METHODOLOGIES TO MEASURE AND QUANTIFY TRANSPORTATION MANAGEMENT CENTER BENEFITS

REVISED DRAFT SYNTHESIS REPORT

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS, VARIABLES AND PARAMETERS

a, b denote domain end points for link level computations
B/C = Benefit-to cost-ratio
BA = Baseline evaluation period
C = Performance characteristic index
CC = Cost of crashes
CF = Cost of fuel
CPI = Consumer price index
CPIR = Consumer price index ratio
CRA = Crashes per year
CRF = Capital recover factor
CVOSD = Cost of commercial vehicle occupant system delay
D = System mainline delay for measurement interval (vehicle hours)
DD = Domain density (veh/mi/lane)
DO = Domain ID
DWL = Weighted average link density
DWLP = Peak hour weighted average link density
E = Current evaluation period
ER = emission rate
FC = Commercial vehicle fraction of traffic volume
FD = Freeway system delay
FP = Private passenger vehicle fraction of traffic volume
FR = Traffic volume fraction of trucks carrying loads (Note: FR does not include deadheading trucks).
FT = Freeway system travel time
FUF = Fuel consumption for freeway (gallons)
FUP = Fuel consumption for intersections for 15-minute period (gallons)
G = Fuel consumption rate for freeway (gallons/mile/vehicle)
GA = Idling fuel consumption rate on arterial during control delay periods (gal/hr)
GID = cost of goods inventory delay
H= Cost coefficient
i denotes index number for probe vehicle in 5 or 15 minute period
I = Interest rate
K_1 = Average number of travelers in private passenger vehicle
K_2 = Average number of occupants in commercial vehicle
K_3 = Average weight of load in trucks carrying goods (tons)
L = Link ID
LCC = Annualized Life cycle cost
LCD = Control delay for the lane group for a vehicle
LE = Length of link, domain or probe sensing region (mi)
LG = Traffic signal lane group
LI = Intersection ID
LPG = Goods delay (ton hours)

LPP = Traveler system delay in private passenger vehicles (person hours)
LPT = Occupant delay in commercial vehicles (person hours)
LR = Number of links on route
LV = Link volume
MB = Monetary benefit of project
MP = Monetary performance of project
N15 = 15-minute evaluation period index number
N5 = 5-minute evaluation period index number
NF = Freeway evaluation time period index number (used for freeway and entry ramps)
NL = Operational system life
P = 15-minute period index
PA = Idling emissions generation rate (grams/hr)
PDC = Design and construction cost
PF = Number of time measurement intervals (T) in a 15-minute period
PHT = Peak hour throughput
PO = Pollutant Identification
POL = Freeway pollutant emission (grams)
POLA = Arterial Pollutant Emission (grams)
PR = Probe sensing region ID
PVOSD = Cost of private vehicle occupant system delay
R = Ramp index
RAT = Satisfaction index score
RD = Entry ramp delay per vehicle (hours)
REI = Uniform annual equivalent investment cost
RET = Reference vehicle travel time at an inter section for the route link
RI = Link on start of selected route
RLTT = Route link travel time at an intersection (hours)
RN – Total number of ramps
RO = Link on end of selected route
ROD = Freeway route delay (hours)
RRT = Reference ramp travel time
RT = Entry ramp travel time (hours)
RTT – Route travel time (hours)
s = Standard deviation
S = Survey respondent index number
SD = Domain speed (mph)
SI = Importance of survey characteristic
SL = Peak hour level of service
SP = Probe sensing region speed (mph)
SPR = Performance of survey characteristic
SR = Reference speed (reference speed for delay) (mph)
SSRD = Surface street route delay (hours)
SSSD = Surface street system delay (veh hr)
T = Time measurement interval (hours)

T15 = 15 minutes (.25 hours) for intersection signals and surface streets
T5 = 5 minutes (.06777 hours) for mainline and ramps
TP = Travel time as sensed by probe vehicles (hours)
TT = System mainline travel time (veh hr)
V = Roadway volume (vph)
VD = Vehicle delay (hours)
VT = Vehicle travel time (hours)
x denotes the number of vehicles in 5- or 15- minute probe vehicle sample

EXECUTIVE SUMMARY

This project provides a useable means to identify and quantify Transportation Management Center (TMC) benefits. It provides direction, guidance, methodologies, and procedures to agencies associated with monitoring, evaluating and reporting on the values and benefits of TMC operations.

The measures and methodologies developed focus on *outcomes*, although a number of *output* measures that emphasize key operations are also included. This report highlights measures used for benefit and cost analysis, including those that may be employed for freeway TMCs, traffic signal system TMCs, and corridor TMCs. Processes for freeway TMCs utilize point detector and probe detector data sources.

The literature identifying measures was reviewed and the following classes of measures were identified:

- System delay
- Safety
- Fuel consumption
- Throughput
- Emissions
- Service quality/user perceptions
- Equity
- Service patrol
- Incident clearance time
- Response to weather situations
- Life cycle cost
- Database to provide motorist information

Most of the classes contain more than one measure, and many of the measures will use input data from freeway management systems and crash databases.

The methodologies require that the identification of a data structure that may be embraced by freeway TMCs whose software has been developed using data structures that differ from one another. Research of the literature revealed little commonality among TMCs in the spatial references that are used to collect and aggregate detector data. Accordingly, a reference structure that systematizes the spatial aggregation of data collected by point detector stations and probe detector locations has been introduced.

Because the research showed that most freeway TMCs used a similar data structure—characterized by data storage by 5-minute, 15-minute, hourly, daily, and yearly periods—the

findings of the project recommend this temporal structure for the freeway evaluation methodologies. Signal system measures will use a 15-minute span for the earliest data storage period.

This document describes in detail the algorithms and processes to compute many of the measures. In the case of system measures, those measures required for benefit-cost analysis—such as system-wide vehicle delay—require measurements of both volume and speed or travel time for each travel link. Other measures such as motorist travel time and travel time reliability require measured speed or travel time.

The report also discusses the effects of bias errors and random errors. Bias errors are most significant in conducting initial evaluations, such as before-and-after studies, for significant ITS improvements. Random errors, most important for year-over-year evaluations, are functions of the quantity of data collected and the size of the network under evaluation.

In addition, the report describes a methodology to obtain the benefit-to-cost ratio. The methodology employs annualized capital and maintenance costs and includes the following benefits:

- Reduction in private vehicle occupant system delay
- Reduction in commercial vehicle occupant system delay
- Reduction in goods inventory delay
- Reduction in cost of crashes
- Reduction in fuel cost.

Examples of agency presentations of TMC benefits are provided.

The methodologies described in the report are only one element of the evaluation process. The relationship of these methodologies to the entire evaluation process is discussed.

1. INTRODUCTION

1.1 Purpose of Project

"What you measure affects what you do. If you don't measure the right thing, you don't do the right thing."[1]

The Transportation Management Centers (TMC) considered in this project include those that are normally responsible for the operation and management of ITS field equipment, freeway management, signal systems management, incident management, and corridor management (including incident management). The purpose of this project was to identify key measures that can be used to implement operational strategies and the methodologies that can be used to implement those measures, including structures for organizing the data and the algorithms and processes required.

The Archived Data Management Systems (ADMS) that provide a key element for this project support the following TMC functions (Federal Highway Administration 2005):

- Developing operational strategies
- Planning for operations
- Long-term planning
- Policy investment decision making

When coupled with performance measures that use this data, the results from applying the methodologies addressed provide the basis for developing reports and presentations that justify project investment to decision makers and the public. Such results also form the basis for future resource allocations and improvements in operations. In many cases agencies develop reports that provide results to the public on the performance of TMCs and the ITS that that they manage.

This project emphasizes the computation of measures from data that is commonly available to TMCs from traffic detectors in the systems managed by those TMCs. Other data, such as crash record data, is also required for cost-benefit evaluations. This report focuses on and emphasizes outcome-oriented measures rather than output-oriented measures.

The contents of the report are as follows:

- Section 1 – Introduction to the report.

[1] Peter S. Goodman quoting Joseph E. Stiglitz, Nobel Prize winning economist, in "Emphasis on Growth Is Called Misguided," the *New York Times*, September 22, 2009. Available at: http://www.nytimes.com/2009/09/23/business/economy/23gdp.html

- Section 2 – Transportation Management Center Functions, and Examples of Systems for Performance Evaluation.
- Section 3 – Performance Measures. A representative set of performance measures is provided.
- Section 4 – Spatial and Temporal Data Structures. This section describes the spatial and temporal data structures to be employed by the processes used for development and computation of the measures.
- Section 5 – Methodologies to Develop Measures. Recommended measures are identified and the algorithms and processes for their computation are provided.
- Section 6 – Techniques to Support Data Collection and Archival. This section describes the following:
    - Technologies for collecting data
    - Data quality control
    - Automation of surface street data collection
    - Standards.
- Section 7 – Methodologies to Develop Measures. Algorithms and other methodologies for obtaining the following classes of measures are provided:
    - Travel time and delay
    - Throughput
    - Safety
    - Fuel Consumption
    - Emissions
    - Service quality and user perceptions
    - Characteristics of incidents
    - Service patrol measures
    - Responses to weather situations
    - Evaluation of motorist information databases.
- Section 8 – Benefit and Cost Analysis. A methodology to develop the benefit to cost ratio and techniques for alternative presentations of benefit and cost data are described.

Three Appendices support these sections.

2. TRANSPORTATION MANAGEMENT CENTER FUNCTIONS AND EXAMPLES OF PERFORMANCE EVALUATION

2.1 TMC Functions

The goals and initiatives established by the agencies for the TMC determine the TMC functions and the measures that evaluate these functions. Appendix A provides one agency's flow sequence for this process.

Table 1 identifies many of the possible functions of TMCs by the types of facilities managed. In later sections these functions will be related to performance measures and the data and parameters needed to implement those measures.

2.2 Examples of Performance Evaluation Systems

Performance evaluation systems may take either of the following forms:

- A system that is integrated with the traffic management system.
- A system that is separate from the traffic management system but derives its data from the traffic management system. In some cases a single performance evaluation system serves a number of the agency's TMCs and traffic management systems.

Performance evaluation systems may include the Archived Data user service functions of the National ITS Architecture (National, nd).

Table 1 provides key functional characteristics for several performance evaluation systems.

Table 1. TMC Functions

TMC Functions	Facilities Managed by TMC				Comments
	Freeways	Signal Systems and Surface Streets	Corridors[a]	Special Facilities[b]	
Active Traffic Management (Note 1)	√		√	√	Ref: Fuhs, 2010
Speed harmonization	√			√	
Temporary shoulder use	√			√	
Queue warning	√			√	
Dynamic truck restrictions	√			√	
Dynamic routing	√		√	√	
Dynamic lane markings	√			√	
Data Analysis and Warehousing	√	√	√	√	Note 3
Incident Response					
Development of incident management plans	√	√	√	√	
Selection of incident management plan	√	Where TMCs have this responsibility	√	√	
Assistance to emergency service providers	√		√	√	
Maintenance					Note 3
Maintenance of TMC facilities	√	√	√	√	
Management of field equipment maintenance	√	√		√	Field equipment maintenance management for corridors depends on division of responsibilities
Configuration management of TMC and ITS facilities	√	√	√	√	
Coordination of roadway maintenance and construction	√	√		√	
Motorist Information					
Management of information for ITS field devices	√	Where agency operates devices	√	√	

TMC Functions	Facilities Managed by TMC				Comments
	Freeways	Signal Systems and Surface Streets	Corridors[a]	Special Facilities[b]	
Provision of information to external services		Sometimes			
Planning	√	√	√	√	Note 3
Ramp Management and Conventional Lane Management					
Ramp metering	√		√	√	
Ramp closure	√		√	√	
Conventional lane controls	√	√	√	√	
Security					Note 3
Security in TMC	√	√	√	√	
Security of ITS field devices	Possibly	Not often	Possibly	Usually	
Other security functions	Possibly	Not often	Possibly	Usually	Security monitoring of other DOT facilities
Service Patrol	√			√	
Signal Timing					
Signal timing plan development		√	Note 2		
Signal timing operations management		√	Note 2		
Emergency vehicle signal preemption		√	Note 2		
Special Functions					Note 3
Roadway ventilation				√	Reference: Transportation...
Roadway fire detection and suppression				√	Reference: Transportation...
Other SCADA functions				√	May include pumping, electrical system control, motorist telephone system (Reference: Transportation...)
Training and Support	√	√	√	√	Note 3

TMC Functions	Facilities Managed by TMC				Comments
	Freeways	Signal Systems and Surface Streets	Corridors[a]	Special Facilities[b]	
Transit Assists					
HOV bypass of metered lanes	√		√	√	
Transit signal priority		√	Note 2		
Weather Monitoring	√	Not usually	√	√	

[a] Includes TMCs with responsibility for operations on alternate routes
[b] Includes bridges and tunnels
Notes:
1 Active traffic management includes speed harmonization, temporary shoulder use, queue warning, dynamic merge control, construction site management (ATM methodologies), dynamic truck restrictions, dynamic routing and traveler information, and dynamic lane markings. Separate lines will be provided for each strategy.
2 Responsibility for timing plan development and operations rests with agency responsible for traffic signal systems. This function is applicable when freeway and signal system TMCs share a common facility.
3 These are support functions. They relate to outputs rather than to outcomes. No measures are provided for these functions in Section 3.

Table 2. Characteristics of Representative ITS Performance Evaluation Systems

System	Key Data Processing Features	Data Collection Periods	Data Source	Key Measures Provided
Caltrans Freeway Performance Measurement System (PeMS) (Urban Crossroads 2006), (Varaiya, nd)	• Detects Missing and bad data • Corrects missing and bad data through imputation techniques. • Computes speed by means of g factor calculations.[a] • Estimates truck volumes.	Collects data at 30 second intervals, then aggregates to 5 minute and hourly periods.	- Inductive loop detectors, generally single loop detectors in each lane. - Incident data from California Highway Patrol. - Weather data.	Volume, occupancy, speed, congestion delay, vehicle-miles-traveled, travel times.
Washington State Traffic Data Acquisition and Distribution System	• Contains flags to alert user to suspect data. • Uses ladder algorithm to compute travel time.[b]	Collects data at twenty second intervals, then aggregates to 5 minute data.	- Inductive loop detectors, generally single loop detectors in each lane. Some stations have loop traps. - Automatic vehicle location data.	Volume, occupancy, speed, travel time, travel time reliability.
Minnesota TMC (Martin and Wu 2003, Archived 2005)	• Contains flags to alert user to suspect data.	Collects data at twenty second intervals, then aggregates to 5 minute data.	Single inductive loop detectors in each lane.	
Florida Statewide Traffic Engineering Warehouse for Regional Traffic Data (STEWARD) (University of Florida 2008). Designed as a statewide system that links to each District	• Strong integration with roadway and detector characteristics. • Data completeness test. • Data threshold checks.	Collects data at 20 second intervals, aggregates to 5, 15 and 60 minute periods.	• Mainline and ramp detectors. • Adaptable to all detector types.	Volume, occupancy speed, lane volume balance, effective vehicle length,[c] input/output balance,[d] vehicle miles, vehicle hours, delay, kinetic energy,[e] level of service.

[a] Additional information is provided in Table 6.1

[b] The g factor represents the effective length of the vehicle a the tuning of the loop detector. It varies over the course of time. An algorithm is in PeMS to provided to calculate the g factor as a function of time.

[c] The ladder algorithm is discussed in Section XX

Effective vehicle length is vehicle length + detection zone length.

[d] Input/output balance is volume entering and leaving each system link.

[e] Kinetic energy is proportional to the product of speed and volume.

3. PERFORMANCE MEASURES

The following general types of measures may be considered:

- Outcome oriented
- Output oriented

Outcome-oriented measures are likely to be of interest to highway users and high-level decision makers because they include such universally high-priority issues as delay and safety. Measures that are components of benefit vs. cost analysis are also outcome measures.

Outputs are the direct results of actions taken by the TMC. These outputs in turn result in outcomes. An extensive description of both outcome and output measures is provided by Park (2005).

Many TMCs utilize measures of outputs as well as outcomes, although the specific measures used vary among TMCs. The number of incident management-related messages is an example of an output measure.

Park (2005) and Shaw (2003) are key sources for descriptions of numerous measures. This project selected those measures that were considered to be most useful and popular. While the focus was on outcome-oriented measures, a number of commonly used output measures were included as well. The criteria for measure selection included the following:

- Data sources must exist, with an emphasis on automated data sources.
- The measure must lend itself to algorithmic expression or to some other form of measurement, such as scales for attitudinal measures.
- In the case of measures for benefit vs. cost analysis, to avoid double-counting a benefit, the measures must not be redundant.
- The measure should be intuitively credible.

Table 3 describes criteria that may be used to evaluate measures Shaw (2003).

Table 3. Performance Measures Comparison Criteria

General Criteria	Specific Criteria
Clarity and simplicity	The measure is simple to present, analyze, and interpret
	The measure is unambiguous
	The measure's units are well defined and quantifiable
	The measure has professional credibility
	Technical and nontechnical audiences understand the measure
Descriptive and predictive ability	The measure describes existing conditions
	The measure can be used to identify problems
	The measure can be used to predict change and forecast condition
	The measure reflects changes in traffic flow conditions only
Analysis capability	The measure can be calculated easily
	The measure can be calculated with existing field data
	There are techniques available to estimate the measure
	The results are easy to analyze
	The measure achieves consistent results
Accuracy and precision	The accuracy level of the estimation techniques is acceptable
	The measure is sensitive to significant changes in assumptions
	The precision of the measure is consistent with planning applications
	The precision of the measure is consistent with an operation analysis
Flexibility	The measure applies to multiple modes
	The measure is meaningful at varying scales and settings.

Figure 1 shows the Texas DOT balanced scorecard approach to developing performance measures (Shaw 2003). Agencies often define measures for highway system operations, and while these operations may include TMCs, they usually cover the more general functions of the highway network, such as the measures used by Florida DOT, which are shown in Table 4 (Park 2005).

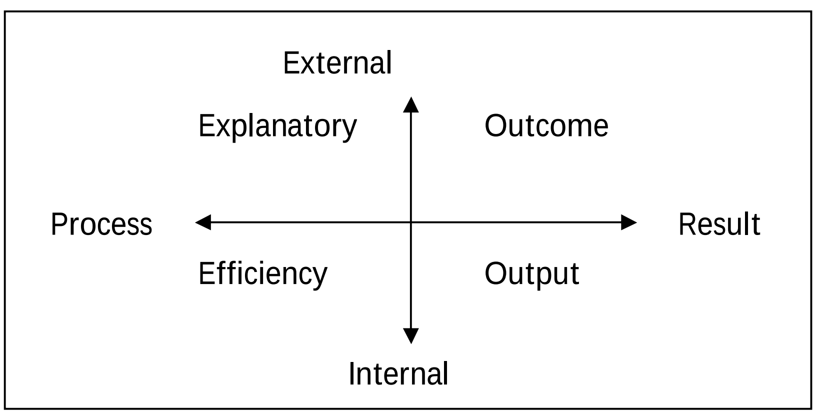


Figure 1 Texas DOT's Balanced Scorecard Approach

Shaw (2003) and Park (2005) provide extensive discussions of measures used by agencies as well as the equations and computational procedures that may be used to develop a number of these measures. While a number of agencies do employ these general techniques, the specific schemes used by these agencies these systems often differ.

Table 4. Measures Used by Florida DOT

Dimension of Mobility	Mobility Performance Measures	State Highway System	Florida Intrastate Highway System	Florida Intrastate Highway System Corridors	Metropolitan Highway Systems	Definitions[1]
Quantity of Travel	Person miles traveled	•	•	•	•	AADT * length * vehicle occupancy
	Truck miles traveled	•	•	•	•	AADT * length * % trucks
	Vehicle miles traveled	•	•	•	•	AADT * length
	Person trips				•	Total person trips
Quality of Travel	Average speed	•	•	•		Average speed[2] weighted by PMT
	Delay	•	•	•	•	Average delay
	Average travel time			•		Distance / speed[2]
	Average trip time				•	Door to door trip travel time
	Reliability			•	•	% of travel times that are acceptable
	Maneuverability			•		Vehicles per hour per lane
Accessibility	Connectivity to intermodal facilities	•	•	•	•	% within 5 miles (1 mile for metropolitan)
	Dwelling unit proximity		•	•	•	% within 5 miles (1 mile for metropolitan)
	Employment proximity		•	•	•	% within 5 miles (1 mile for metropolitan)
	Industrial/warehouse facility proximity		•			% within 5 miles
	% miles bicycle accomodations	•			•	% miles with bike lane/shoulder coverage
	% miles pedestrain accomodations	•			•	% miles with sidewalk coverage
Utilization	% system heavily congested	•	•	•	•	% miles at LOS E or F
	% travel heavily congested	•	•	•	•	% daily VMT at LOS E or F
	Vehicles per lane mile	•	•	•	•	AADT * length / lane miles
	Duration of congestion	•	•	•	•	Lane-miles-hours at LOS E or F

[1] Definitions shown are generally for daily analysis. Calculations for the peak are based on prevailing conditions during the typical weekeday 5:00 to 6:00 PM peak.
[2] Speed based on models using the HCM or field data.

This project focuses on influencing the development, use, and implementation of performance measures, data collection and management, monitoring, evaluation of effectiveness, and reporting on the benefits of TMCs and their traffic management-related functions and services.[2] Therefore, this document frames this information in a way that provides agencies that currently have management systems—but that do not have a robust evaluation methodology—with specific data structures, including algorithms and computational procedures, that will allow them to compute measures that satisfy their needs and objectives.

The project includes measures that may be used to provide monetary benefits for a benefit-cost analysis. The classes of monetary benefits resulting from ITS improvements, and a typical breakdown for those benefits on an urban freeway, are shown in Table 5.

[2] FHWA Scope of Work for Methodologies to Measure and Quantify Transportation Management Center Benefits.

Table 5. Example of Percentage of ITS Monetary Benefits for Benefits Classes[3]

Benefit Class	Benefit Percentage
Private vehicle occupant delay	66.1
Commercial vehicle occupant delay	4.3
Cost of crashes	13.1
Value of delay for goods	8.0
Fuel cost of delay	8.6
TOTAL	100

Table 6 provides a representative set of measures that may be used for ITS performance evaluation. Table 7 relates the outcome oriented TMC functions in Table 1 to the measures in Table 6.

