h
K17 = Fraction of stops for which assistance is provided. The default value of 0.46 is based on INFORM ITS data
K35 = Correction factor. Possible default values are:

K35 = 1.0 where peak hour level of service is D or worse
K35 = 0.7 where peak hour level of service is C
K35 = 0.0 where peak hour level of service is B or better

K40 = Number of annual hours for which service is provided/2600
MTSSV = Average delay reduced per assisted vehicle. A representative default value is 95 h [1]. It is based on a freeway with level of service D or worse

Reference

1. Wohlschlaeger SD, Balke KN (1992) Incident response and clearance in the State of Texas: case studies of four motorist assistance patrols. Report No. FHWA/TX-92/1232-15, Texas Transportation Institute, College Station, TX

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Appendix G
National Incident Management System and Incident Classification

This appendix describes the basics of the National Incident Management System and a commonly used incident classification system. The appendix contains material from the document *Emergency Traffic Control and Scene Management Guidelines, Version 2.0* Wisconsin Department of Transportation, Feb. 12, 2012.

National Incident Management System and Incident Command System

The National Incident Management System (NIMS) is a comprehensive, national approach to incident management that is applicable at all jurisdictional levels and across functional disciplines. The intent of NIMS is to:

- Be applicable across a full spectrum of potential incidents and hazard scenarios, regardless of size or complexity.
- Improve coordination and cooperation between public and private entities in a variety of domestic incident management activities. One of the key features of NIMS is the Incident Command System (ICS). ICS is a standardized, on-scene, all-hazards incident management concept that allows its users to adopt an integrated organizational structure to match the complexities and demands of single or multiple incidents without being hindered by jurisdictional boundaries. ICS consists of procedures for controlling personnel, facilities, equipment and communications. It is also a system designed to be used or applied from the time an incident occurs until the requirement for management and operations no longer exists. ***ICS should be established and used for every incident***.

ICS has an Incident Commander who has complete responsibility for incident management. The Incident Commander must account for all personnel working at the scene. This includes those that arrived on the scene initially (law enforcement,

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fire, emergency medical services, etc.) as well as those who arrive later to assist with the scene (highway department personnel, insurance investigators, engineers, etc.).

When incidents require a multi-jurisdictional or multi-agency response, the guidelines of Unified Command should be followed. Unified Command allows agencies with different legal, geographic, and functional authorities and responsibilities to work together effectively without affecting individual agency authority, responsibility or accountability. Unified Command enables all responsible agencies to manage an incident together by establishing a common set of incident objectives and strategies. Use of Unified Command helps minimize duplication of efforts and confusion on the scene.

It is recommended that when command is established or transferred from one person to another, this information, as well as the location of the command post, be communicated for all responders to hear. In many instances, and for a variety of reasons, there are challenges with on-scene responder communication. In such cases, it is necessary that the Incident Commander ensure that all parties have been made aware of any pertinent information.

Additionally, ambiguous codes and acronyms have proven to be a major obstacle in communications at incidents that involve multiple agencies. As such, ICS requires that all responders use plain English, or clear text, when responding to an incident, which means that radio codes, agency-specific codes or jargon should not be used.

Incident Response Priorities

Incident objectives should be established based on the following incident response priorities:

- Priority 1: Life safety
- Priority 2: Incident stabilization
- Priority 3: Preservation of property and the environment

Incident Classification

All traffic incidents will be classified based on the expected incident duration as outlined in Chapter 6I of the MUTCD. The three incident classes to be used are as follows:

- **Major**—expected duration of more than 2 h
  - Major traffic incidents typically involve closing all or part of a roadway facility for a period exceeding 2 h. During major incidents, motorists are usually diverted through lane shifts or directed around the incident using an emergency alternate route.