[3] Calculated using Design ITS evaluation model. See http://designints.com for further information on this model.

Table 6. Measures of Effectiveness

Type of Measure	Sub-Measure	Identifier	Quantity measures or Description	Benefit vs. cost analysis	Traffic flow quality and safety measures	Benefits perceived by the public	Measure for TMC operations performance
System Delay Measures		D					
	Vehicle system delay*	D.1	Veh. hrs. per year Archived on a link, ramp and intersection basis and aggregated to the system level	√	√	√	√
	Private passenger vehicle occupant delay*	D.2	Person hrs. per year	√	√	√	
	Commercial vehicle occupant delay*	D.3	Person hrs. per year	√	√	√	
	Goods inventory delay*	D.4	Ton hrs. per year	√			
	Transit vehicle occupant delay	D.5	Person hrs. per year	√		√	
Safety		S					
	Freeway crashes*	S.1	Crashes per million vehicle miles per year. Archived on a link and ramp basis and aggregated to the system level	√	√		√
	Secondary crashes	S.2			√		√
	Crashes at intersections*	S.3	Crashes per million vehicles entering intersection	√	√		√
	Property damage only crashes	S.4		√	√		√
	Fatal crashes	S.5	Fatal crashes per million vehicle miles Fatal crashes per million vehicles entering intersection	√	√		√

Type of Measure	Sub-Measure	Identifier	Quantity measures or Description	Benefit vs. cost analysis	Traffic flow quality and safety measures	Benefits perceived by the public	Measure for TMC operations performance
	Injuries resulting from crashes	S.6	Injury crashes per million vehicle miles Injury crashes per million vehicles entering intersection	√	√		√
	Work zone related crashes	S.7	Work zone crashes for the TMC coverage region		√		√
	Pedestrian crashes	S.8	Pedestrian injuries/deaths per million vehicles entering intersection		√		√
	Safety performance index	S.9	Weighted crash frequency and severity		√		√
*Fuel consumption		F	Gallons/year	√		√	
Throughput		T					
	Freeway throughput	T.1	Vehicle miles per year during peak hour		√		
	Intersection throughput	T.2	Vehicles per peak hour at an intersection		√		
Emissions		E	Kg per year for each emission constituent				
Service quality/user perceptions		Q					
	Route travel time	Q.1	Peak hour route travel time (hours)		√	√	√
	Route travel time reliability	Q.2	Buffer index, planning time index		√	√	√
	User satisfaction	Q.3	User satisfaction scales and surveys			√	√
	User satisfaction	Q.4	Complaints received by agency			√	√

Type of Measure	Sub-Measure	Identifier	Quantity measures or Description	Benefit vs. cost analysis	Traffic flow quality and safety measures	Benefits perceived by the public	Measure for TMC operations performance
Equity		U					
	User perception	U.1	User complaints received by agency			√	√
	Gini Coefficient or Lorenz Curve	U.2	Users relatively disbenefitted / total users				
Service patrol measures		M					
	Service patrol assists	M.1	Assists/year			√	√
	Quality of service	M.2	Patrol coverage periods (hours per year)			√	√
	Quality of service	M.3	Average motorist waiting time (minutes)			√	√
	Quality of service	M.4	Extent of roadway serviced (centerline miles)			√	√
	Rating by public	M.5	Rating scale			√	√
Incident clearance time	Average incident clearance time	C	Annual average incident clearance time for moving lanes minutes	√			√
Response to weather situations	Response time to provide actionable information to motorists	W	Average time in minutes from receipt of information by RWIS or other means to provide motorist information and to provide information to other response services		√	√	√
Life Cycle cost*		P	Dollars per year	√			√
Database to provide motorist information	See Section 5.9	I	Rating scales		√	√	√

* Measures used for benefit and cost analysis

Table 7. Relationship of TMC Functions to Measures of Effectiveness

Type of Measure	Sub-Measure	Identifier	TMC Functions							
			Active Traffic Management	Incident Response	Motorist Information	Ramp Management and Conventional Lane Management	Service patrol	Signal Timing	Transit Assists	Weather Monitoring
System Delay Measures		D								
	Vehicle system delay*	D.1	√	√	√	√	√	√	√	√
	Private passenger vehicle occupant delay*	D.2	√	√	√	√	√	√		√
	Commercial vehicle occupant delay*	D.3	√	√	√	√	√	√		√
	Goods inventory delay*	D.4	√	√	√	√	√	√		√
	Transit vehicle occupant delay	D.5	√	√	√	√	√	√	√	√
Safety		S								
	Freeway crashes*	S.1	√	√	√	√	√			√
	Secondary crashes	S.2	√	√	√	√	√			√
	Crashes at intersections*	S.3			√			√		√
	Property damage only crashes	S.4	√	√	√	√	√	√		√
	Fatal crashes	S.5	√	√	√	√	√	√		√
	Injuries resulting from crashes	S.6	√	√	√	√	√	√		√
	Work zone related crashes	S.7	√	√	√	√	√			√
	Pedestrian crashes	S.8								
	Safety performance index	S.9	√	√	√	√	√	√		√
Fuel consumption*		F	√	√	√	√	√	√	√	√

Type of Measure	Sub-Measure	Identifier	TMC Functions: Active Traffic Management	Incident Response	Motorist Information	Ramp Management and Conventional Lane Management	Service patrol	Signal Timing	Transit Assists	Weather Monitoring
Throughput		T								
	Freeway throughput	T.1	√	√	√	√	√			√
	Intersection throughput	T.2						√		√
Emissions		E	√	√	√	√	√	√	√	√
Service quality/user perceptions		Q								
	Route travel time	Q.1	√	√	√	√	√	√	√	√
	Route travel time reliability	Q.2	√	√	√	√	√	√	√	√
	User satisfaction	Q.3	√	√	√	√	√	√		√
	User satisfaction	Q.4	√	√	√	√	√	√		√
Equity		U								
	User perception	U.1				√			√	
	Gini Coefficient or Lorenz Curve	U.2				√			√	
Quality of assistance to motorists		M								
	Service patrol assists	M.1					√			
	Quality of service	M.2					√			
	Quality of service	M.3					√			
	Quality of service	M.4					√			
	Rating by Public	M.5					√			
Incident clearance time	Average incident clearance time	C	√	√	√	√	√			√

Type of Measure	Sub-Measure	Identifier	TMC Functions							
			Active Traffic Management	Incident Response	Motorist Information	Ramp Management and Conventional Lane Management	Service patrol	Signal Timing	Transit Assists	Weather Monitoring
Response to weather situations	Response time to provide actionable information to motorists	W	√	√	√	√		√		√
Life Cycle cost*		P	√	√	√	√	√	√	√	√
Database to provide motorist information	See Section 5.9	I	√	√	√					√

*Measures used for benefit and cost analysis

4. SPATIAL AND TEMPORAL DATA STRUCTURES

4.1 Data Capabilities of Freeway Management Systems and Traffic Signal Systems

The following describes a set of data collection, storage and data manipulation capabilities that are common to most Freeway Management Systems (FMS):

- *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 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).

Time periods for data collection and archiving that are commonly employed by FMS are shown in Table 8.

Table 8. Data Periods

Data Period Description	Typical Period	Examples of Use
Discrete data element	Each event	Crash report, Incident report, equipment event or failure.
Data sampling or collection period	20 seconds to 1 minute	Traffic detector collection period for field detectors.
Action periods	1 minute to 10 minutes	Data accumulation periods for TMC actions such as traffic map displays, data filter updates, system-wide ramp metering, incident management, automatic DMS messaging and system tuning.
Common reporting and analysis interval	5 minutes 15 minutes One hour	Studies of traffic patterns by TMC personnel and others.
Daily reports	One day	Daily data consolidations, planning
Annual reports	One year	Performance evaluations, planning

An example of the general relationship between data uses and data characteristics is shown in Table 9 (Dailey, et al 2002).[4]

[4] The notation PSRC in Table 9 denotes the region's Metropolitan Planning Organization.

Table 9. Data Uses and Data Characteristics

Type of Data Use	User	Data Used	Source
Long-Term Planning	PSRC	AADT Volume HPMS VMT 24 Hr. & Peak Volume Counts 24 Hr. Volume Counts	Annual Traffic Report WSDOT Data Office Ramp & Roadway Report City & County Tube Collections
	WSDOT Planning Office	Volume Counts Forecasted Efficiency Data	Annual Traffic Report PSRC
Performance Monitoring	PSRC	AADT Volume 24 Hr. & Peak Volume Counts 24 Hr. Volume Counts	Annual Traffic Report Ramp & Roadway Report City & County Tube Collections
Long-Range Planning & Project Planning	WSDOT Transportation Data Office	AADT Volumes Projected Volume Data Turning Movements Vehicle Occupancy Vehicle Classification Specific Volume Counts Travel Time & Speed Transit Use Pedestrian & Bicylce Counts	Annual Traffic Report PSRC NW Region Planning Office NW Region Planning Office NW Region Planning Office NW Region Planning Office Consultants Consultants Consultants
Performance Monitoring	WSDOT Office of Urban Mobility	Volume Counts Incident Data	TRIPS system TRIPS system
Research	TRAC, TRANSNOW, & University of Washington Researchers	20 sec., 1 min., 5 min., 15 min. Volume Counts & Lane Occupancy Peak Volume Counts AADT Volumes Speed Vehicle Classification Vehicle Occupancy	TSMC Ramp & Roadway Report Annual Traffic Report ADCs, autoscope WSDOT Data Office, ADCS, autoscope TRAC

This project develops methodologies for employing FMS data to generate many of the evaluation measures described in Table 6. Five minute data is taken as the building block for freeway-based measures that develop or utilize travel time or delay. Figure 2 shows an example of a data aggregation structure for freeway point detector data (Turner et al 2004).

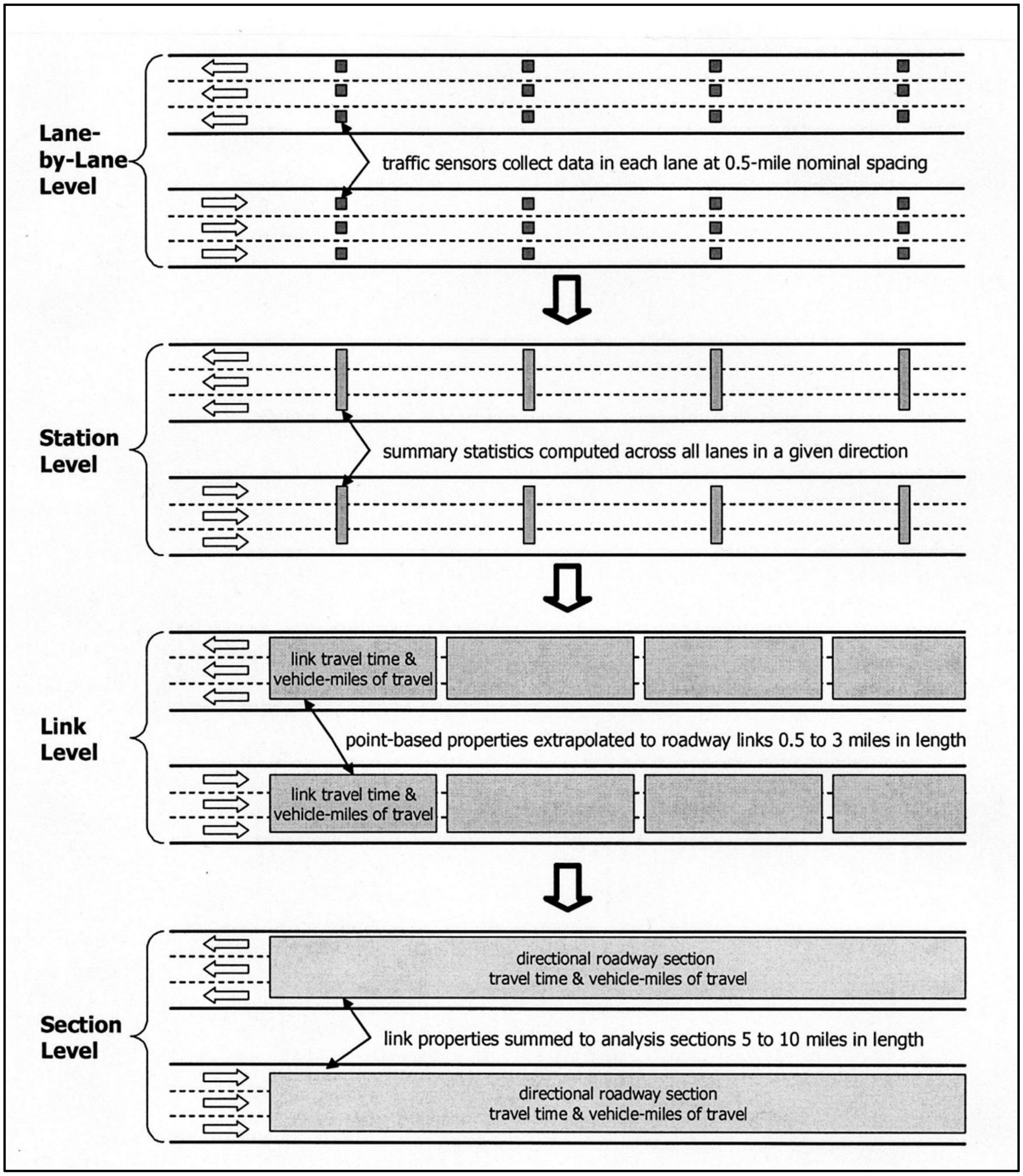


Figure 2 Example of Data Aggregation Structure

Although the capability exists in traffic signal systems to collect and archive volume, occupancy, and speed data (at a particular location), other than some adaptive signal systems, traffic signal systems generally do not have the capability to provide data for the measures needed to obtain key parameters such as travel time and delay. Section 6 describes some recently developed techniques that may be employed to provide these measures. To be consistent with independent volume measures such as automatic traffic recorders and manual count collections, a 15-minute period is recommended as the basic surface street evaluation interval.

4.2 Spatial Requirements and Data Structures for Evaluation

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. An example of a construct that might be used for evaluation purposes includes the following:

- Links:
  - Freeway link - For each type of roadway service (e.g., general traffic, HOV), a link consists of a unidirectional roadway section between entry and exit points. In some cases, sublinks may be used to denote such features as service area entry and exit points, or DMS locations.
  - Surface street link – In many cases, models used for signal timing purposes define links as the unidirectional roadway section between intersections on the arterial or in the grid network of interest. In some cases, the entire section between signalized intersections or between the intersection upstream of a signalized intersection and the next upstream signalized intersection may be defined as a link.
- Signalized Intersection – Signalized intersections are often evaluated on a stand-alone basis.
- Route Segment – A route segment is a set of links defined for evaluation purposes. A *route* may consist of a set of route segments.
- Network – A network is a set of geographically bounded interconnected route segments and isolated intersections.
- Corridor – A corridor is a subset of route segments that emphasizes directional travel patterns. Corridors often stress alternate route or alternate mode choices.

Freeway management systems generally contain a software capability to provide a reference framework to relate detectors to the link structure for the freeway network. If the freeway management system does not have such a capability, the evaluation methodology must provide it. A reference system that is based on traffic flow entry and exit points is preferred because:

- It simplifies the evaluation methodology. Freeway volume is discontinuous at these points, and these volume changes often result in speed changes at these points.
- Evaluations are most meaningful when the evaluation boundaries are easily identifiable.
- These boundaries are consistent with the way motorist information is usually provided.

- Other traffic information systems often use standardized identification formats based on these boundaries. Traffic Message Channel Codes are based on this concept and are commonly used by information service providers (INRIX 2009).

An example of a reference system that meets this requirement is shown in Figure 3. 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 and dynamic message signs[5] (DMS) 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 and at DMS. Where a link encompasses more than one detector station, domain boundaries are used to separate the regions for which each detector station will be employed. Note that no detector in Figure 3 lies within the physical boundaries of Domain 4; that domain obtains its information from Detector Station 4. Section 6 discusses detector deployment requirements.

Figure 4 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 the system-based measures required for benefit-cost analysis. In order to obtain system-wide delay and travel time measures with probe detection, at least one source of volume per link is required. Technologies for implementing probes and other sensors are discussed in Section 6.

4.3 Temporal Relationships

For archiving purposes, freeway management system volume, speed, and occupancy data from point detectors may be stored at 5-minute intervals and aggregated into 15-minute and 1-hour intervals as in the Florida Steward system (University of Florida 2008). The 5- and 15-minute intervals provide convenient processing intervals for many of the delay related computations described in Section 5. Building on these concepts, a useful methodology develops these measures using the spatial/temporal relationship shown in Table 10. The methodology described uses the domain concept (Figures 3 and 4) as the basis for freeway mainline data accumulation.

[5] Although not strictly needed for the detector to link relationship, the diagram includes DMS in the domain definitions to facilitate the implementation of messaging using a common reference frame.

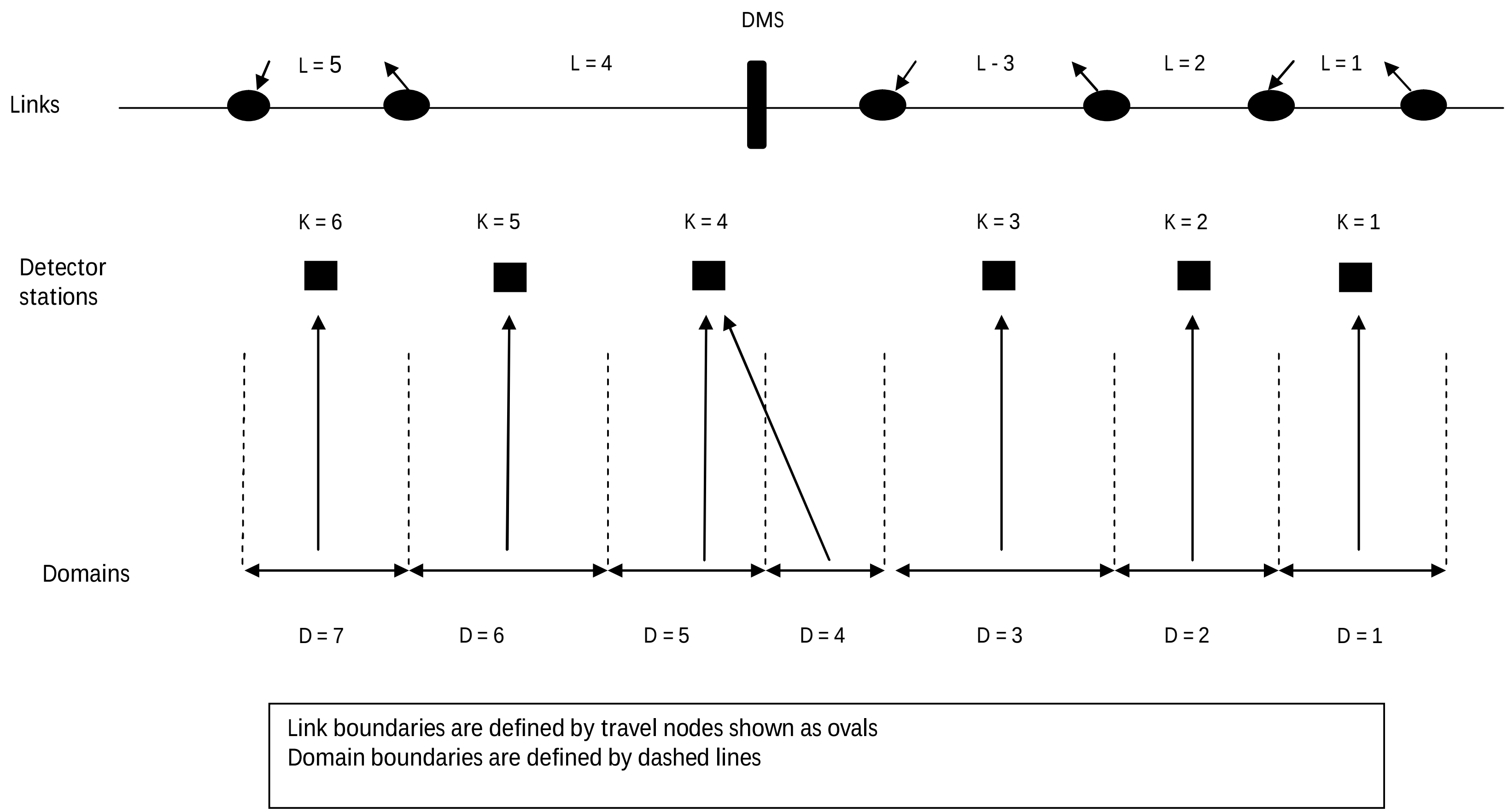


Figure 3 Example of link, domain and detector station relationships

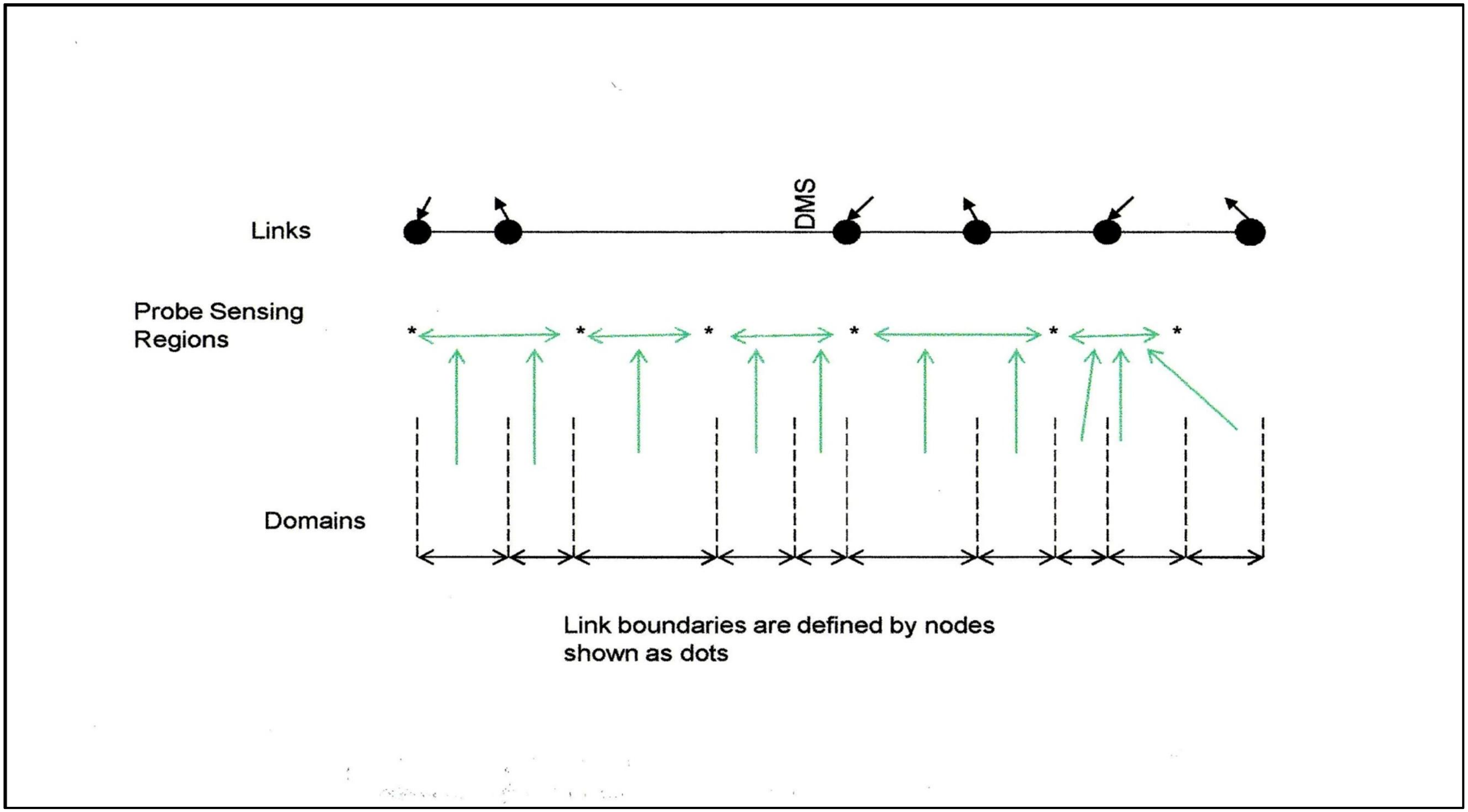
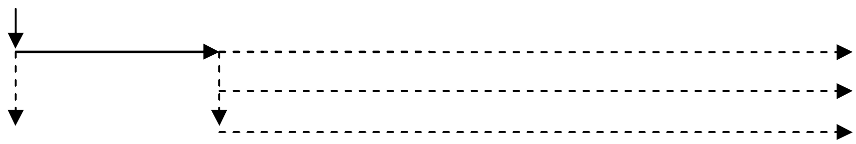


Figure 4 Example of Link, Domain and Probe Site Relationships

Table 10. Data Accumulation Methodology

Spatial Relationship	5 minutes	15 minutes	One hour	One day	One year
Domain					
Link					
Route					
System					



Detector data is used to obtain these measures at the domain level for 5-minute periods and is accumulated at the link level. The 15-minute 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-minute period is shown by the solid trace. 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-minute data may be aggregated by time according to the particular spatial relationship required for the purpose.

5. METHODOLOGIES FOR DEVELOPING MEASURES

This section describes the methodologies used to select and obtain many of these measures. In many cases, the data structures described in this section are employed. (Note that Table 6 identifies the measures examined in this study.)

5.1 Delay and Travel Time Measures

5.1.1 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.

Many of the measures in Table 6 involve the computation of travel time and delay. *System delay* is the sum of freeway mainline delay, freeway ramp delay, and intersection delay for all vehicles. *System travel time* has a similar relationship. *Vehicle travel time and delay* consider these quantities on an individual trip basis.

The relationships provided below describe the requirements for obtaining freeway mainline data. Symbol definitions are provided in the front matter on page vii as well as in the following discussion.

5.1.1.1 Mainline Delay and Travel Time Evaluation for Point Detectors

Domain System Travel Time

$$TT(DO,N5) = T5 \cdot V(DO,N5) \cdot LE(DO)/SD(DO,N5) \qquad (5\text{-}1)$$

Where:
TT = System mainline travel time (veh hr)
DO = Domain ID
N5 = 5-minute evaluation period index number
T5 = 5 minutes (.06777 hours) 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 SD represents weighted speed (Park 2005). 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

$$If\ (TT(DO,N5) - T5 \cdot V(DO,N5)\ \cdot LE(DO)/SR(DO)) > 0\ then\ D(DO,N5) = (TT(DO,N5) - \ T5\ \cdot V(DO,N5)\ \cdot LE(DO)/SR(DO))\ \ else\ \ D(DO,N5)\ = 0 \quad (5\text{-}2)$$

Link system travel time

$$TT(L,N5) = \ \sum_{DO=a}^{b} TT(DO,N5) \quad (5\text{-}3)$$

Where

L = Link ID

Link system travel time for 15-minute periods

$$TT(L,P) = \ \sum_{NF=N5}^{NF+3} TT(L,N5) \quad (5\text{-}4)$$

Where

P = 15-minute period index

NF = NF 5-minute index at the beginning of the 15-minute period

Link system delay

$$D(L,N5) = \ \sum_{DO=a}^{b} D(DO,N5) \quad (5\text{-}5)$$

Where

D = System mainline delay for measurement interval (vehicle hours)

Link system delay for 15-minute periods

$$D(L,P) = \ \sum_{NF=5}^{NF+3} D(L,N5) \quad (5\text{-}6)$$

Domain vehicle travel time

$$VT(DO,N5) = T5\ \cdot\ LE(DO)/SD(DO,N5) \quad (5\text{-}7)$$

Where

VT = Vehicle travel time (hours)

Domain vehicle delay

$$If\ (VT(DO,N5) - T5\ \cdot LE(DO)/SR(DO) > 0)\ then\ VD(DO,N5) = (VT(DO,N5) - T5\ \cdot\ LE(DO)/SR(DO))\ \ else\ VD(DO,N5)\ = 0 \quad (5\text{-}8)$$

Where

VD = Vehicle delay (hours)

SR = Reference speed (reference speed for delay) (mph)

Link vehicle travel time

$$VT(L, N5) = \sum_{DO=a}^{b} VT(DO, N5) \quad (5\text{-}9)$$

Link vehicle travel time for each 15-minute period

$$VT(L, P) = \sum_{NF=N5}^{NF+3} VT(L, N5) \quad (5\text{-}10)$$

Link vehicle delay

$$VD(L, NF) = \sum_{DO=a}^{b} VD(DO, N5) \quad (5\text{-}11)$$

Link vehicle delay for each 15-minute period

$$VD(L, P) = \sum_{NF=N5}^{NF+3} VD(L, N5) \quad (5\text{-}12)$$

5.1.1.2 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 Figure 4, 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 Equations 5-13 and 5-14. 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 equations 5-7 through 5-12 at the 5-minute level. It is used for probe detection in place of SD in Equations 5-1 and 5-7.

$$TP(PR, T5) = \frac{1}{x} \cdot \sum_{i=1}^{x} TP(i) \quad (5\text{-}13)$$

$$SP(PR) = LE(PR)/TP(PR, T5) \quad (5\text{-}14)$$

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 minute probe vehicle sample

SP = Probe sensing region speed (mph)

RRT = Reference ramp travel time

Probe detection technologies are discussed in Section 6.

In order to develop system delay and system travel time measures, the volume variable required by equations 5-1 and 5-2 must be obtained. A source of link volume data such as a point-detector station is required.

5.1.1.3 Entry Ramp Travel Time

Unlike the mainline, most ITS do not provide an automatically based sensing methodology for obtaining entry ramp time and delay.   Ramp data (RT), if employed, is most conveniently accumulated on a 15-minute basis, considering the ramp as a link.

5.1.1.4 Freeway System Travel Time and Delay

Freeway travel time and delay is the sum of mainline travel times and (optionally) ramp travel times and delays. Computation on a 15-minute basis is convenient for further development of measures.

Freeway system travel time

$$FT(L,P) = TT(L,P) + T15 \cdot V(R) \cdot \sum_{R=1}^{RN} RT(R,P) \tag{5-15}$$

Freeway system delay

$$FD(L,P) = FT(L,P) - T15 \cdot LE(L)/SR(L) - V(R) \cdot \sum_{R=1}^{RN} RRT(R,P) \tag{5-16}$$

Where

FT = Freeway system travel time
RT = Entry ramp travel time (hours)
R = Ramp index
RN =Total number of ramps
FD = Freeway system delay

5.1.1.5 Private Vehicle Occupant System Delay

The basic measure is computed on a 15-minute and link basis and aggregated annually on a system-wide basis.

$$LPP(L,P) = K_1 \cdot FP(L,P) \cdot FD(L,P) \tag{5-17}$$

Where

K_1 = Average number of travelers in private passenger vehicle

FP = Private passenger vehicle fraction of traffic volume
LPP = Traveler system delay in private passenger vehicles (person hours)

5.1.1.6 Commercial Vehicle Occupant System Delay

The basic measure is computed on a 15-minute and link basis and aggregated annually on a system-wide basis.

$$LPT(L,P) = K_2 \cdot FC(L,P) \cdot FD(L,P) \tag{5-18}$$

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)

5.1.1.7 Goods Inventory Delay

The basic measure is computed on a 15-minute and link basis and aggregated annually on a system-wide basis.

$$LPG(L,P) = K_3 \cdot FR(L,P) \cdot FD(L,P) \tag{5-19}$$

Where
K_3 = Average weight of load in trucks carrying goods (tons)
FR = Traffic volume fraction of trucks carrying loads (Note: FR does not include deadheading trucks).
LPG = Goods delay (ton hours)

5.1.2 Route Travel Time and Reliability of Route Travel Time

5.1.2.1 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 (Ishimaru and Hallenbeck, 1999).

Route travel time is the sum of route link travel times (VT) and may be computed as follows.

$$RTT = \sum_{L=RI}^{RO} VT\,(L,N5) \tag{5-20}$$

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-minute 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 covered during different time periods, and consequently at different speeds, a laddered concept for computing route travel times (RTT) is discussed by Ishimaru and Hallenbeck (1999). Route travel time is the sum of route link travel times (VT) and is computed for the appropriate time period for that link. The concept is described as follows.

If VT for this link < 5 minutes, then the travel time for the next link uses the same 5-minute time period. If VT ≥ 5 minutes, then the travel time for the next link uses the subsequent 5-minute time period. Higatani et al (2009) indicate that this approach is more accurate than the summation of link travel times computed for a single time period.

Figure 5 provides a flow chart that implements this concept.

Similarly, freeway route delay (ROD) may be computed as follows.

$$ROD = RTT - \sum_{L=RI}^{RO} LE(L)/SR(L) \quad (5\text{-}21)$$

For evaluation purposes, route delay is most meaningful when used as an average value for a peak hour or peak period. To be statistically meaningful, a sufficiently large data sample (number of days for data collection) is required. For a peak hour evaluation, 12 data samples will be generated per day. It may be expected during the course of one month, after eliminating weekends, holidays and other days that may not be typical because of weather problems, special events, etc. that data will be available for a minimum of fifteen days. Based on these values, the standard estimate of the mean value of route delay is approximately 7.5% (Weiss and Hassett 1988).

5.1.2.2 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* (FHWA, nd).

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 (2003) recommends a minimum data collection period of four weeks at 15 minute intervals. Coupling this criterion with the previous discussion of route travel time, if a "trip" is considered to be a calculation of three 5-minute travel times for each 15-minute period in a weekday peak hour, eliminating holidays and other non-representative days, a one month data collection cycle provides a sufficiently representative data cycle.

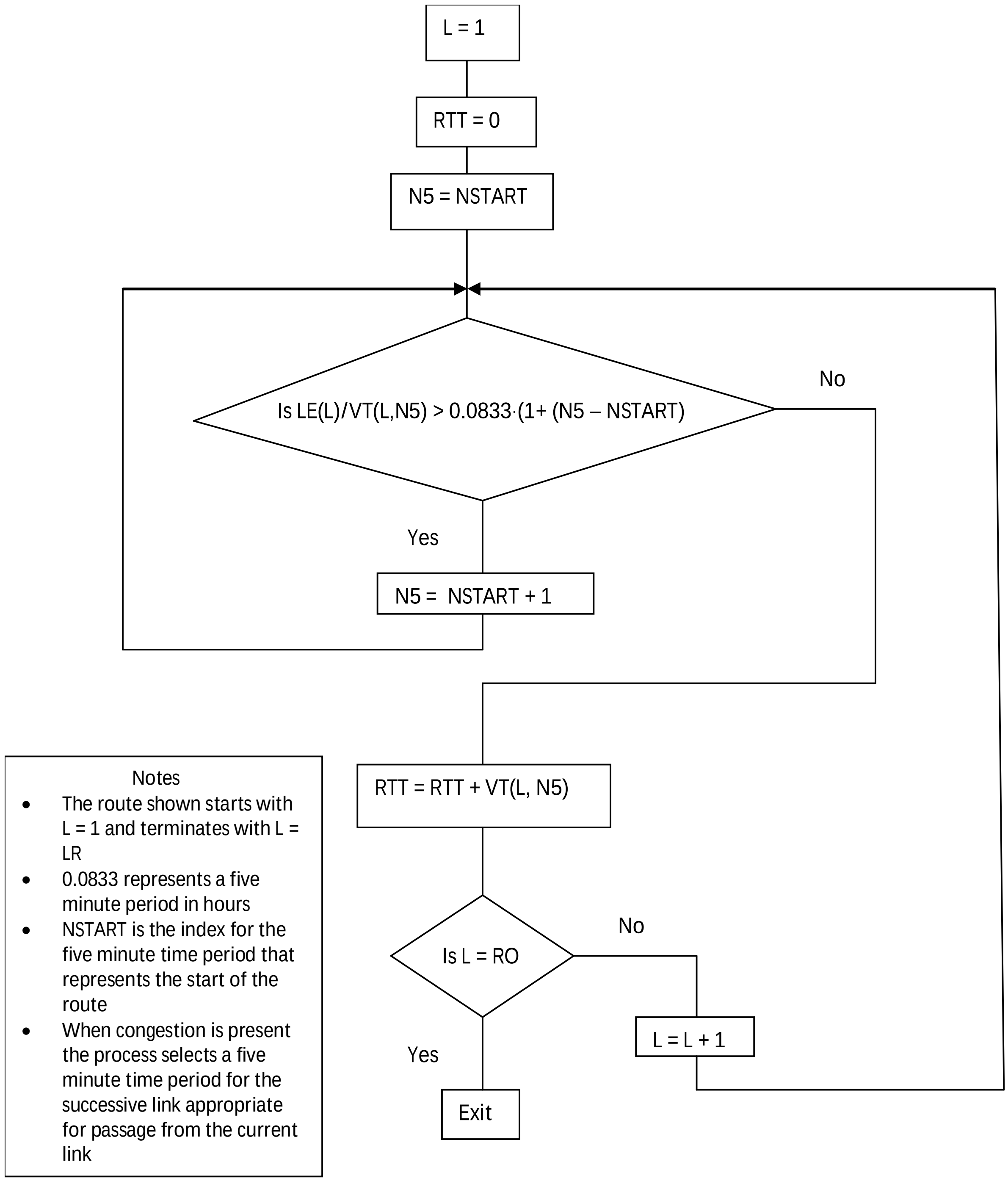


Figure 5 Flow Chart for Route Travel Times

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 (2003) as:

$$s^2 = \frac{\sum(T_j - M)^2}{n-1} \quad (5\text{-}22)$$

Where:

s =estimate of travel time standard deviation
Tj = the travel time of the i^{th} trip on a specific route
M = the mean travel time of a set of sample trips for the period (e.g. 15 minutes)
n = the number of sample trips

Commonly used measures of route travel time reliability are the completion of 90 percent or 95 percent 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 percent reliability corresponds to 1.28 standard deviations
- A 95 percent reliability corresponds to 1.64 standard deviation

Measures that are commonly used include (FHWA, nd):

- *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 Equation 5-23.

$$Buffer\ time = 1.64 \cdot s \quad (5\text{-}23)$$

- *Planning time* – The total travel time, which includes buffer time (i.e., calculated as the 95th percentile travel time).

Planning time = Route Travel Time + Buffer time (5-24)

- *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 Figure 6 (FHWA, nd).

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 (FHWA, nd):

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.

5.1.3 Throughput

Throughput may be evaluated as the vehicle miles for a link for the peak hour. The evaluation process consists of the following:

- For each five minutes of the peak hour identify the lowest volume for each domain in the link. This is identified as link volume (LV).
- Peak hour throughput (PHT) is provided by Equation 5-25.

$$PHT(L) = \sum_{N5=five\ minute\ period\ identifier\ for\ peak\ hour\ start}^{N5+12} T5 \cdot LE(L) \cdot LV(L, N5) \qquad (5\text{-}25)$$

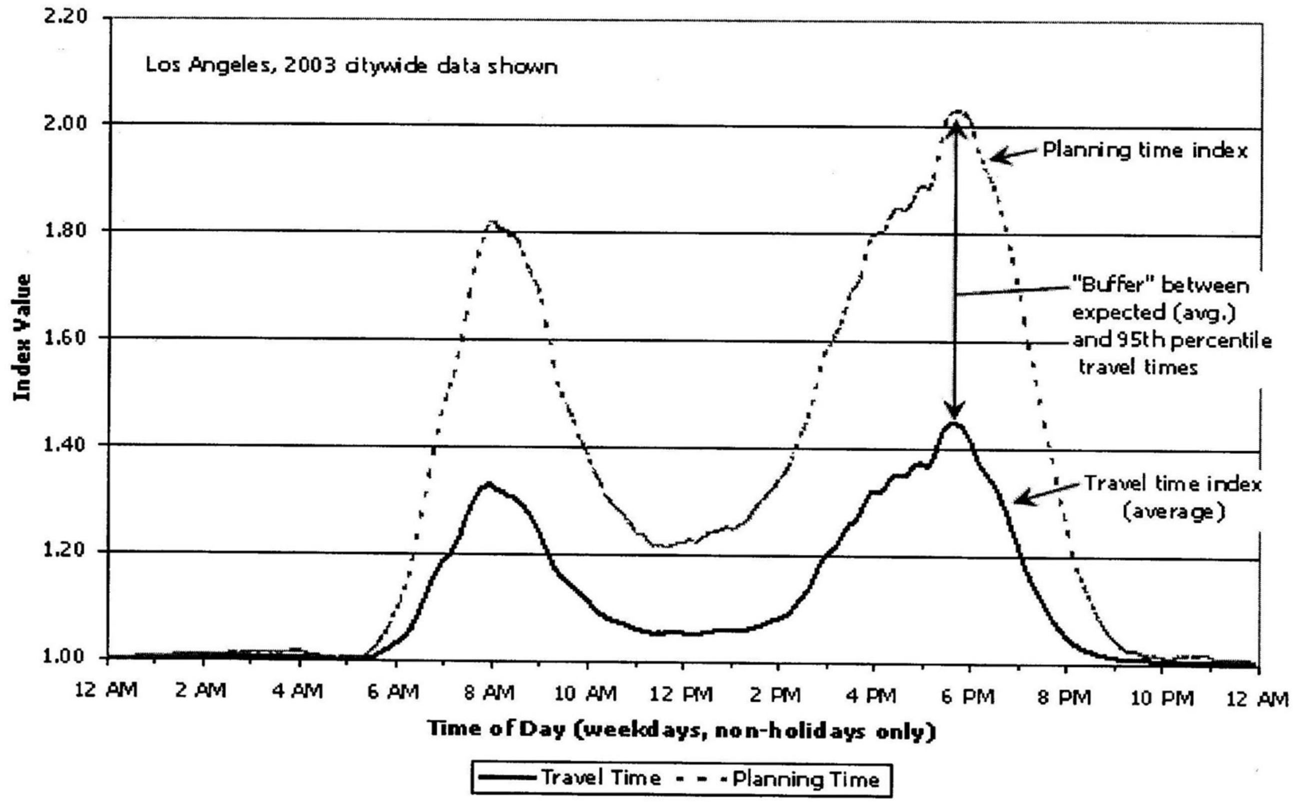


Figure 6 Relationship of Travel Time Reliability Indices

Throughput may be considered as a measure of system efficiency for a freeway link, particularly during the peak period. Gordon (1996) suggests that plots of traveler miles vs. traveler hours for various conditions may be useful for evaluating the general performance of ITS improvements. This concept is shown in Figure 7. In this figure, the solid curve represents improved system operation for all traffic conditions relative to the dashed curve. The slope of a line from the origin to a point on the curve represents speed for the link.

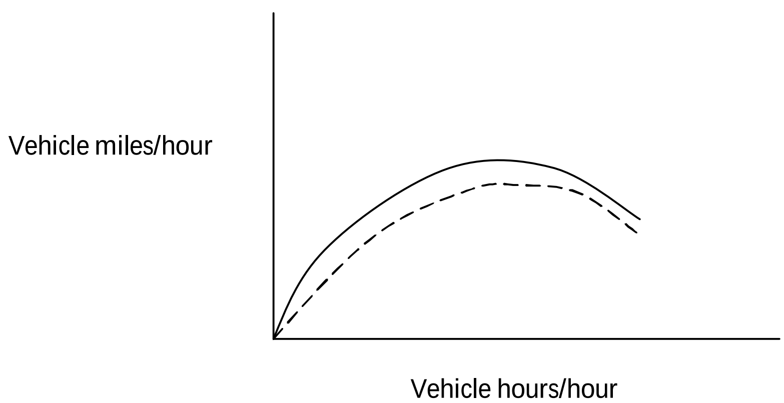


Figure 7 Link Throughput

The throughput measures originally shown in Table 6 include:

- Freeway throughput – Vehicle miles during a weekday peak hour for a link.
- Intersection throughput – Vehicles per weekday peak hour serviced at an intersection.