  - Examples include:

    Fatal crashes or incidents that require a crash investigation
    Incidents involving a hazardous materials spill
    Overturned truck or tractor-trailer
    Structural damage
    Wildfires near the roadway

- **Intermediate**—expected duration of 30 min to 2 h
  - Intermediate traffic incidents usually require traffic control on the scene to divert motorists past the blockage. Full roadway closures might be needed for short periods during incident clearance to allow responders to accomplish their tasks.
  - Examples include:

    Rollover or multi-vehicle crashes
    Crashes involving personal injury
    Truck or tractor-trailer crashes

- **Minor**—expected duration under 30 min
  - For minor traffic incidents, it is not generally possible or practical to set up a lane closure with traffic control devices.
  - Examples include:

    Disabled vehicles
    Minor crashes (e.g., property damage only)
    Roadway debris

Appendix H
Special Corridor Traffic Decision Support and Demand Management System Concept

This appendix provides further detail for the detailed motorist information that assists the system operator to provide displays of traffic conditions for the special corridor described in Sect. 11.3.2.

Concept

Section 11.3.2 describes a special corridor (Fig. 11.5) in Philadelphia that is managed by the Pennsylvania Department of Transportation. When congestion occurs resulting from incidents or construction in the special corridor, the decision support system advises the TMC operators to take additional remedial actions including the provision of additional detailed motorist messages. These messages apply to the major alternate routes in the corridor (I-95 and Aramingo Ave.). In addition, recommendations are provided to implement appropriate signal timing plans to help accommodate traffic volume increases on the arterials to which traffic is diverted. The principal alternates include I-95 and Aramingo Ave. Other alternates include portions of Delaware Avenue, Richmond Street and Tacony Street (see Fig. 11.6).

I-95 contains existing point detectors and travel time tag readers and Aramingo Ave. has Bluetooth probe detectors. Some Bluetooth detectors are present on the other arterials. These detectors, together with sufficient traffic volumes enable detection of abnormal traffic conditions on I-95 and on Aramingo Ave. to provide displays and to identify the need for dynamic message sign (DMS) and arterial dynamic message sign (ADMS) messages. The traffic information is also used to identify the type of message to be provided. CCTV is also used to detect abnormal traffic conditions.

The operator display and messaging support concepts notify the operator of "abnormal" traffic conditions. The management concept does not seek the fastest route, but is based on the premise that on a "normal" day the traffic balances itself

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optimally, although recurrent congestion may be present. This premise is in accord with Wardrop's principles (Sect. 3.1.5). To determine what is "abnormal", the concept of travel time reliability (Appendix A) is used. Thus the operators' displays and suggested DMS and ADMS messages are targeted towards conditions that are not within the range of expected normality and that originate from conditions inside the special corridor.

Travel time reliability is a measure of how much current travel time deviates from historic, non-incident travel times for that time of day. This variation is measured in terms of a standard deviation that is compiled from historic data. Recommended operator displays and DMS and ADMS messaging recommendations are provided for the major routes (I-95 and Aramingo Ave.). I-95 has point detectors and Aramingo Ave. often has sufficient traffic volume to support enable its Bluetooth detectors to provide timely information. Algorithmic guidance for the remaining alternate routes (Richmond Street, Delaware Avenue) is not provided by this software.

Traffic Condition Development

Traffic conditions on I-95 are best identified by existing point detectors. Rapid detection is feasible during daytime periods. Analysis shows that the Bluetooth data on Aramingo Avenue is likely to provide appropriate response times for many traffic conditions. The Bluetooth data on the other arterials in the special corridor (Delaware Ave., Tacony St., Richmond St.) is slower to respond and must be considered as supplemental. No display or messaging assistance is provided for those arterials by the software.

The management approach, based on travel time reliability compares measured travel times with archived historic travel times. A historic statistic, the standard deviation (SD) is developed for each time period. If the measured travel time is outside of some upper boundary, the travel time is not "normal". The operator display indicates this abnormal travel time (ATT) condition, and a message is advised. An example of such a boundary is where 85 % of the trips do not exceed the historic travel time.

On the section of I-95 in the corridor,

$$If\ ATT > TAA + K1 * SD\ then\ the\ I\quad 95\ section\ is\ abnormal\left(AB\right) \tag{20.1}$$

where

ATT = measured travel time
TTA = average historic travel time
$K1$ = a parameter that establishes the threshold
SD = standard deviation of historic travel time

For example for an 85 % threshold, K1 = 1.04. If the situation is worse (e.g. where K is significantly greater than K1), the situation might be classified as "unusually long delay". An equation for this situation, called "unusually long delay" (ULD), is

$$If\ ATT > TTA + K2 \times SD\ then\ I - 95\ section\ is\ ULD \tag{20.2}$$

where

K2 is a larger multiplier (e.g. 1.8)

Similar considerations apply to the Aramingo Ave. section in the corridor.