5.1.4 Surface Street Delay and Travel Time

Signalized surface streets experience discontinuous flow, thus speeds measured by point detectors (where available) do not provide information that may directly be used to develop link speeds and travel times. While technologies that make greater use of automatic data are emerging, current evaluations often feature a strong manual component. Chapter 6 provides more information on these technologies.

The total delay experienced by a road user can be defined as the difference between the travel time actually experienced and the reference travel time that would result in the absence of traffic control, changes in speed due to geometric conditions, any incidents, and the interaction with any other road users. Control delay is the portion of delay that is attributable to the control device (the signal, its assignment of right-of-way, and the timing used to transition right-of-way in a safe manner) plus the time decelerating to a queue, waiting in queue, and accelerating from a queue. For typical through movements at a signalized intersection, total delay and control delay are the same in the absence of any incidents (Koonce 2008). Figure (Transportation Research Board 2010) shows control delay in a time-space context.

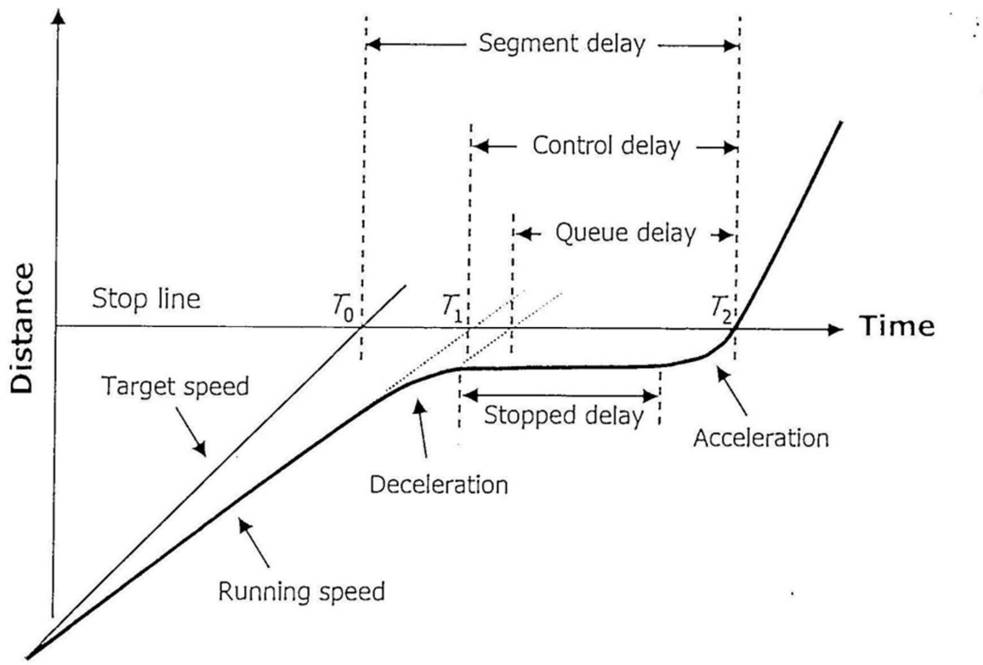


Figure 8 Control Delay

Control delay for a lane group may be obtained by observations at the intersection or by measuring the time for a vehicle to traverse a path. The relationship between travel time and control delay for a lane group[6] is given by equation 5-26.

$$LCD(LI,LG) = RLTT(LI,LG) - RET(LI,LG) \quad (5\text{-}26)$$

Where

LCD = Control delay for the intersection lane group associated with a travel ink for a 15-minute time period

RET(LI,LG) = Reference vehicle travel time for the lane group for the travel link

RLTT(LI,LG) = Vehicle travel time for the lane group for the travel link

Evaluation methodologies generally include either measuring control delay and computing vehicle travel time using Equation 5-26 or measurement of link travel time and identification of control delay using that equation.

[6] Guidelines for the establishment of lane groups are provided in the Transportation Research Board's *2010 Highway Capacity Manual*.

Current evaluation methodologies primarily use intersection observations and/or measurements using floating vehicles to obtain one or the other of the variables. Recent technology developments, as described in Chapter 6, have resulted in a more efficient use of the manual labor required as well as automated techniques to obtain this data.

Chapter 31 of HCM 2010 provides worksheets to assist in recording manual queue observations and computing control delay from these observations.

Table 11 provides an estimate of the number of runs required to achieve a 95% level of confidence (Florida Department of Transportation 2000).

Equation 5-26 provides the basis for evaluating individual vehicle travel time and control delay for a lane group at a signalized intersection approach, and the measures derived from them.

5.1.4.1 Surface Street System Delay

Intersection delay for a 15-minute period is provided by equation 5-27

$$LCD(LI) = \sum_{\mathrm{LG=1}}^{Intersection\ lane\ groups} LCD(LI, LG) \cdot V(LI, LG) \cdot T15 \qquad (5\text{-}27)$$

Where

LI = Intersection ID
LG = Traffic signal lane group
T15 = 15 minutes (.25 hours) for intersection signals and surface streets

Table 11. Sample Size Requirements

APPROXIMATE MINIMUM SAMPLE SIZE REQUIREMENTS FOR TRAVEL TIME AND DELAY STUDIES WITH CONFIDENCE LEVEL OF 95.0 PERCENT					
Average Range in Running Speed (mph)* R	Minimum Number of Runs for Specified Permitted Error				
	± 1.0 mph	± 2.0 mph	± 3.0 mph	± 4.0 mph	± 5.0 mph
2.5	4	22	2	2	2
5.0	8	4	3	2	2
10.0	21	8	5	4	3
15.0	38	14	8	6	5
20.0	59	221	12	8	6
*Interpolation should be used when R is other than the numbers shown in column 1.					

System delay (SSSD) for a 15-minute period is given by

$$SSSD = \sum_{LI=1}^{System\ intersections} LCD(\ LI) \qquad (5\text{-}28)$$

5.1.4.2 *Surface Street Route Delay (SSRD)*

$$SSRD = \sum_{LI=First\ link\ on\ route}^{Last\ link\ on\ route} LCD(LI, Lane\ group\ on\ route) \qquad (5\text{-}29)$$

5.1.4.3 *Surface Street Route Travel Time*

$$RTT = \sum_{LI=First\ link\ on\ route}^{Last\ link\ on\ route} RLTT(LI, Lane\ group\ on\ route) \qquad (5\text{-}30)$$

5.1.4.4 *Other Surface Street Delay Measures*

By substituting SSSD for FD, equations 5-17, 5-18 and 5-19 may be used to compute system delay for private vehicle occupants, commercial vehicle occupants and goods inventory.

5.2 Safety Measures

5.2.1 General Crash Measures

Agencies typically collect and classify crash data based on crash reports to identify trends and areas requiring improvement. Depending on the type of data collected, the database management systems used by these agencies have a great deal of flexibility in providing data at required locations for various functions.

Table 12 (2009 Washington) shows an example of statewide statistics for Washington State. Tables 13 (2009 Washington) shows an example of a Washington State summary report of crashes by type.

The methodologies developed under this study focus on developing the data for the safety measures identified in Table 6 by location. The measures required for the benefit-cost evaluation approach described in this report are:

- *Freeway crashes*. This data may be expressed in crashes per million vehicle miles for each freeway link.
- *Crashes at intersections*. This data may be expressed in crashes per million vehicles entering the intersection.

Table 12. Average Collision Rates

2009 AVERAGE COLLISION RATES BY FUNCTIONAL CLASS
Northwest Region (State Routes only)

RURAL AREAS	PRINCIPAL ARTERIAL	MINOR ARTERIAL	COLLECTOR	INTERSTATE	ALL HIGHWAYS
Vehicle Miles of Travel (Millions)	554.74	455.55	216.70	940.03	2,167.02
Miles of Highway	133.41	255.98	158.96	57.61	605.96
Total Collisions	587	518	394	494	1,993
Collision Rate (1)	**1.06**	**1.14**	**1.82**	**0.53**	**0.92**
Property Damage Only Collisions	378	292	249	347	1,266
Property Damage Only Collision Rate (1)	**0.68**	**0.64**	**1.15**	**0.37**	**0.58**
Injury Collisions	205	219	143	145	712
Injury Collision Rate (1)	**0.37**	**0.48**	**0.66**	**0.15**	**0.33**
Fatal Collisions	4	7	2	2	15
Fatal Collision Rate (2)	**0.72**	**1.54**	**0.92**	**0.21**	**0.69**

URBAN AREAS	PRINCIPAL ARTERIAL	MINOR ARTERIAL	COLLECTOR	INTERSTATE	ALL HIGHWAYS
Vehicle Miles of Travel (Millions)	4,124.91	503.58	0.00	6,827.04	11,455.53
Miles of Highway	333.18	98.04	0.00	141.43	572.65
Total Collisions	9,032	1,501	0	9,266	19,799
Collision Rate (1)	**2.19**	**2.98**	**0.00**	**1.36**	**1.73**
Property Damage Only Collisions	5,981	943	0	6,351	13,275
Property Damage Only Collision Rate (1)	**1.45**	**1.87**	**0.00**	**0.93**	**1.16**
Injury Collisions	3,034	551	0	2,898	6,483
Injury Collision Rate (1)	**0.74**	**1.09**	**0.00**	**0.42**	**0.57**
Fatal Collisions	17	7	0	17	41
Fatal Collision Rate (2)	**0.41**	**1.39**	**0.00**	**0.25**	**0.36**

ALL AREAS	PRINCIPAL ARTERIAL	MINOR ARTERIAL	COLLECTOR	INTERSTATE	ALL HIGHWAYS
Vehicle Miles of Travel (Millions)	4,679.65	959.13	216.70	7,767.07	13,622.55
Miles of Highway	466.59	354.02	158.96	199.04	1,178.61
Total Collisions	9,619	2,019	394	9,760	21,792
Collision Rate (1)	**2.06**	**2.11**	**1.82**	**1.26**	**1.60**
Property Damage Only Collisions	6,359	1,235	249	6,698	14,541
Property Damage Only Collision Rate (1)	**1.36**	**1.29**	**1.15**	**0.86**	**1.07**
Injury Collisions	3,239	770	143	3,043	7,195
Injury Collision Rate (1)	**0.69**	**0.80**	**0.66**	**0.39**	**0.53**
Fatal Collisions	21	14	2	19	56
Fatal Collision Rate (2)	**0.45**	**1.46**	**0.92**	**0.24**	**0.41**

(1) Per Million Vehicle Miles of Travel
(2) Per 100 Million Vehicle Miles of Travel

Washington State Collision Data Summary

Table 13
Washington State Collision Type Statistics

State Routes Only: Leading Collision Type for All Collisions - 2009

FIRST COLLISION TYPE	Eastern Region		North Central Region		Northwest Region		Olympic Region		South Central Region		Southwest Region	
REAR-END (ALL TYPES)	748	24%	408	22%	10,457	48%	4,254	44%	736	23%	914	28%
HIT FIXED OBJECT	691	22%	485	26%	3,276	15%	1,824	19%	898	28%	969	29%
SIDE-SWIPE (OPPOSITE OR SAME DIRECTION)	181	6%	85	5%	2,856	13%	963	10%	245	8%	293	9%
ENTERING AT ANGLE	417	13%	194	11%	1,715	8%	1,055	11%	231	7%	289	9%
ALL OTHER- SAME DIRECTION	145	5%	81	4%	951	4%	401	4%	187	6%	144	4%
OVERTURN	268	9%	162	9%	416	2%	276	3%	386	12%	153	5%
ALL OTHER-OPPOSITE DIRECTION	173	6%	98	5%	1,180	5%	408	4%	128	4%	135	4%
VEHICLE STRIKES DEER	287	9%	145	8%	171	1%	186	2%	139	4%	154	5%
ALL OTHER - NON COLLISION	31	1%	44	2%	133	1%	79	1%	91	3%	47	1%
VEHICLE - PEDESTRIAN	43	1%	10	1%	193	1%	80	1%	9	0%	19	1%
ONE PARKED-ONE MOVING	18	1%	25	1%	118	1%	76	1%	47	1%	63	2%
HIT NON FIXED OBJECT	14	0%	31	2%	57	0%	32	0%	43	1%	40	1%
VEHICLE - PEDALCYCLIST	22	1%	8	0%	106	0%	43	0%	4	0%	25	1%
HEAD-ON	20	1%	14	1%	67	0%	39	0%	17	1%	16	0%
VEHICLE STRIKES ELK	3	0%	8	0%	18	0%	13	0%	41	1%	29	1%
DOMESTIC ANIMAL	15	0%	19	1%	15	0%	15	0%	24	1%	12	0%
PARKED POSITION (ONE CAR ENTERING/LEAVING)	10	0%	4	0%	22	0%	18	0%	2	0%	3	0%

Alternatively, the components of the general category of crashes may be used for benefit vs. cost analysis. These components include:

- Property damage only (PDO) crashes (crashes/million vehicle miles)
- Fatal crashes (freeway crashes/hundred million vehicle miles, or alternatively crashes per million vehicle miles; intersection crashes/million entering vehicles
- Injury crashes (freeway crashes/hundred million vehicle miles, or alternatively crashes per million vehicle miles; intersection crashes/million entering vehicles)

An example of the data from the New York State DOT crash record data base that was used for a benefit-cost analysis is shown in Tables 14 and 15 (Fisher Associates 2004). The table shows the data sorted by the specific freeway links required for the study.

Depending on the TMC's hours of operation and the crash classifications provided by the freeway management system, TMC-generated data may be used to supplement crash record data.

Table 14
Crash Rates for Selected Links in Rochester, N.Y.

Roadway	Accident Period - March 1, 2000 to February 28, 2002					
Link	**Link Description**	**Total Accidents**	**Average AADT**	**Link Length (miles)**	**Accident Rate**	**Statewide Average Rate**
NYS Route 104	Goodman Street Interchange	120	68,200	0.80	2.68	2.26
	Culver Road Interchange	72	73,000	0.80	1.50	2.26
	Route 590 Interchange	71	70,000	0.80	1.54	1.94
	Route 590 to Bay Road	46	68,000	1.60	0.55	1.78
	Bay Road Interchange	32	62,000	0.80	0.79	2.26
	Bay Road to Five Mile Line Road	12	57,000	1.25	0.21	1.09
	Five Mile Line Road to Route 250	88	45,000	2.86	0.91	1.47
	Phillips Road to Salt Road	16	42,000	0.90	0.52	1.47
	Salt Road Interchange	8	33,000	0.40	0.66	1.47
	Route 104 Totals	**465**	**64,257**	**10.21**	**0.96**	**1.94**
Interstate 490	Route 390 Interchange	141	90,000	1.46	1.38	1.94
	Mt. Read Interchange	60	100,000	0.47	1.44	2.26
	Mt. Read Boulevard to Inner Loop Area	229	92,000	1.46	2.19	2.26
	Inner Loop Area	330	107,000	1.59	2.50	1.94
	Goodman Street Interchange	80	92,000	0.50	1.99	2.26
	Route 490 Totals	**840**	**105,770**	**5.48**	**1.95**	**1.94**
NYS Route 590	Browncroft Boulevard Interchange	29	90,000	0.40	0.88	2.26
	Browncroft Boulevard to Empire Boulevard	31	101,000	0.67	0.55	1.78
	Empire Boulevard Interchange	113	101,000	0.58	2.25	2.26
	Empire Boulevard to Route 104	55	98,000	0.85	0.81	1.78
	Route 104 Interchange	27	76,000	0.60	0.70	1.47
	Ridge Road Interchange	18	22,000	0.60	1.60	1.47
	Route 590 Totals	**273**	**50,725**	**3.70**	**1.94**	**1.94**

X.XX - Average Accident Rate higher than the Statewide Average Rate for similar facility type.

Table 15. Crash Classification by Link in Rochester, N.Y.

Roadway	Accident Period - March 1, 2000 to February 28, 2002							
		Severity						
Link	Link Description	Fatality		Injury		Property Damage		Total Accidents
		Total	Percent	Total	Percent	Total	Percent	
NYS Route 104	Goodman Street Interchange	0	0.00%	31	25.83%	89	74.17%	120
	Culver Road Interchange	0	0.00%	17	23.61%	55	76.39%	72
	Route 590 Interchange	0	0.00%	11	15.49%	60	84.51%	71
	Route 590 to Bay Road	0	0.00%	13	28.26%	33	71.74%	46
	Bay Road Interchange	0	0.00%	14	43.75%	18	56.25%	32
	Bay Road to Five Mile Line Road	0	0.00%	5	41.67%	7	58.33%	12
	Five Mile Line, Hard, Holt, Route 250 Interchanges	1	1.14%	26	29.55%	61	69.32%	88
	Phillips Road to Salt Road	0	0.00%	4	25.00%	12	75.00%	16
	Salt Road Interchange	0	0.00%	4	50.00%	4	50.00%	8
	Route 104 Total Accidents and Severity Distribution	**1**	**0.22%**	**125**	**26.88%**	**339**	**72.90%**	**465**
	NYSDOT Average Severity Distribution		**0.35%**		**33.12%**		**66.53%**	
Interstate 490	Route 390 Interchange	0	0.00%	38	26.95%	103	73.05%	141
	Mt. Read Interchange	0	0.00%	18	30.00%	42	70.00%	60
	Mt. Read Boulevard to Inner Loop Area	0	0.00%	58	25.33%	171	74.67%	229
	Inner Loop Area	1	0.30%	84	25.45%	245	74.24%	330
	Goodman Street Interchange	0	0.00%	19	23.75%	61	76.25%	80
	Route 490 Total Accidents and Severity Distribution	**1**	**0.12%**	**217**	**25.83%**	**622**	**74.05%**	**840**
	NYSDOT Average Severity Distribution		**0.35%**		**33.12%**		**66.53%**	
NYS Route 590	Browncroft Boulevard Interchange	0	0.00%	5	17.24%	24	82.76%	29
	Browncroft Boulevard to Empire Boulevard	0	0.00%	9	29.03%	22	70.97%	31
	Empire Boulevard Interchange	0	0.00%	29	25.66%	84	74.34%	113
	Empire Boulevard to Route 104	0	0.00%	18	32.73%	37	67.27%	55
	Route 104 Interchange	0	0.00%	2	7.41%	25	92.59%	27
	Ridge Road Interchange	1	5.56%	1	5.56%	16	88.89%	18
	Route 590 Total Accidents and Severity Distribution	**1**	**0.37%**	**64**	**23.44%**	**208**	**76.19%**	**273**
	NYSDOT Average Severity Distribution		**0.35%**		**33.12%**		**66.53%**	

While freeway crash data is generally best organized by links for benefit-cost analyses and when trying to identify locations requiring increased attention, crash data on surface streets is most often classified by intersection location. Crash record databases may be used to organize and analyze data in particular systems for comparison to agency averages. One measure that is useful in making these comparisons is crashes per million vehicles entering the intersection or freeway ramp. Table 16 is an example of average values provided by New York State DOT (new York State Department of Transportation, nd).

Table 16. Average Intersection Accident Rates

AVERAGE INTERSECTION ACCIDENT RATES FOR STATE HIGHWAYS BY INTERSECTION TYPE
(BASED ON ACCIDENT DATA JANUARY 1, 2007 TO DECEMBER 31, 2008)

INTERSECTION TYPE RURAL FUNCTION CLASS	ALL TYPES ACC/MEV	WET ROAD ACC/MEV	LEFT TURN ACC/MEV	REAR END ACC/MEV	OVER-TAKING ACC/MEV	RIGHT ANGLE ACC/MEV	RIGHT TURN ACC/MEV	HEAD ON ACC/MEV	SIDE-SWIPE ACC/MEV
3 LEGGED INTERSECTIONS									
SIGNAL ALL LANES	0.22	0.04	0.02	0.06	0.01	0.03	0.01	0.01	0.01
SIGN ALL LANES	0.15	0.03	0.01	0.03	0	0.01	0	0	0
NO CONTROL ALL LANES	0.09	0.01	0.01	0.01	0	0.01	0	0	0
4 LEGGED INTERSECTIONS									
SIGNAL ALL LANES	0.50	0.09	0.06	0.11	0.02	0.11	0.02	0.01	0.01
SIGN ALL LANES	0.31	0.06	0.02	0.04	0.01	0.08	0.01	0	0
NO CONTROL ALL LANES	0.12	0.02	0	0.01	0.01	0.02	0	0	0.01
ON RAMP (ALL CONTROL)									
MERGE W/ 1 LANE	0.07	0	--	--	--	--	--	--	--
MERGE W/ 2&> LANES	0.04	0.01	--	--	--	--	--	--	--
OFF RAMP (ALL CONTROL)									
MERGE W/ 1 LANE	0.08	0.08	--	--	--	--	--	--	--
MERGE W/ 2&> LANES	0.04	0.01	--	--	--	--	--	--	--

++ NYSDMV stopped processing most Non-Reportable accidents beginning with 2002 accident data. Therefore, the rates in Table II are based primarily on just reportable accident from NYSDMV.

Kar and Datta (2010) describe a complex weighting of PDO, injury, and fatality crash costs as well as crash frequency to develop a safety performance index (SPI). Kar and Datta indicate that the SPI may be used for planning resource allocations to reduce crashes.

5.2.1.1 Crash Causality

Some agencies maintain extensive databases for classification of crashes by causality factors. For example, Washington State DOT (Washington State Departme2nt of Transportation 2009) maintains a database that reports on the details of a number of factors including the following:

- Work zone crashes
- Speed-related crashes
- Alcohol-related crashes
- Weather-related crass, including type of weather occurrence
- Type of object struck
- Driver contributing circumstances (see Table 17)

Because ITS has different impacts on these factors and because agencies collect and report crash causality data using different formats with varying levels of detail and using different importance scales to address these issues, this project has generally not developed specific measures to deal with these items. However, it is recognized that work zone crashes are important to most agencies and TMC operations often significantly include management assistance for this issue. A measure is therefore included in Tables 6 and 7 for work zone crashes.

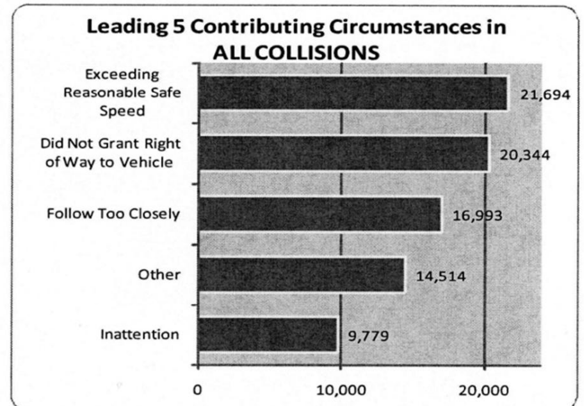
Table 17. Washington State DOT Crash Data for Contributing Circumstances

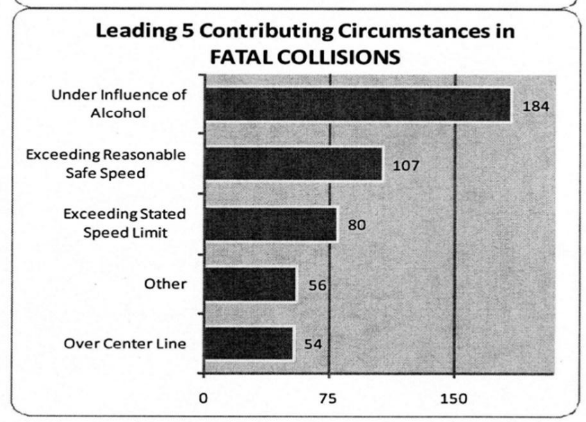
Driver *Contributing Circumstances by Most Severe Injury per Collision - 2009

**Up to three officer reported contributing circumstances are possible per driver. It is important to remember that the attached listing does not represent the number of collisions, but rather lists the total of officer reported contributing circumstances associated with each driver.*

STATEWIDE ALL PUBLIC ROADS

*DRIVER CONTRIBUTING CIRCUMSTANCE	FATAL COLLISIONS	SERIOUS INJURY COLLISIONS	MINOR INJURY COLLISIONS	PROPERTY DAMAGE ONLY COLLISIONS	ALL COLLISIONS
Exceeding Reasonable Safe Speed	107	462	7,317	13,808	21,694
Did Not Grant Right of Way to Vehicle	24	255	5,754	14,311	20,344
Follow Too Closely	4	118	6,323	10,548	16,993
Other	56	281	2,818	11,359	14,514
Inattention	25	167	3,347	6,240	9,779
Under Influence of Alcohol	184	386	2,464	3,459	6,493
Disregard Stop and Go Light	8	70	1,408	1,935	3,421
Improper Turn	2	16	560	2,662	3,240
Driver Distractions Outside Vehicle	2	35	961	1,645	2,643
Exceeding Stated Speed Limit	80	216	932	1,346	2,574
Operating Defective Equipment	12	56	668	1,639	2,375
Improper Backing	0	6	127	2,159	2,292
Disregard Stop Sign - Flashing Red	20	60	854	1,301	2,235
Over Center Line	54	154	679	884	1,771
Apparently Asleep	10	70	665	907	1,652
Did Not Grant Right of Way to Pedestrian/Pedalcyclist	16	136	1,286	40	1,478
Driver Interacting with Passengers, Animals or Objects in the Vehicle	6	26	589	782	1,403
Other Driver Distractions Inside Vehicle	1	22	481	717	1,221
Improper Passing	22	45	296	847	1,210
Unknown Driver Distraction	1	8	299	594	902
Driver Operating Handheld Telecommunication Device	4	19	313	470	806
Apparently Ill	8	43	413	342	806
Under Influence of Drugs	11	53	332	399	795
Improper U-Turn	2	15	205	562	784
Driver Adjusting Audio or Entertainment System	0	6	160	252	418
Driver Eating or Drinking	4	9	119	225	357
Apparently Fatigued	1	8	142	164	315
Improper Parking Location	0	7	17	188	212
Driver Operating Other Electronic Device	1	3	71	107	182
Disregard Yield Sign - Flashing Yellow	0	1	51	114	166
Had Taken Medication	0	5	75	79	159
Failing to Signal	0	1	47	111	159
Driver Smoking	0	4	47	84	135
Headlight Violation	1	4	32	49	86
Driver Reading or Writing	0	0	32	50	82
Driver Operating Hands-free Wireless Telecommunication Device	0	1	17	47	65
Improper Signal	0	2	11	51	64
Disregard Flagger - Officer	0	3	20	26	49
Driver Grooming	0	0	6	12	18





2009 Washington State Collision Data Summary

The Work Zone Safety Performance Measures Guidance Booklet[7] suggests the safety measure in Table.18.

Table 18. Safety Work Zone Performance Measure

Condition	Site crash rate during construction/ site crash rate prior to construction < 1.0	Site crash rate during construction/ site crash rate prior to construction = 1.0	Site crash rate during construction/ site crash rate prior to construction < 1.2	Site crash rate during construction/ site crash rate prior to construction < 1.3	Site crash rate during construction/ site crash rate prior to construction > 1.3
Measure	Excellent	Good	Fair	Poor	Very Poor

An overall measure for the TMC is the average of the annual evaluations of the work zones included in the TMC's management region.

5.2.1.2 Secondary Crashes

Secondary crashes are crashes that result from an existing incident. Many of these crashes occur at the tail of queues that result from the incident. It has been estimated that 14 to 30 percent of crashes are secondary crashes (ITS Florida, nd, National 2002).

Secondary crashes are often not identified as such by many of the accident reporting and classification systems used. Since the ITS techniques that support more rapid incident clearance and provide advance motorist warning of queues may substantially reduce secondary crashes, secondary crashes are an important measure for ITS performance. This data is best obtained by ensuring that secondary crashes are included as a crash classification parameter in the freeway management system. An overall measure for the TMC is the annual sum of the secondary crashes included in the TMC's management region.

5.3 Fuel Consumption

5.3.1 Freeways

Congestion significantly increases fuel consumption rates per vehicle mile travelled. The fuel consumption rates (G) shown in Table 19 were computed by Mr. Jeff Houk of FHWA using the EPA MOVES model. The model employs a representative vehicle class mix. The speeds in the table are average speeds for the driving cycle for which the model is based. The domain speed may be used in conjunction with the table.

[7] Federal Highway Administration and American Traffic Safety Services Association, "Work Zone Safety Performance Measures Guidance Booklet." Available at: http://www.atssa.com/galleries/default-file/Performance_Measures_Guide_-_FINAL[1].pdf

Table 19. Fuel Consumption Rates in Gallons per Vehicle Mile

Speed range	Year 2011	Year 2016
10mph > s	0.175	0.167
20 mph > s ≥ 10 mph	0.077	0.073
30 mph > s ≥ 20 mph	0.059	0.056
40 mph > s ≥ 30 mph	0.052	0.050
50 mph > s ≥ 40 mph	0.050	0.048
60 mph > s ≥ 50 mph	0.048	0.046
s > 60 mph	0.049	0.046

The fuel consumption (FUF) in gallons for a domain for a 5-minute period may be computed as follows:

$$FUF(DO, T5) = 0.0833 \cdot G \cdot LE(DO) \cdot V(DO) \qquad (5\text{-}31)$$

Fuel consumption and changes in fuel consumption are often reported on an annual basis.

5.3.2 Surface Streets

Because surface street travel is characterized by several factors at locations upstream of a queue at a controlled intersection and by delays at the intersection, and because detailed observations are usually unavailable at locations away from the intersection, an appropriate measure of system performance is the *fuel consumption resulting from control delay at traffic signals*.

FHWA data developed for this project provides the following conservative fuel consumption rates (GA) when intersections experience control delay:

- 0.67 gallons per hour per vehicle for year 2011
- 0.61 gallons per hour per vehicle for year 2016

Fuel consumption resulting from control delay for each lane group for a 15-minute evaluation period is given by:

$$\mathrm{FUP(LI,LG,N15)} = 0.25 \cdot \mathrm{GA} \cdot \mathrm{V(LI,LG,N15)} \cdot \mathrm{LCD(LI,LG,N15)} \qquad (5\text{-}32)$$

Where

FUP = Fuel consumption for intersections for 15-minute period (gallons)
N15 = 15-minute evaluation period index number

Aggregation of these data to an annual period provides a meaningful measure for improvements to traffic control measures.

5.4 Emissions

Appendix B discusses emissions models and how they apply to performance evaluation.

5.5 Service Quality and User Perceptions

5.5.1 Route Delay

Travel time information is commonly made available to motorists through DMS and other information delivery methods. As a result, motorists are aware of variations in travel time throughout the day and from day to day. This information is usually provided in terms of the time to reach a freeway exit from a specific DMS or from a prescribed freeway entry location. Route delay is essentially route travel time less the travel time for a reference speed. For surface streets, it is provided by Equation 5-29. Freeway route delay is the sum of link delay (Equation 5-11) for the links comprising the route.

5.5.2 Route Travel Time Reliability

Section 5.1.2.1 describes the methodology to compute freeway route travel time. Some agencies provide information on travel time reliability to motorists, often by means of electronic information delivery techniques. Section 5.1.2.2 discusses the various measures for freeway travel time reliability.

5.5.2.1 Level-of-Service (LOS)

LOS is a commonly used measure for quality of service (Shaw 2003).

Freeway Level of Service The characteristics for freeway LOS are summarized in Table 20 (Federal Highway Administration, nd):

Table 20. Freeway Level-of Service Characteristics

Level of Service	Description
A	Free flow with low volumes and high speeds.
B	Reasonably free flow, but speeds beginning to be restricted by traffic conditions.
C	In stable flow zone, but most drivers are restricted in the freedom to select their own speeds.
D	Approaching unstable flow; drivers have little freedom to select their own speeds.
E	Unstable flow; may be short stoppages.
F	Unacceptable congestion; stop-and-go; forced flow.

While the AASHTO Green Book (American Association of State highway and Transportation Officials) suggests a C LOS for urban and suburban freeways, it indicated that the decision is based on a number of factors for the local agency to consider. Agencies may also consider the availability of transit alternatives in the selection of a design LOS (Puget Sound Regional Council 2003).

The recommended measure includes those LOS worse than Level C as well as a grouping of Levels A, B and C. Table 21 defines LOS in terms of traffic density LOS (Transportation Research Board 2010).

Table 21. Level of Service Criteria for Freeway Facilities

Level of Service	Density (passenger cars/mi/lane)
A	≤11
B	11-18
C	>18-26
D	>26-35
E	.35-45
F	• >45 or • Any component of demand volume to capacity ratio > 1.00

Density (DD) may be computed from detector measurements by Equation 5-33.

$$DD(DO, N5) = \frac{V(DO,N5)}{SD(DO,N5)} \quad (5\text{-}33)$$

Commonly used level of service measures include:

- Peak hour level of service for a link. The weighted average link density (DWL) for a 5-minute period during the peak hour may be computed by Equation 5-34. In Equation 5-35 these 5-minute link speeds are averaged over the peak hour to provide DWLP.

$$DWL(L, N5) = \frac{\sum_{DO=1}^{Domains\ in\ link} DD(DO) \cdot V(DO) \cdot LE(DO)}{\sum_{DO=1}^{Domains\ in\ link} V(DO) \cdot LE(DO)} \quad (5\text{-}34)$$

$$DWLP(L, N60) = 0.083 \cdot \sum_{N5=Index\ for\ start\ of\ peak\ hour}^{N5+12} DWL(L, N5) \quad (5\text{-}35)$$

The level of service for the peak hour is then obtained from Table 21.

Signalized Intersection Level of Service . Table 22 provides the HCM 2010 level of service description for signalized intersections. Level of Service F applies if the volume to capacity ratio exceeds 1.0 for any row in the table. Control delay measurements for the intersections may be used to identify the LOS. Equation 5-27 provides the intersection control delay (LCD) for 15-minute periods. When LCD is divided by 15-minute intersection volume, the Level of Service may be obtained from Table 22.

Table 22. Level of Service for Signalized Intersections

Level of Service	Description
A	Control delay ≤ 10 sec/veh
B	20 sec/veh ≥ control delay > 10 sec
C	35 sec/veh ≥ control delay > 20 sec
D	55 sec/veh ≥ control delay > 35 sec
E	80 sec/veh ≥ control delay > 55 sec
F	Control delay > 80 sec/veh

5.5.2.2 User Satisfaction

Commonly used measures include:

- Rating scales to analyze user surveys. In some cases, the surveys may evaluate characteristics other than ITS services. Measures may include simple scales used for the evaluation of the survey.

  As an example, a Georgia DOT conducted a detailed motorist mail survey (Georgia State university 2006). 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 percent. The survey was detailed and evaluated specific ITS functions. Appendix C discusses the survey results in greater detail.

- Motorist complaints. 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.

5.5.2.3 Equity

While most ITS functions and operations result in improvement in travel time for the entire system as well as for each motorist, there are functions and operations that may result in delay reduction or reduction in crashes for the entire system but may adversely affect some individual highway users. Examples include:

- Ramp metering
- HOV and HOT lanes
- Signal phasing to enhance pedestrian safety.

Measures for equity include:

- Motorist complaints about equity. Usually a subset of all motorist complaints, an increasing year-over-year trend may indicate an increasingly severe issue.
- Gini coefficient. Levinson, et al (2004) describe an approach to measuring equity. The Lorenz Curve (heavy line in Figure 9) identifies the relationship between the proportion of delay and the proportion of vehicles incurring the delay. The thin line in the figure represents a condition where there is no equity discrepancy. Thus area AD in the figure identifies the users that are relatively disbenefitted by the treatment. The Gini coefficient is computed as:

  $$G = AD/(AD + AT) \qquad (5\text{-}36)$$

  It quantifies the level of inequality among users. Levinson et al (2004) describes a methodology for computing the Gini coefficient.

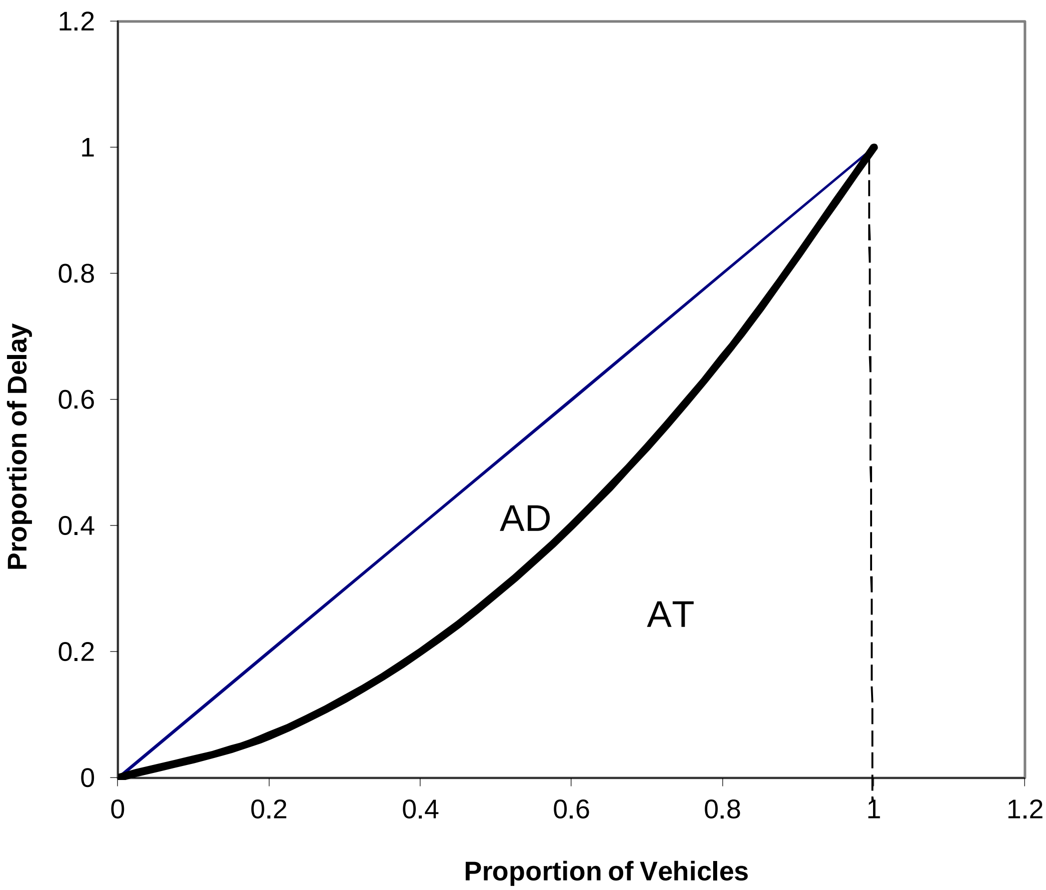


Figure 9 Example of Lorenz Curve for a Metered Freeway Entrance Ramp

5.5.3 Incident Clearance Time

A major benefit of the use of ITS to reduce delay is the ability it provides operations managers to reduce incident clearance time. Although this benefit is included in the general category of *delay and travel time measures* (Section 5.1), its importance to the evaluation of TMC operations may merit special attention.

Gordon (2010) describes the following simplistic model for the total system delay from the time an incident occurs until the queue clears.

$$D_T = (q_2 - q_3) \bullet T^2/2 + (q_2 - q_3)^2 \bullet T^2/(2 \bullet (q_1 - q_2)) \quad (5\text{-}37)$$

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 (capacity is restored)

Rewriting Equation 5-37 as Equation 5-38, Gordon shows that the ratio of change in delay as a result of reduced incident clearance time to incident clearance time is given by Equation 5-39.

$$D_T = K \cdot T^2 \quad (5\text{-}38)$$

$$\frac{\frac{dD_T}{dT}}{T} = 2 \cdot K \quad (5\text{-}39)$$

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

Measures to consider include the recording of the time to clear an incident and the total delay resulting from the incident. A number of evaluation studies conducted by research teams (Nee 2001, Skabardonis 1998) employed techniques to estimate delay and the reduction in delay by service patrols; however, these methodologies are not well suited to non-research related evaluation efforts.

Incident clearance time (T) data may be obtained by subtracting the recorded clock time from the time that the incident is detected from the time that it is cleared (moving lanes cleared). An average incident detection period should be added to obtain the value for T. This data, along with the classification of incidents, is usually collected at the TMC by the traffic management system's incident management screens. Prior to obtaining the average value for T over the evaluation period for each incident class, it is recommended that incidents exceeding six hours in length be deleted from the average (or, at least, limited to six hours) because these long periods are often the result of conditions over which the TMC has little control or influence, such as weather, roadway damage, or special HAZMAT situations.

5.5.4 Service Patrol Measures

Motorist service patrols have proved very popular with the public University of California at Berkeley and Caltrans 2007, Nee 2001). Measures for evaluation include the following.

5.5.4.1 Service Patrol Assists

Most of the agencies that operate service patrols agencies maintain and often publish records of the number of assists and the type of service provided for each response.

5.5.4.2 Quality of Service

The following measures may be used to evaluate the quality of service provided:

- Patrol coverage periods (hours).
- Average motorist waiting time (minutes). This may be obtained from motorist surveys.
- Miles of roadway serviced.

Service patrol vehicle operators generally fill out a report for each assist provided such as that used by Washington State DOT and shown in Figure 10 (Nee 2001). The detailed information collected is useful for operations improvements.

5.5.4.3 Rating by Public

Feedback from the public is often obtained through surveys completed by motorists at the time service is provided. Figure 11 shows a survey form used by Washington State DOT. The public's rating on service is shown in Figure 12.

5.5.5 Response to Weather Situations

ITS may provide motorist information and information to police and highway maintenance agencies to assist in responding to weather situations that affect travelling conditions. These conditions include:

- Snow and ice
- Fog
- High winds
- Flooding.

These conditions may be detected by road weather information systems, fog detectors, and reports by service patrols, motorists, and police. A measure for this service is the average time in minutes from receipt of the alert to the time that information is provided to motorists and to other response services.

WSDOT Service Patrol Assist Form

Your Name	Agency/Company	Month	Day	Year

Location of Disabled Vehicle:

Hwy / Direction / MP/St	Lane Type	Lane Number
Hwy	❑ Mainline ❑ On-ramp	❑ Right Shoulder ❑ Lane 4
Direction	❑ HOV ❑ Exit-ramp	❑ Lane 1 ❑ Lane 5
MP/St	❑ Collector Distributor	❑ Lane 2 ❑ Left Shoulder
	❑ Express Lane	❑ Lane 3

Time logs for your response:

Detection/Notification	
❑ Subject was found by you	Time you detected or being notified __________
❑ Information broadcast by WSP	Time you arrived at the scene __________
❑ Other: ____________________	Time road cleared, vehicle out of travel lane __________
	Time you departed from the assisted vehicle __________

Check all that apply:

Cause	Problem	
❑ Disabled	❑ Fuel	❑ Push: a) ❑ off fwy, _______ ; b) ❑ to shoulder
❑ Accident	❑ Tire	❑ Tow: a) ❑ off fwy, _______ ; b) ❑ to shoulder
❑ Injury Accident	❑ Mechanical	❑ Assist
❑ Debris	❑ Overheat	❑ Clear off
❑ Pedestrian	❑ Electrical	❑ Transport
❑ Fire	❑ Abandoned	❑ Call additional tow service a) ❑ rotation tow; b) ❑ owner requested (tow name______________)
❑ UTL	❑ Blocking	❑ Call for assist a) ❑ WSP; b) ❑ Fire; c) ❑ EMT; d) ❑ Other: _________________
❑ Other: __________	❑ Other: ____________	❑ Photos taken
		❑ Other: ________________________________

Description of disabled vehicle:

	License No.	State	Color	Make	
Vehicle I					
Vehicle II					

Figure 10 Washington State Service Patrol Assist Form

WSDOT Service Patrol Survey

SERVICE PATROL
WSDOT • WSP • WTTA

Washington State
Department of Transportation

Dear Motorist: Assistance from this WSDOT Service Patrol is provided to you free of charge by the Washington State Department of Transportation. It is designed to reduce traffic congestion during your daily commute. To help us improve the service, please take a moment to answer these survey questions and mail the form back. No postage is necessary.

No gratuities or payments will be accepted by WSDOT Service Patrol drivers.
In addition, they cannot recommend secondary tow operators.