Diversions between the I-95 and Aramingo Ave. routes require the use of connector arterials (Bridge St., Allegheny Ave., Castor Ave.) that may not have sufficient traffic volume to provide reliable and timely Bluetooth detection. The operation requires that these links be monitored by CCTV to identify incidents or unusual congestion that might affect the messages to be provided.

Operator Displays

A graphical display shows congestion levels on I-95 and parallel arterials using level of service (LOS) conditions.

LOS on I-95 is developed by using either speed and volume (to compute density) or occupancy from point detectors. LOS definitions are provided in Exhibit 10-7 of HCM 2010 [2]. The display shows the current congestion level using LOS as follows in Table H.1.

The display shows conditions for each segment as well as for the entire route in the corridor. Historic conditions are shown by a dashed line, current conditions by a solid line. When abnormal conditions are experienced, the solid line flashes. When long unusual travel time conditions are experienced, the solid line flashes quickly.

Similarly, the screen displays the Aramingo Ave. segments represented by the Bluetooth pairs and the entire route. Arterial LOS criteria are provided by HCM 2010 Exhibit 16-4 [2].

The screen displays will assist operators to identify the relative traffic conditions on both routes and to request the appropriate signal timing plan.

Table H.1 Congestion level conditions and corresponding operator display colors

Congestion level	LOS (consistent with Pa 511 site)	Display color
Free flowing	LOS A, B, C	Green
Moderate	LOS D	Yellow
Heavy traffic	LOS E	Red
Stop and go	LOS F	Black

DMS/ADMS Messaging Recommendations

The DMS and ADMS messages describe exception conditions on I-95 and on Aramingo Ave. They cover the entire section of the roadways between Allegheny Ave. and Bridge St. Thus the surveillance data, standard deviation and computations for AB and ULD apply to the entire section. The messages are described below by message content The recommended messaging is confined to these two routes. Since the Richmond St. alternate may not have sufficient volume to support rapid condition identification. In addition, its capacity limitations will likely limit the capability to support significant diversion. Diversions to this route will be entirely operator controlled.

Message Development

The conditions to be displayed that are unique to this algorithm are long delays (LD) and unusually long delays (ULD). Long delays are represented by abnormal (AB) conditions. The DMS have sufficient display capability to indicate abnormal congestion on both routes (using a message for each route on a single display page). Space limitations on the ADMS limit the message display to congestion on one route. ADMS can also display congestion on both routes when the types of congestion on both routes are the same. The software provides the capability to implement the following message types.

- Message Type 0—Conventional RTMC message (e.g. travel time)
- Message Type 1—Unusual delay on interstate
- Message Type 2—Unusually long delay on arterial
- Message Type 3—Long delay on interstate
- Message Type 4—Long delay on arterial
- Message Type 5—Unusually long delay on both routes
- Message Type 6—Long delay on both routes

Table H.2 below provides on possible set of message formulations that may be employed.

Messages are targeted to motorists familiar with the corridor.

Table H.2 Possible DMS/ADMS message formulations

Interstate (I-95) DMS message			Arterial (Aramingo Ave.) ADMS message		
Interstate condition	Arterial condition	Message type	Arterial condition	Interstate condition	Message type
UD	UD	1 and 2	UD	UD	5
UD	LD	1 and 4	UD	LD	2
UD	ND	1 and 0	UD	ND	2
LD	UD	3 and 2	LD	UD	1
LD	LD	3 and 4	LD	LD	6
LD	ND	3	LD	ND	4
ND	UD	0	ND	UD	1
ND	LD	0	ND	LD	3
ND	ND	0	ND	ND	0

References

1. I-95 Corridor Intelligent Transportation System, Systems Engineering Report, Version 4.0, STV, Incorporated, Aug 2014
2. HCM 2010 highway capacity manual (2010) Transportation Research Board, Washington, DC

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