1. How did the WSDOT Service Patrol know you needed assistance?
- ❑ 1 Another driver saw me ❑ 2 Used a call box ❑ 3 State Patrol assistance
- ❑ 4 Other: ______________________________

2. How long did you wait for Service Patrol assistance?
- ❑ 1 Less than 5 minutes ❑ 2 5-10 minutes ❑ 3 10-20 minutes
- ❑ 4 20-30 minutes ❑ 5 30-40 minutes ❑ 6 Longer

3. If the Service Patrol moved your car to a safe area, how long did you wait for additional help?
- ❑ 1 Less than 15 minutes ❑ 2 15-30 minutes ❑ 3 30-45 minutes
- ❑ 4 45-60 minutes ❑ 5 60-90 minutes ❑ 6 Longer
- ❑ 7 No more help is needed

4. If you needed a secondary tow, what company did you choose and why?

____

5. What was the Service Patrol driver's attitude toward you while providing assistance?

____

6. Overall, how would you rate the service?
- ❑ 1 Excellent ❑ 2 Good ❑ 3 Fair ❑ 4 Poor ❑ 5 Other

7. How did you know about the Service Patrol Program?
- ❑ 1 Newspaper ❑ 2 Radio ❑ 3 TV
- ❑ 4 Brochure ❑ 5 Friend ❑ 6 Billboard
- ❑ 7 Other ______________ ❑ 8 Did know until today

8. How would you improve the WSDOT Service Patrol program?

____

____

____

For more information regarding the WSDOT Service Patrol, please call: (206) 726-6752

Figure 11 Washington State DOT Service Patrol Survey

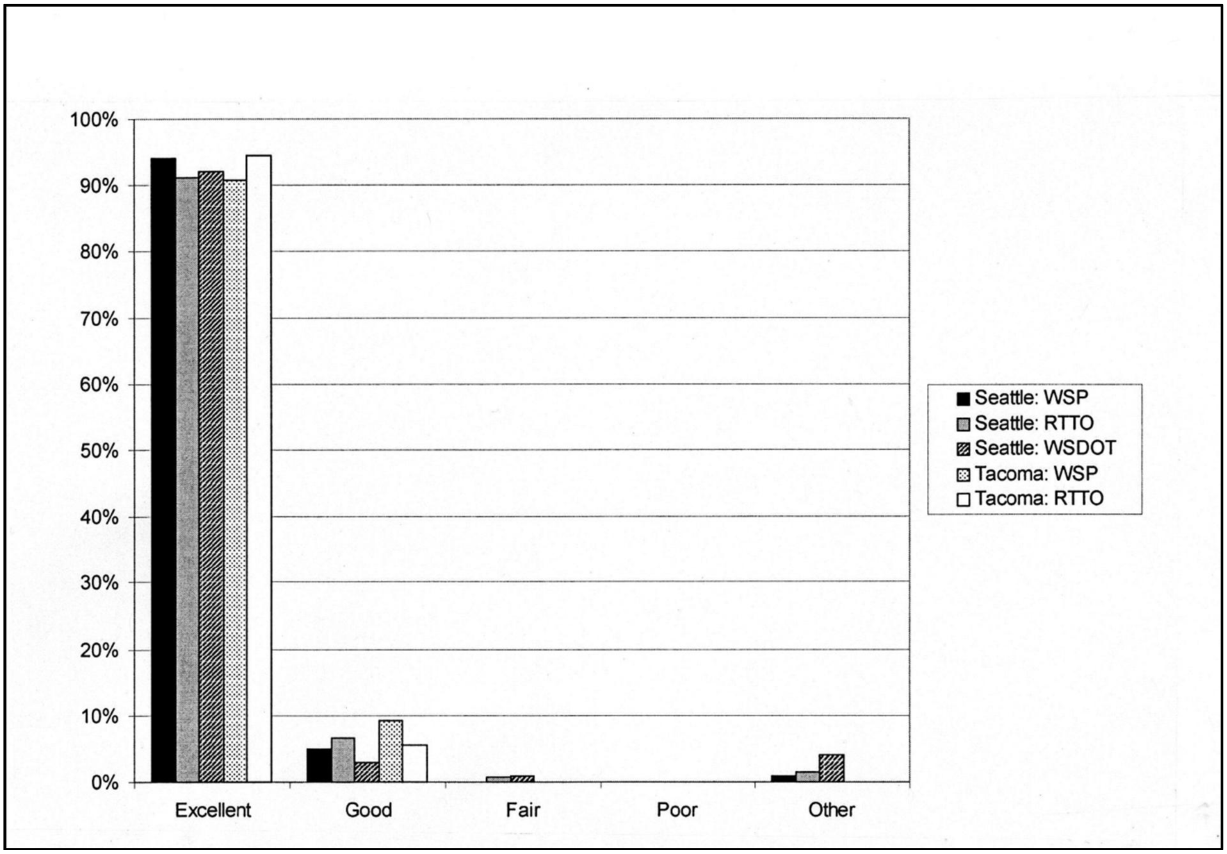


Figure 12 Public Rating on Washington State DOT Service Patrol Program

5.6 Database to Provide Motorist Information

Providing information to motorists is a key function of freeway and corridor TMCs. Information may be provided via:

- Devices on the roadway such as dynamic message signs (DMS) and highway advisory radio (HAR) that are operated by the TMC.
- Web and telephone based information services such as 511 that are operated by the TMC.
- Other delivery mechanisms such as media and private traffic information services.

It is important for the information provided by the TMC to be complete and consistent for all information delivery techniques. The following classes of information may be considered:

- Incidents
- Incident location
- Lanes closed

- Incident current delay
- Diversion information
- End of queue location
- General delay
- Travel time
- Travel time reliability
- Weather
- Ice/ snow
- Fog
- Slippery conditions
- Construction
- Location
- Lanes closed
- Delay.

The capability of the TMC to provide data that may be accessed by the delivery methods described above may be rated on a scale of 0 to 10 for each of the above classes.

6. TECHNIQUES TO SUPPORT DATA COLLECTION AND ARCHIVAL

This section discusses the following:

- Surveillance technologies
- Data validation
- Data quality
- Standards
- Relationship of benefits evaluation to project implementation phase
- Overview of the benefits evaluation process

6.1 Data Warehousing and Archived Data Management Systems for Freeways

Automatic measurement methodologies are based on the use of traffic detectors at selected locations on the roadway or on probe technologies (the tracking of vehicles on the roadway),

6.1.1 Point Detection and Generation of Traffic Data

A number of agencies currently have the capability to provide evaluations. Table 23 describes the data collection characteristics for several agencies. This data is initially generally aggregated to 5 minute periods before it is processed further for evaluation studies.

These systems are generally based on the measurement of traffic parameters at specific locations on the roadway and have historically relied on inductive loop detectors spaced at average distances of one third to two thirds of a mile. They provide volume and occupancy, and in some cases speed data to the TMC at intervals ranging from 20 seconds to one minute. If speed is not provided by the detectors themselves (a loop trap is required in order to sense speed), then speed is estimated at the TMC. A loop trap consists of two closely spaced loop detectors. The travel time between presence indications is a measure of speed. Recently other types of point detectors such as radar detectors have been used with increasing frequency.

Where loop traps are not available, speed may be estimated at the TMC from loop detector occupancy and volume measurements. A relationship employed by Washington State DOT (Ishimaru and Hallenbeck 1999) is provided by Equation 6-1.

$$v = \frac{q}{o \cdot g} \qquad (6\text{-}1)$$

Where

g is a factor that incorporates vehicle length and loop detector length
o = percentage occupancy
q = volume in vph
v = estimated speed

The Caltrans PeMS system accomplishes this function by using a continuously computed g factor (Varaiga, nd).

Table 23. Basic Data Generation for Representative Performance Monitoring Systems

System	California Performance Measurement System (PeMS)	Florida (STEWARD)	Minnesota	Oregon (PORTAL)	Washington State
Reference	Chan et al (2001)	Courage and Lee (2008)	Levinson (2004)	Bertini et al (2005)	Ishimaru and Hallenbeck (1999)
Principal Data Source	Single loop detectors in each lane reported every 20 seconds. Spacing approx 0.5 miles	Example installation uses RTMS radar detectors at approximately 0.25 to 0.5 mile spacing. Data reported every 20 seconds	Single loop detectors in each lane reported every 20 seconds. Spacing approx 0.5 miles	Loop traps in each lane reporting data every 20 seconds.	Single loop detectors in each lane reported every 20 seconds. Spacing approx 0.5 miles
Volume	From loop detectors	From RTMS detectors	From loop detectors	From loop detectors	From loop detectors
Occupancy	From loop detectors		From loop detectors	From loop detectors	From loop detectors
Speed	Computed from volume and occupancy by developing "g" factor in real time for each lane	From RTMS detectors	Computed from volume and occupancy assuming an average effective vehicle length (vehicle length plus loop length) of 22 feet	From loop detectors	Computed from volume and occupancy by use of "g" factor
Basic spatial definition	Segment – region between detector stations	Detector data migrated to travel links	Segment – region between detector stations	Segment – region halfway between detector stations	Segments defined by analyst reviewing spaces between detector locations
Short period time data organization	5 minutes	5 minutes, 15 minutes, 60 minutes	5 minutes	5 minutes, one minute data recoverable from 20 second data	1 minute 5 minutes
Notes	Statewide system that collects data from individual TMCs	State Statewide system that collects data from individual TMCs			

Where loop detector traps are employed, in addition to the measurement of speed, vehicle length may also be obtained, thus providing the potential to classify vehicles by length.

In recent years, point detectors other than inductive loop detectors have become more frequently. Commonly used technologies include FMCW (frequency modulated continuous wave) microwave radar detectors, passive acoustic detectors and video processor based detectors. While they may offer advantages in terms of installation and maintenance cost, and in the ease of communicating data to a communications node point, they are generally considered to be less accurate than inductive loop detectors. Examples of the technologies along with errors as reported in Hagemann (2010) are shown in Table 24. Other sources have reported other performance characteristics (e.g. Klein 2001). The errors often depend on the manufacturer's specific model, the type of mounting used, and the type of roadway environment. Weather may also affect performance. Supporting structures for these detectors are often located somewhat beyond the roadway shoulder.

6.1.2 Detector Station Location

During the design of a project, locations for point detector stations are often selected based on criteria such as ramp metering requirements or requirements to develop traveler information. Detector station locations based on these criteria may not satisfy the requirements for evaluation measures. *It should be noted that, as a minimum, volume and speed (obtained directly or inferred from other data) are required for each travel link (mainline section between ramp entry and/or exit locations as shown in Figure 3) in order to compute system delay measures, fuel consumption, throughput and emissions. For benefits evaluation purposes, the addition of supplementary detector stations may, in some cases, be required in order to fill these gaps.*

6.1.3 Traffic Data Screening and Data Imputation

Traffic management systems collect data from detectors for a wide variety of purposes. These systems generally include quality control techniques to validate the data and to synthesize missing data if the missing data would otherwise prevent the implementation of these functions. These techniques are briefly discussed below.

Table 24. Error Rate of Different Surveillance Technologies in Field Tests

Technology	Example of Technology	Mounting	Count Error %	Speed Error %
Inductive loop				
		Pavement saw-cut	0.1 - 3	1.2-3.3
Pneumatic road tube				
		Pavement	0.92-30	
Microwave radar				
	TDN 30	Overhead	2.5-13.8	1
	RTMS	Overhead	2	7.9
Active infrared				
	Autosense II	Overhead	0.7	5.8
Passive infrared				
	ASIM IR 254	Overhead	10	10.8
Video image processing				
	Autoscope Solo	Side-fire	5	8
	Autoscope Solo	Overhead	5	2.5-7
Ultrasonic				
	Lane King	Overhead	1.2	
Passive acoustic				
	SAS-1	Side-fire	8-16	4.8-6.3
Wireless sensor networks				
	VSN240	Pavement	1-3	

6.1.3.1 Data Screening

Most of the freeway management systems that are commonly used for performance evaluation purposes have the capability to screen the collected data for accuracy and in some cases to synthesize data where screening has shown it to be missing or incorrect. The following discussion describes a number of techniques that are used to perform these functions.

Smith and Venkatanarayana (2007) divide data screening tests into the following categories:

- Known errors recorded in the field
- Thresholds on single variable
- Relationship among the variables
- Relationship among records at the same sensor over time
- Relationship among records reported by neighboring sensors over time

Turner (2001) provides the following thresholds for acceptable data for thresholds on a single variable:

- Maximum volume < 250 vehicles per hour for 5 minutes
- Maximum occupancy < 90 percent for 5 minutes
- Maximum speed > 3 mph
- If the same volume is reported for four or more consecutive time periods, assume the detector is malfunctioning
- Rapid fluctuations in data values in consecutive 5 minute time periods (e.g. speeds going from 60 mph to 20 mph and back to 60 mph in consecutive time periods) imply faulty data

6.1.3.2 Data Imputation (Park 2005)

Imputation is the process of filling in the gaps that occur from missing data due to equipment, software, or communication failures. A number of techniques including, for example, simple historic averages, regression models, expectation maximization, and interpolations have been employed.

6.2 Data Quality Requirements

TMC performance evaluation requirements depend on the purpose and objectives of the evaluation as well as the quality of the data collection equipment and software available.

Errors for measured traffic data variables such as volume, speed, and occupancy may be classified as follows:

- Mean or bias errors. If successive measurements are made at a particular value of the variable (e.g., speed) the mean or average value of a large number of measurements made at this value is a resulting error that does not "average out." When evaluations are performed for the purpose of establishing absolute values of benefits (such as may be required to evaluate the benefits of ITS relative to other transportation options or other government services) it is necessary to establish the expected value of bias errors by means of testing.
- Random errors. When successive measurements of a traffic parameter are made, random errors tend toward zero as the number of sample points is increased. Thus the error in the evaluation is a function of the random error of the sensing component and the way that this error propagates into the measure and the sample size. Since many TMCs perform evaluations on a year-over-year basis, the most significant issue is the *change* in the measure during the periods between evaluations. If bias errors are stable over a period of time (and testing may be required to establish any changes in bias values), the random error component thus becomes the key error source for these cases. Since year-to-year changes in measures are usually small, it is important to design a measurement and evaluation process that is sufficiently accurate to identify small changes. To detect these changes in a statistically meaningful way, the measurement periods and physical regions must be defined so that a sufficient data

sample is collected to enable the data collection errors to be statistically reduced to an acceptable value.

It is recommended that agencies that are planning to conduct a benefits evaluation program prepare a detailed plan for implementing each measure selected. This plan should include accuracy objectives, traffic variable error estimates, geographical coverage areas, and sample size requirements.

6.3 Probe Detection and Generation of Traffic Data

6.3.1 Probe-Based Technologies

In recent years, probe data has become increasingly popular for obtaining speed and travel time information. In order to provide estimates for the system oriented measures described in Section 3, volume information is additionally required. The following probe technologies have been used for ITS applications.

GPS information provided by a service provider. In many cases the service provider combines GPS information with information obtained from other sources to provide a better estimate than any one source can provide. Large-scale testing of this technology, as provided by the INRIX Corporation has been performed by the I-95 Corridor Coalition. An example of the test results for tests in all States in the Coalition is shown in Table 25 (I-95 Corridor Coalition 2010).

Table 25. I-95 Corridor Coalition Probe Detection Test Results

Speed Bin	Requirement Absolute Average Speed Error < 10 mph	Requirement Speed Error Bias < 5 mph	Hours of Data Collection	Percent of Total Data
0-30 MPH	5.3	2.7	800.5	3.4%
30-45 MPH	6.3	2.1	777.5	3.3%
PH	2.4	0.0	4,625.0	19.4%
>60 MPH	2.6	-2.3	17,566.2	73.9%
All Speeds	2.8	-1.5	23,769.2	100%

The information obtained from a traffic service provider may only be used in the ways that are identified in the contractual arrangements. This may constrain its application (as compared with information generated by the operational agency).

Bluetooth traffic monitoring. A number of vehicles employ devices using the Bluetooth short range point-to-point networking protocol. In many cases these are detectable by roadside detectors. Using Machine Access Control (MAC) addresses, these vehicles can be tracked. The I-95 Corridor Coalition tested this technology in conjunction with the testing of INRIX data. An example of the comparative results (with several floating vehicle tests performed by the

University of Maryland) is shown in Figure 13 for an AM peak period (I-95 Corridor Coalition ND).

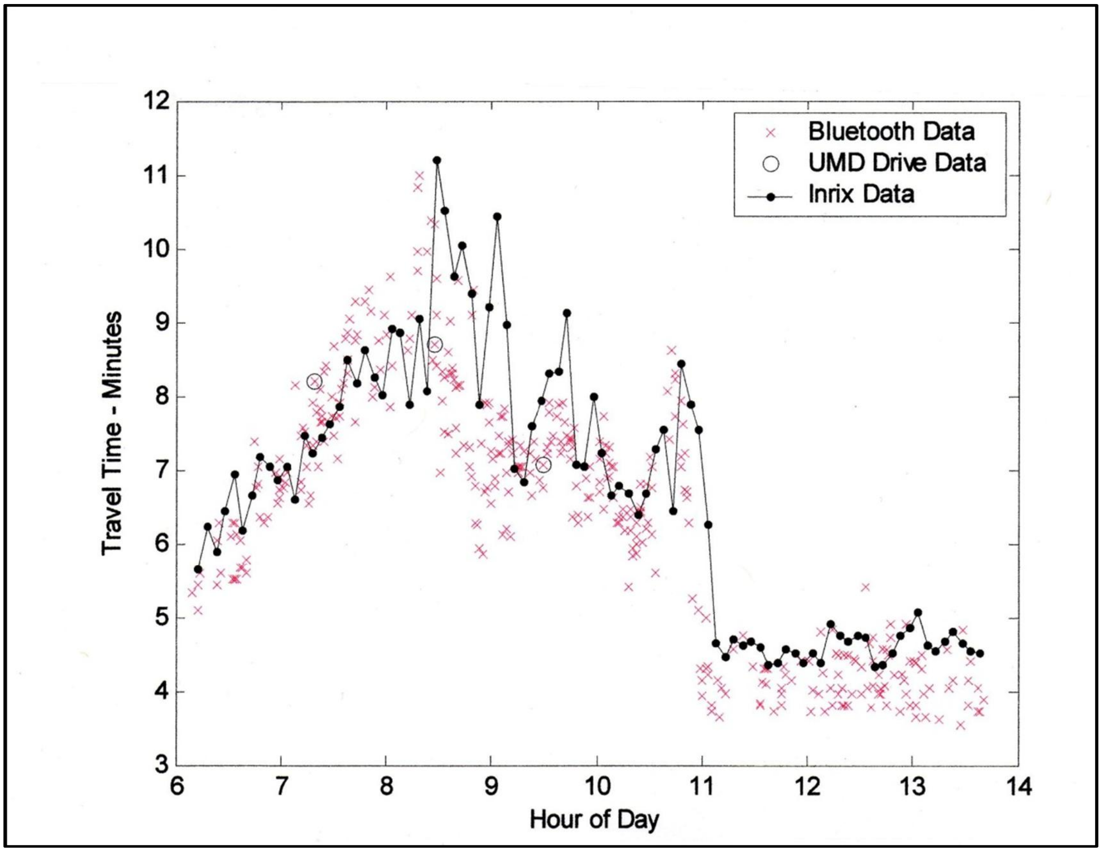


Figure 13 Comparison of INRIX Data with Bluetooth Data and Measured Travel Time

Toll tag reader-based probe surveillance. Some agencies use toll tag readers to serve as probe vehicle detectors, primarily for the purpose of providing travel time information to motorists and to illuminate a traffic condition map (Niver 1990). This technology is effective in determining travel time in those locations with a high market penetration of toll tags. The relatively high price for the readers may limit the number of readers that may be installed.

Cellular telephone-based probe technologies. Speed and travel time may be obtained by using the GPS features of cellular telephones or by triangulating the signal received at cellular telephone towers, a service provided by some private firms. While this technology is being improved, results to date have not shown sufficiently consistent accuracy, particularly at low speeds, to warrant its employment for evaluation purposes (Hagemann 2010).

6.3.2 Use of Probes for Benefits Evaluation

At this time it appears that probe information developed by service providers, Bluetooth probe readers, and toll tag readers have the potential to provide information to develop travel-time-related measures (measures Q.1 and Q.2 in Table 6). *As with point detection, a well designed evaluation program is required to assure that the accuracy of the results is consistent with the objectives of the evaluation.*

To obtain data for the system-based measures (measures D, F, T and E in Table 6), this information must be supplemented by volume information for each mainline link. Where ITS are not sufficiently equipped with point detectors to meet this requirement, but are equipped with CCTV camera coverage for these links, it may be possible to use video processor detectors located at the TMC to develop this information. During evaluation periods the field of view for these cameras cannot be changed, thus it will be possible to develop only a limited data set for this situation.

6.4 Automation of Data Collection for Surface Street Measures

As indicated in Section 5.1.4, signal timing evaluation is traditionally performed using manual techniques: intersection delay is measured by manual observation of queues and travel time is obtained by floating vehicle techniques. Evaluations of this type are often conducted in conjunction with a signal retiming project. Because of the number of observations and floating vehicle runs required to obtain statistically significant data for different time periods, these evaluations may be expensive if conducted frequently.

In recent years there has been considerable interest in researching automatic data collection and reduction processes to obtain intersection delay data. The following techniques have been described:

- Addition of field equipment to provide delay measures. Balke and Herrick (2004) describe the Traffic Signal Performance Monitoring System (TSPMS) which develops measures for isolated intersections. Liu and Ma (2007) report on the SMART-SIGNAL system. Figure 14 shows the SMART-SIGNAL system's architecture. The system was developed by the University of Minnesota, and the figure shows the data processing as located at that facility. The local data collection units are SMART-SIGNAL equipment that must be added to the controller cabinet. The parameters generated by the SMART-SIGNAL system include intersection delay, stops, level of service, queue length, and corridor travel time.
- Modification of software in traffic controllers. Using detectors at the intersection and upstream of the intersection, Smaglik, et al. (2007) describe a data logger added to the intersection controller software that enables it to be downloaded to a central facility for processing. Time stamped detector data and phase change data are returned from the controller and processed to develop delay data using the difference between the arrival profile and the departure profile. Algorithm details are described in Sharma et al. (2007).

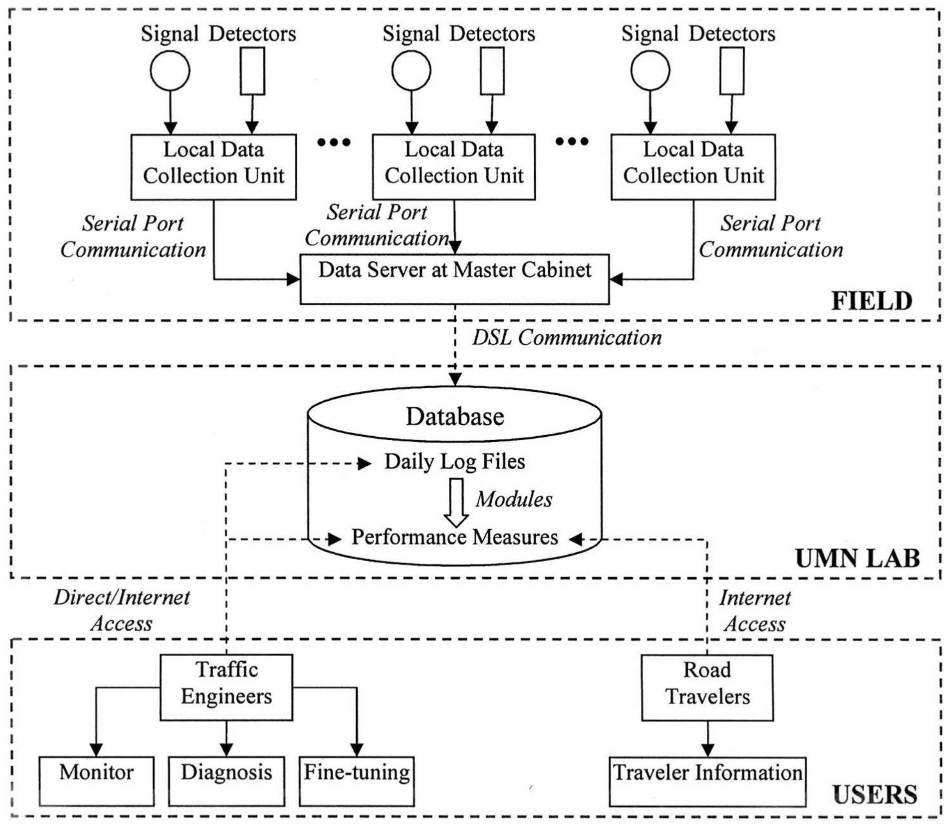


Figure 14 The SMART-SIGNAL System Architecture

6.5 Standards

The National ITS Architecture provides general guidelines regarding Archived Data User Services. The development of standards was assigned to the ASTM ADUS Subcommittee (ASTM E17.54). The following relevant standards have been developed:

- ASTM E2259-03a Standard Guide for Archiving and Retrieving Intelligent Transportation System-Generated Data
    - This is a guide and not a standard in that it does not specify formats and processes. Key guidelines include the following:
        - Data should be archived at the finest possible resolution provided by the sensors.
        - Raw sensor data should be archived for a sufficient period to allow the collection of statistically significant information.
        - Raw sensor data should be stored at the resolution for which it was collected.
        - Traffic parameters generated from these data should be archived.
        - Indicators of data quality, collection conditions and the type of data source should be documented.

- ASTM E2468-05 Standard Practice for Metadata to Support Archived Data Management Systems
  - This document provides guidance on the following:
    - Data set identification
    - Data quality
    - Representation of spatial information
    - Coordinate reference frames and encoding
    - Entity types, attributes and value domains
    - Timeliness of information
- ASTM E2665-08 Standard Specifications for Archiving ITS-Generated Traffic Monitoring Data
  - This document defines the names of the data elements, their interrelationships, data collection methodologies and calculation of traffic statistics. Entities such as detector stations and lanes are defined.

6.6 Relationship of Benefits Evaluation to the Project Implementation Phase

The functions of the evaluation will vary with the time phase of the project. When the project becomes operational, the initial evaluations often center on the benefits achieved by the project in a before-and-after context. As time progresses, interest becomes more focused on the year-over-year benefit changes achieved by improvements to TMC operations as well as demand changes. Table 26 identifies general approaches that may be employed as the evaluation emphasis changes.

Table 26. Evaluation Approaches

Evaluation Objective	Project Phase	Possible Evaluation Approach
Continuous year-over-year evaluation	Project operational	Use methodologies as described in this report. Consider adding supplementary surveillance to correct deficiencies in providing automated data.
Before and after evaluation followed by year-over-year evaluation	Project complete or under construction but no "before" data available	Use methodologies described in this report for "after" data. Evaluate after conditions using a simulation model and calibrate the simulation to the field results. Use calibrated simulation to evaluate "before" conditions.
Before and after evaluation followed by year-over-year evaluation	Project in design or design has not yet started	Concurrently develop evaluation plan and provide field devices for data collection consistent with methodologies described in this report. After implementation is complete, using the project's field devices, collect data for a period of time. This will serve as "before" data. Subsequently initiate ITS operation and collect "after" data.

6.7 Overview of the Benefits Evaluation Process

The following steps are required to implement the benefits evaluation process described in this report:

- Define the purpose and objectives of the evaluation. For example, if the evaluation focuses on benefits as sensed by highway users, then travel time and related measures are emphasized. It may be possible to implement these measures using only probe detection; however, measures involving benefit vs. cost analysis such as system delay require volume detection as well. The level of accuracy required for the evaluation should also be identified.
- Define the evaluation network and the time period of the evaluation. These include the physical boundaries of the net work to be evaluated and the time periods or function (e.g., before -after analysis).
- Develop an evaluation plan. The plan should include the following elements:
  - Determine need for additional surveillance – Additional surveillance may be needed to close surveillance gaps in the network to be evaluated.
  - Estimate errors in surveillance system – An estimate of these errors is required for the following step.
  - Develop sample size and data collection periods and define evaluation regions. Using the evaluation accuracy requirements, the sample size and data collection periods should be defined. The evaluated region may need to be subdivided to maintain accuracy.
  - Collect data for the period defined by the plan.
- Compute the measures. Section 5 describes algorithms and computational procedures for evaluating the measures.
- Report and Document the Results.

7. EVALUATION REPORTING

Evaluation reports may be prepared for the following purposes:

- Reports indicating performance changes in day-to-day operations. Examples of TMC operating changes that may result include changes to DMS and HAR message formats, changes to signal timing plans and changes to ramp metering rates. These reports may be informal and are intended for use within the TMC.
- Reports to higher levels in the agency's management. These reports may be used to assess operational deficiencies and to establish resource priorities within the agency.
- Reports intended for widespread review by jurisdictional government officials and by the public. They may assist officials in assigning resources among agencies in the jurisdiction or in assessing the overall worth of the project.

Examples of reports prepared by agencies include the following:

- Houston TranStar 2009 Annual Report (Houston TranStar Consortium, nd) – This report describes the project's mission, , management structure activities, agency participants, and user statistics. In addition to providing such performance measures as the number of managed incidents and the number of motorist aid program assists on a system-wide basis, it describes such outcome oriented measures as:
  - Average incident clearance time (Figure 15)
  - Motorist cost savings (Figure 16)
  - Benefit to cost ratio (Figure 17)

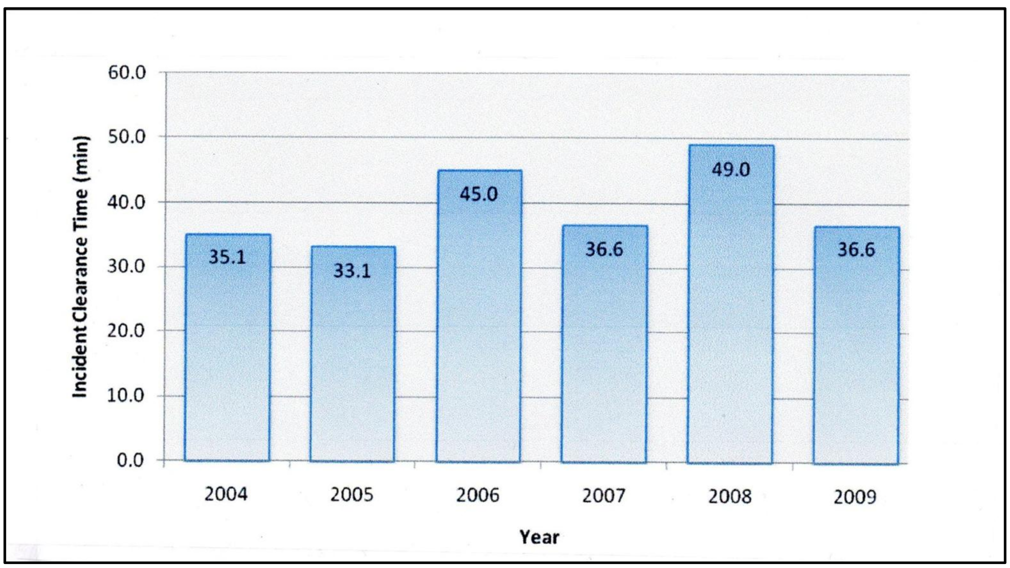


Figure 15 Annual Average Incident Clearance Time, 2004-2009

Agencies might consider the addition of a band in the columns of such figures as Figures 16 and 17 that represents the standard error of the estimate or some other measure of error.

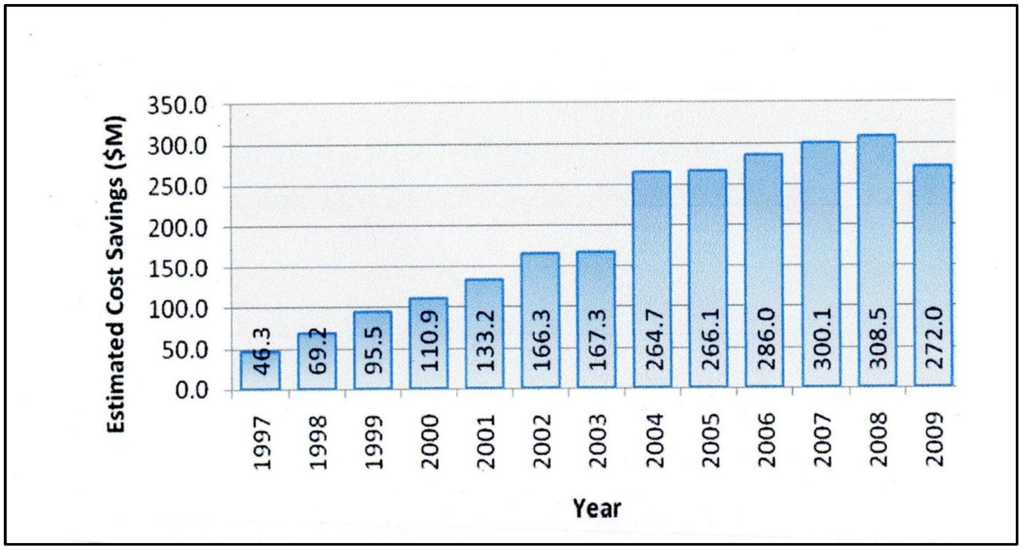


Figure 16 Estimated Annual Motorist Cost Savings Attributed to Houston TranStar Operation

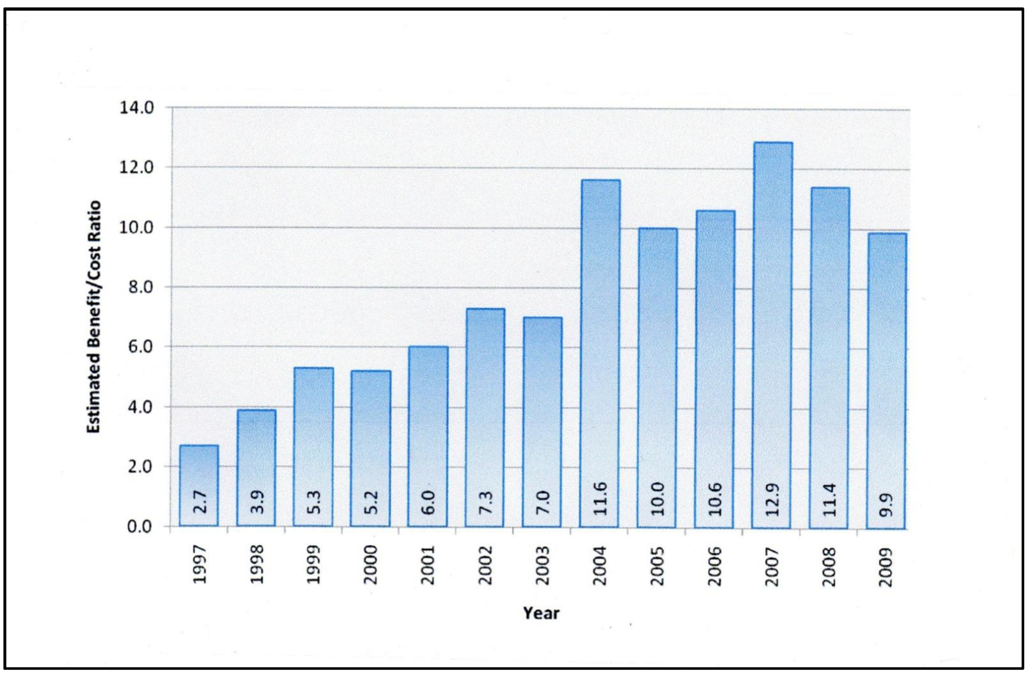


Figure 17 Houston TranStar Benefit/Cost Ratios 1997-2009

Michigan Intelligent Transportation Systems Center

The monthly report developed by the Michigan Intelligent Transportation Systems Center (Michigan Department of Transportation 2010) provides a detailed overview of performance. In addition to providing measures such as the number of motorist messages provided, it provides outcome oriented statistics such as freeway service patrol response and clear times (Table 27)

Table 27. Freeway Service Patrol Performance Statistics

Freeway Segment		TOTAL ASSISTS		ASSIST DENSITY		AVERAGE RESPONSE TIME (min)		AVERAGE CLEAR TIME (min)	
	(miles)	Sep. 2010	FYTD Avg.	Sep. 2010	FYTD Avg.	Sep. 2010	FYTD Avg.	Sep. 2010	FYTD Avg.
I-75									
Oakland County Line to I-696	37.0	420	391.0	11.4	10.6	17.6	16.7	8.8	10.0
I-696 to I-94	8.0	273	252.3	34.1	31.5	9.8	10.2	13.5	10.8
I-94 to I-96	5.6	88	71.0	15.7	12.7	12.0	11.0	11.5	10.3
I-96 to I-275	37.0	270	281.7	7.3	7.6	14.0	14.4	8.0	8.2
	87.6	1,051	995.9	12.0	136.4	13.6	13.4	10.0	9.7
I-94									
Washtenaw County Line to M-39	20.7	357	329.3	17.2	15.9	12.5	13.5	8.8	9.0
M-39 to I-75	9.0	278	275.8	30.9	30.6	12.8	11.5	10.3	9.6
I-75 to I-696	10.0	294	281.3	29.4	28.1	13.8	12.4	9.2	9.0
I-696 to St. Clair County Line	21.0	130	194.6	6.2	9.3	19.0	13.7	6.0	7.8
	60.7	1,059	1,080.9	17.4	213.7	13.6	12.5	9.0	8.9
I-96									
Livingston County Line to I-275/I-696	11.0	137	122.9	12.5	11.2	15.3	17.3	8.2	8.2
I-275/M-14 to M-39	12.0	244	243.5	20.3	20.3	11.6	12.5	10.6	8.7
M-39 to I-75	11.0	370	312.6	33.6	28.4	10.6	11.6	9.0	8.1
	34.0	751	679.0	22.1	239.6	12.0	13.3	9.4	8.4
I-275									
I-96/I-696 to M-14/I-96	8.0	121	116.2	15.1	14.5	12.5	15.1	8.2	8.8
M-14/I-96 to I-94	12.0	120	146.8	10.0	12.2	14.3	13.6	9.0	8.0
I-94 to I-75	17.5	63	72.9	3.6	4.2	11.6	13.6	11.2	8.0
	37.5	304	335.8	8.1	107.5	13.4	14.2	9.1	8.3
I-696									
I-96/I-275 to M-10	9.3	176	146.8	18.9	15.8	14.1	14.4	8.9	8.7
M-10 to I-75	9.0	143	145.7	15.9	16.2	14.0	12.6	8.0	8.8
I-75 to I-94	10.4	181	194.4	17.4	18.7	14.5	12.5	8.2	8.5
	28.7	500	486.9	17.4	203.6	14.2	13.0	8.4	8.7
M-59 (Veterans)	24.0	26	28.9	1.1	1.2	15.0	19.9	9.7	10.1
I-375	1.2	6	8.7	5.0	7.2	11.0	13.1	3.3	8.7
M-10 (Lodge)	17.9	332	351.8	18.5	19.7	11.2	11.2	8.7	9.4
M-14	6.4	60	70.3	9.4	11.0	11.4	13.9	6.2	7.7
M-39 (Southfield)	14.2	249	269.1	17.5	18.9	10.7	11.9	10.0	9.6
M-5 (Grand River)	10.3	43	37.8	4.2	3.7	12.6	14.5	7.9	8.0
M-8 (Davison)	2.2	29	45.7	13.2	20.8	8.9	8.7	9.3	9.7
Total	324.7	4,410	4,390.8						

Naperville, Illinois (website)

New timing plans are implemented based on periodic examination of traffic conditions. Formal evaluations are conducted in conjunction with signal retiming projects. An example of such a study is shown in Table 28 (Naperville website).

Table 28. Example of Naperville, Illinois Evaluation of Signal Retiming Results

Ogden Avenue/US Route 34 Traffic Signal System
Fort Hill Drive to Columbia Street
(4.7 Miles)
2007

TRAVEL TIME / DELAY SUMMARY

Time Period	Travel Direction	Condition	Travel Time (seconds)	Delay (seconds)	Stops	Average Speed (mph)
AM Peak	Eastbound	Before	920.0	474.3	11.7	17.2
		After	697.0	245.7	7	22.7
		Change	223.0	228.6	4.7	5.5
		% Change	24.2%	48.2%	40.2%	32.0%
	Westbound	Before	675.3	239.3	6.3	23.5
		After	568.0	168.7	3.7	27.9
		Change	107.3	70.6	2.6	4.4
		% Change	15.9%	29.5%	41.3%	18.7%
Midday	Eastbound	Before	624.0	194	6	25.4
		After	542.7	111	5	29.3
		Change	81.3	83.0	1.0	3.9
		% Change	13.0%	42.8%	16.7%	15.4%
	Westbound	Before	687.3	251	6.7	23.1
		After	552.0	152	3	28.7
		Change	135.3	99.0	3.7	5.6
		% Change	19.7%	39.4%	55.2%	24.2%
PM Peak	Eastbound	Before	732.3	293	6	21.7
		After	635.3	194.7	3.7	25
		Change	97.0	98.3	2.3	3.3
		% Change	13.2%	33.5%	38.3%	15.2%
	Westbound	Before	916.3	486.7	9.3	17.3
		After	736.0	312.7	7.3	21.6
		Change	180.3	174.0	2.0	4.3
		% Change	19.7%	35.8%	21.5%	24.9%

VEHICLE EMISSIONS SUMMARY
PERCENT REDUCTION

Time Period	Travel Direction	Hydrocarbons (grams/day)	Carbon Monoxide (grams/day)	Nitrogen Oxide (grams/day)
AM Peak	Eastbound	7%	2%	-11%
	Westbound	5%	-5%	-1%
Midday	Eastbound	5%	2%	-2%
	Westbound	13%	1%	12%
PM Peak	Eastbound	9%	8%	5%
	Westbound	10%	2%	3%

VEHICLE EMISSIONS SUMMARY
ANNUAL EMISSION REDUCTION

Time Period	Hydrocarbons (tons/year)	Carbon Monoxide (tons/year)	Nitrogen Oxide (tons/year)
AM Peak	-16	10	10
Midday	-40	-71	-13
PM Peak	-28	-140	-6

8. BENEFIT AND COST ANALYSIS

8.1 Life Cycle Cost

A number of different formulations may be used to relate the value of money and the annual cost of a project. Because many of the costs in a project are incurred annually and because the project benefits are incurred annually, life cycle cost is conveniently expressed as annualized cost (Maccubin 2003). Computation of life cycle cost is described in New York State Department of Transportation (2004).

The value of design cost and construction cost (PDC) is given by Equation 8-1.

$$PDC = Design\ cost + Construction\ cost \quad (8\text{-}1)$$

The capital recovery factor (CRF) relates the interest rate (I) and system operational life (NL) to these capital costs by equation 8-2.

$$crf = \frac{I \cdot (1+I)^{NL}}{(1+I)^{NL} - 1} \quad (8\text{-}2)$$

Tables for CRF are also provided in standard economics texts. Historical interest rates for a period of several years are more likely to be appropriate than the use of the current interest rate.

The uniform annual equivalent investment cost (REI) is provided by equation 8-3.

$$REI = PDC \cdot CRF \quad (8\text{-}3)$$

Annualized life cycle cost (LCC) is provided by Equation 8-4.

$$LCC = REI + Annual\ operating\ cost + Annual\ maintenance\ cost \quad (8\text{-}4)$$

In Equation 8-2, the system operational life (NL) may be considered to be the average life of a component weighted by the furnish and install cost of the component for the project. It is recommended that an estimate for NL be obtained by evaluating the weighted average life for 10 of the most costly components.

8.2 Estimating Monetary Benefits

Section 8.1 describes the development-of-project cost on an annualized basis. The benefit evaluation techniques discussed in this report generally provide system-wide performance values on an annual basis. The monetary value of project benefits is provided by the difference between the performance for the baseline period for the evaluation and the current operation period. The baseline period may be taken as the performance period prior to the introduction of the ITS or a major change in operation. Section 6.6 discusses evaluation alternatives when prior evaluations have not been performed. Table 29 identifies the monetary performance components included in each of these evaluations.

Table 29. Performance Component for Benefit vs. Cost Analysis

Component	Expression	Reference for key parameters
Private vehicle occupant system delay	PVOSD = H1 · LPP	Equation 5-17
Commercial vehicle occupant system delay	CVOSD = H2 · LPT	Equation 5-18
Goods inventory delay	GID = H3 · LPG	Equation 5-19
Cost of crashes	CC = H4 · CRA	
Cost of fuel	$CF = H5 \cdot \sum_{\text{Domains}} \sum_{\text{Five minute periods}} FUF(DO, T5)$	Equation 5-31

Representative values for coefficients H1 through H5 in Table 29 are provided in Table 30.

Table 30. Representative Value Coefficients

Coefficient	Definition	Representative Value in 2010	Reference for Value
H1	Private vehicle occupant system delay ($ per vehicle occupant)	17.02	Average of: Nee and Hallenbeck (2001) Houston (2009) New York State Department of Transportation (2004) All adjusted to 2010
H2	Commercial vehicle occupant system delay ($ per vehicle occupant)	27.49	Intelligent Transportation (2004) adjusted to 2010
H3	Goods inventory delay ($ per ton hour)	30.81	New York State Department of Transportation (2004) adjusted to 2010
H4	Cost of crashes ($ per crash)	45,585.00	Average of: Nee and Hallenbeck (2001) Houston (2009) New York State Department of Transportation (2004) All adjusted to 2010
H5	Cost of fuel ($ per gallon)	Average of past 3 years	

Crash costs provided are the cost of fatality, injury, and property damage only crashes weighted by the frequency of the accident class.

Costs were adjusted to year 2010 levels by using the relationship:

$$CPIR = \frac{CPI\ for\ year\ 2010}{CPI\ for\ year\ data\ obtained} \quad (8\text{-}5)$$

The consumer price index (CPI) may be obtained from the Bureau of Labor Statistics website ftp://ftp.bls.gov/pub/special.requests/cpi/cpiai.txt. The annual average value column was used in all cases for the representative data in Table 30.

The annualized monetary performance for the project is provided by Equation 8-6.

$$MP = H1 + H2 + H3 + H4 + H5 \quad (8\text{-}6)$$

The annualized monetary benefit for the project is given by Equation 8-7.

$$MB(E) = MP(BA) - MP(E) \quad (8\text{-}7)$$

where BA is the baseline year and E is the year for which the evaluation is performed. Note that the values for H1 through H5 for the evaluation year should be used for the base year as well.

8.3 Benefit and Cost Relationships

Comparisons of benefits and costs often provide the basis for initiating projects, continuing to operate projects, and modifying project equipment or operations.

8.3.1 Benefit-to-Cost Ratio

The benefit to cost ratio provided in Equation 8-8 is the most commonly used measure of the value of a project and is often used to assist in prioritizing resources among competing requirements for resources. While a benefit-to-cost ratio of greater than 1.0 is required for viable projects, projects with higher benefit-to-cost ratios often provide decision makers with preferred rationales for project funding. Note that values for both MB and LCC are in evaluation-year dollars.

$$\frac{B}{C} = \frac{MB}{LCC} \quad (8\text{-}8)$$

8.3.2 Other Benefit and Cost Relationships

Although benefit-cost (B/C) is a commonly used measure, when design alternatives for a new project or a major addition to a current project is contemplated, it should be considered in the context of overall costs and benefits.

Figure 18 shows several possible system design or operation alternatives. The slopes of the dotted lines (when the axes scales are considered) is the B/C. Although Alternative A has the higher B/C, Alternative B provides significantly greater benefits. The slope a line from Alternative A to Alternative B shows the marginal benefit-to cost ratio of Alternative B relative to Alternative A. If this slope is significantly greater than 1.0, Alternative B may be preferred, as it provides significantly greater benefits at an acceptable incremental cost.

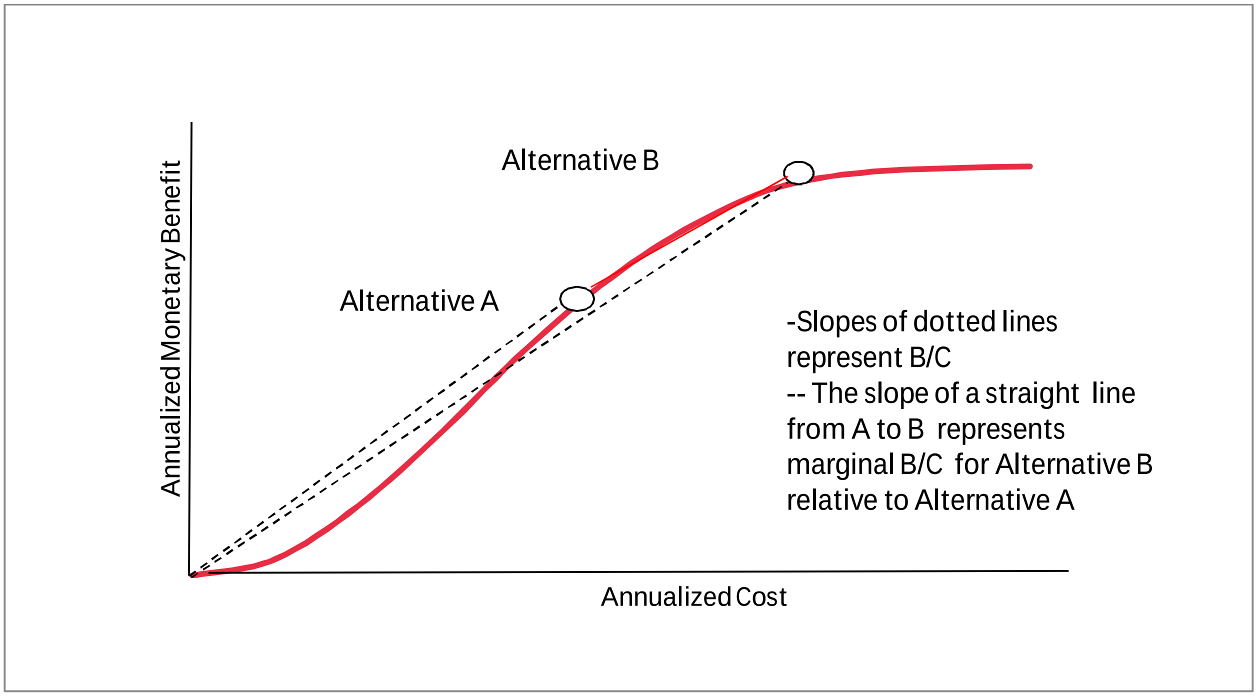


Figure 18 Monetary Benefits and Costs for Project Alternatives

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Appendix A. Example of Progression to Performance Measures

The following sequence illustrates the process used by the Maricopa Association of Governments (Maricopa Association of Governments 2003). The process starts with the development of goals (Table A.1) and progresses to the development of initiatives to achieve these goals and the functions required (Table A.2). Figure A.1 shows the measures used to evaluate the goals.

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Table A.1 (Page 1 of 2)
Goals

Operational Categories	Three-Year Goal	Five-Year Goal
Freeway Mobility	▪ Limit the percent increase in average travel time to less than the percent increase in traffic volume.	▪ Same as three-year goal.
Arterial Mobility	▪ Limit the percent increase in average arterial travel time to less than the percent increase in traffic volume. ▪ Optimize traffic signal coordination within and between cities on major arterials, or where appropriate.	▪ Continue to limit the percent increase in average arterial travel time to less than the percent increase in traffic volume. ▪ Update the traffic signal coordination within cities and between cities every two years or when traffic volumes through the intersection change by more than five percent.
Freeway Incident Management	▪ Reduce incident duration by 10 percent.	▪ Reduce incident duration by 20 percent.
Freeway-Arterial Interface	▪ Establish integrated freeway-arterial corridor operations on one corridor.	▪ Establish integrated freeway-arterial corridor operations on three corridors.
Arterial Incident Management	▪ Conduct a feasibility and planning study for a multi-jurisdictional arterial incident management program.	▪ Implement a multi-jurisdictional arterial incident management program (based on outcomes of feasibility study).
Arterial Operations	▪ Establish a regional standard for implementation of emergency vehicle signal preemption (EVSP).	▪ Ensure adoption of the EVSP standard by each of the MAG member agencies, and implement the standard on 100 percent of the traffic signals with EVSP.
Transit Mobility	▪ Deploy a transit signal priority pilot project.	▪ Where beneficial, deploy transit signal priority to BRT routes.
Computer System Reliability	▪ Operate the system with up time of 95 percent – no more than 450 hours down time per year. Allows for approximately eight hours of system maintenance per week. Maintenance is preferably conducted in off-peak periods. ▪ Minimize system down time to an average of one hour per system failure.	▪ The five-year goals for system reliability are the same as the three-year goals.

Table A.1 (Page 2 of 2)

OPERATIONAL CATEGORIES	THREE-YEAR GOAL	FIVE-YEAR GOAL
MULTI-AGENCY COORDINATION	▪ Establish center-to-center communications between 15 agencies in the region. These agencies should include traffic and transportation, enforcement, emergency management, and transit. ▪ Facilitate incident and emergency response and travel information sharing between 15 agencies.	▪ Establish center-to-center communications between 20 agencies in the region. These agencies should include traffic and transportation, enforcement, emergency services, and transit. ▪ Facilitate incident and emergency response and travel information sharing between 20 agencies.
TRAVEL INFORMATION PROVISION	▪ Increase travel information usage (web, 511, television, radio, etc.) by 100 percent, and achieve a 75 percent customer satisfaction rating. On a scale of 1 to 10, a score of 7 or higher is desired. ▪ Expand Phase 1 of the ADOT / MCDOT / City of Scottsdale web-based HCRS pilot project for local closure and restriction information to include 5 additional MAG member agencies (Phase 2). ▪ Incorporate transit status information from AVL data from buses into travel information services. ▪ Develop web-based arterial maps for 100% of instrumented smart corridors.	▪ Increase travel information usage (web, 511, television, radio, etc.) by 200 percent, and achieve a 75 percent customer satisfaction rating. On a scale of 1 to 10, a score of 7 or higher is desired. ▪ Evaluate performance capabilities of Phase 2 web based HCRS pilot project for local closure and restriction information and expand to include additional MAG member agencies. ▪ Obtain travel time information on 50% of instrumented arterial roadways and post this information to Web, 511, and variable message signs.

Table A.2 (Page 1 of 3)

INITIATIVES		FUNCTIONS
REGIONAL TRAFFIC SIGNAL OPTIMIZATION PROGRAM	**Improved traffic signal timing within cities and across jurisdictional boundaries will result from better regional traffic engineering collaboration.**	▪ **Optimize agency traffic signal system operations.** ▪ **Optimize traffic signal operations of cross-border traffic signals and regional arterials.** ▪ **Develop regional pre-set traffic signal timing structure and criteria for traffic signal timing plan changes during incidents.**
ARTERIAL AND FREEWAY INCIDENT MANAGEMENT	**Improved incident management can be achieved with better collaboration of the fire and public safety personnel with the transportation departments.**	**Freeways** ▪ **Improve agency-specific incident management practices and guidelines to reduce incident clearance times.** ▪ **Schedule incident debriefing sessions after large incidents with representatives of public safety, fire departments, and applicable local transportation agencies.**

Table A.2 (Page 2 of 3)

INITIATIVES		FUNCTIONS
ARTERIAL AND FREEWAY INCIDENT MANAGEMENT (CONTINUED)		▪ Improve the pre-qualified list of towing and recovery vehicles. ▪ Facilitate agreements between agencies to extract computer-aided-dispatch (CAD) information for travel information services and ADOT TOC. ▪ Facilitate improvement of practices for on-scene coordination and communication. ▪ Facilitate improvement of practices for placement of emergency vehicles at incident scenes. **Arterials** ▪ Implement and maintain a multi-jurisdictional Arterial Incident Management Program, based on results of feasibility study and pilot project. ▪ Facilitate agreements between agencies to extract CAD information for local traffic management centers.
SHARED MAINTENANCE RESOURCES	Improved system performance and significant cost savings to the region will result from sharing resources (staff and equipment).	▪ Improve preventive maintenance and prompt repair of locally owned ITS field devices and central systems. ▪ Improve preventive maintenance and prompt repair of regionally significant ITS field devices and central systems. ▪ Maintain regional communications infrastructure. ▪ Develop cost sharing agreements between agencies.
FREEWAY-ARTERIAL OPERATIONS	An emphasis and focus on improving the operations of the arterials and freeways at traffic interchanges can be beneficial in optimizing the operation of the freeways and arterials.	▪ Plan, deploy, operate and maintain a freeway-arterial corridor operations pilot project.
EMERGENCY VEHICLE SIGNAL PREEMPTION	Preemption on a regional basis will be more effective and safer with a common set of standards for its implementation.	▪ Develop regionally accepted standard for emergency vehicle signal preemption.
TRANSIT SIGNAL PRIORITY	The implementation of transit signal priority on a corridor will demonstrate the effectiveness of this concept for regional transit mobility.	▪ Plan, deploy, operate, maintain and evaluate a Transit Signal Priority pilot project.

Table A.2 (Page 3 of 3)

INITIATIVES		FUNCTIONS
CENTER-TO-CENTER COMMUNICATIONS	Better communications between agencies.	▪ Establish center-to-center communications between agencies.
ARCHIVED DATA	Collecting and storing data from implemented transportation systems will be an excellent resource for the region in planning operational enhancements.	▪ Develop and implement a regional data archiving system.
LOCAL TMC AND ADOT TMC OPERATORS	The effectiveness of TMC operators will be improved with better coordination and communication between themselves.	▪ Develop and maintain a comprehensive personnel and logistics resource list. ▪ Develop practices for after-hours monitoring of local TMC systems and devices. ▪ Improve inter-agency communication between TMCs during incidents.
TRAVEL INFORMATION	Improved travel information in the MAG region will benefit the regional mobility.	▪ Make available work zone and incident information to HCRS and/or 511. ▪ Integrate transit information with travel information services (e.g., provide AVL data to 511). ▪ Develop practices for collecting information from arterial detectors. ▪ Post travel information/messages on freeway and arterial VMS. ▪ Market travel information services.
PERFORMANCE MEASUREMENT	The effectiveness of all the initiatives can be measured through a performance measurement program.	▪ Develop performance measurement program.

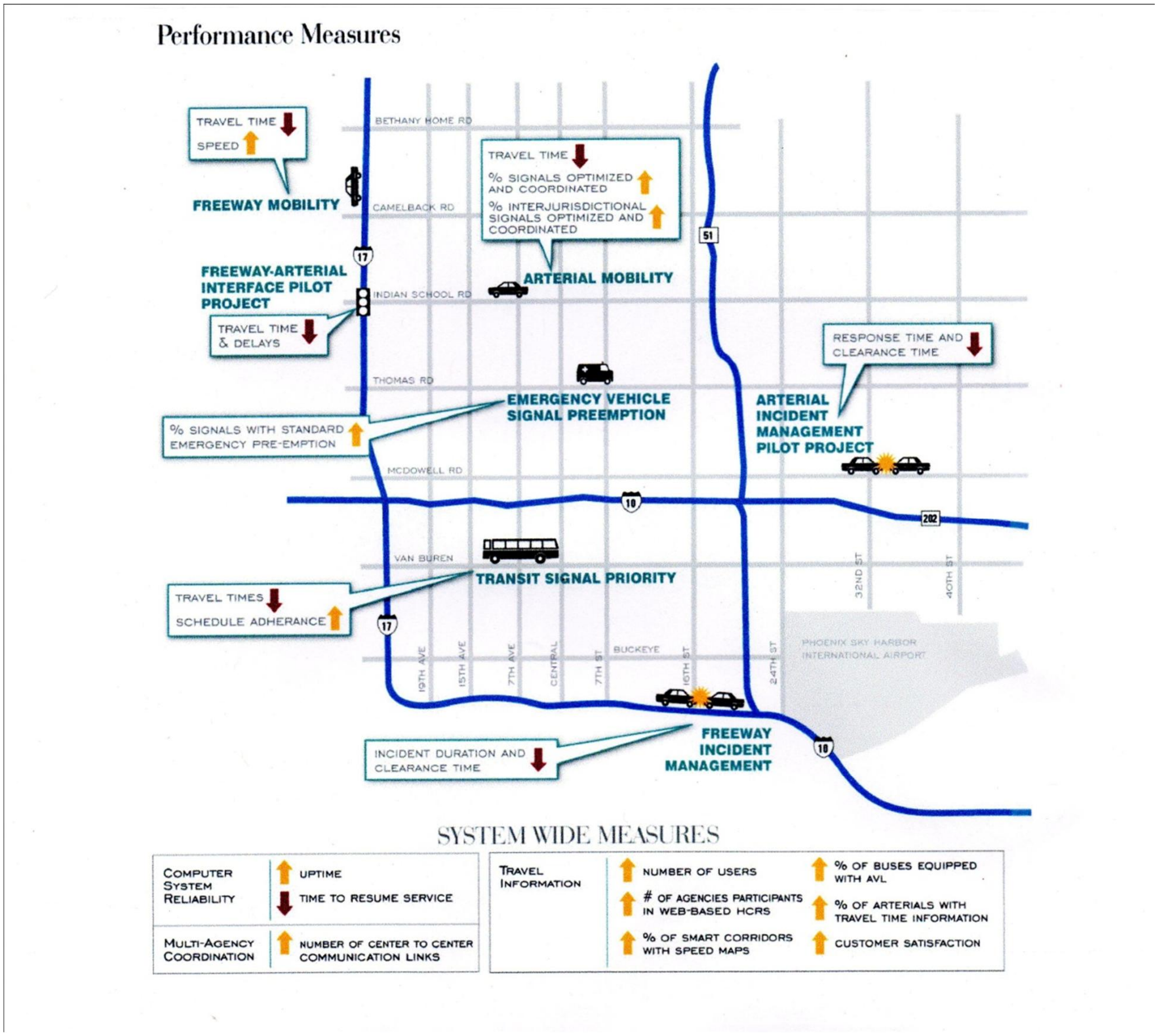

Figure A.1 Performance Measures

Appendix B. Pollutant Emissions

This appendix describes the computations for pollutant emissions. The pollutants discussed include:

Pollutant	Pollutant Index Identification
Volatile organic compounds (VOC)	PO = 1
Sulfur dioxide (SO2)	PO = 2
Oxides of nitrogen (NO_X)	PO = 3
Particles of 2.5 micrometers or less (PM 2.5)	PO = 4
Particles of 10 micrometers or less (PM 10)	PO = 5

The emission data in this appendix was provided by Mr. Jeff Houk of FHWA using the MOVES (Motor Vehicle Emission Simulator) model.

<u>Freeways</u>

Emission rates in terms of grams per vehicle mile travelled are typically relatively low at high speeds (e.g. 75 mph), reduce somewhat as speed decreases, and then increase significantly as the speed continues to decrease. Emissions (POL) for each pollutant (PO) for 5-minute time periods are modeled by Equation B-1.

$$POL\ (PO, N5) = V(DO, N5) \cdot LE(DO) \cdot \frac{ER(PO, SD(PO, N5))}{12} \qquad \text{(B-1)}$$

The emission rate (ER) for each pollutant (PO) as a function of speed for years 2011 and 2016 is provided in Tables B.1 and B.2.

Table B.1
Emission Rates for Year 2011

	Emission Rate (Grams per Mile)				
Speed (mph)	NO_X	SO2	VOC	PM 2.5	PM 10
75	1.062	0.00768	0.1021	0.0261	0.0275
70	1.014	0.00731	0.0934	0.0247	0.0260
65	0.959	0.00705	0. 0893	0.0235	0.0247
60	0.922	0.00696	0.0899	0.0228	0.0239
55	0.915	0.00698	0.0930	0.0236	0.0248
50	0.917	0.00707	0.0976	0.0256	0.0268
45	0.923	0.00722	0. 1043	0.0274	0.0288
40	0.935	0.00742	0.1137	0.0288	0.0302
35	0.955	0.00770	0. 1265	0.0306	0.0321
30	01.028	0.00821	0.1434	0.0370	0.0387
25	1.105	0.00913	0.1638	0.0395	0.0413

	Emission Rate (Grams per Mile)				
Speed (mph)	NO_X	SO2	VOC	PM 2.5	PM 10
20	1.187	0.0102	0.1918	0.0454	0.04766
15	1.294	0.0118	0. 2306	0.0511	0.0536
10	1.472	0.0148	0.3025	0.0582	0. 0609
5	2.131	0.0240	0.5198	0.0905	0.0945
2.5	3.652	0.0427	0.9618	0.1665	0.1734

Table B.2
Emission Rates for Year 2016

	Emission Rate (Grams per Mile)				
Speed (mph)	NO_X	SO2	VOC	PM 2.5	PM 10
75	0.621	0.00646	0.0596	0.0172	0.0182
70	0.591	0.00615	0.0523	0.0159	0.0169
65	0.557	0.00593	0.0491	0.0151	0.0160
60	0.536	0.00585	0.0488	0.0146	0.0155
55	0.532	0.00587	0.0504	0.0150	0.0159
50	0.532	0.00595	0.0530	0.0161	0.0169
45	0.534	0.00608	0.0569	0.0171	0.0180
40	0.540	0.00625	0.0626	0.0179	0.0188
35	0.549	0.00648	0.0703	0.0190	0.0200
30	0.589	0.00691	0.0804	0.0226	0.0238
25	0.628	0.00768	0.0910	0.0243	0.0255
20	0.677	0.00857	0.1067	0.0280	0.0294
15	0.741	0.00990	0.1271	0.0315	0.0331
10	0.847	0.01243	0.1637	0. 0360	0.0378
5	1.237	0.02028	0.2746	0. 0553	0.0581
2.5	2.143	0.03617	0.5019	0.1003	0.1050

To obtain the appropriate emissions rate, interpolation for both speed and the evaluation year should be performed.

Surface Streets

Signal delay includes the deceleration and acceleration periods associated with a stop for a traffic signal. Since the emission rates associated with these moving periods is somewhat higher than for the idling period, the use of the idling emissions rate to represent the emissions during signal delay period provides a low estimate for the emissions generated during these periods. The relationship for 15-minute period emission levels is provided by Equation B-2.

$$POLA(PO, LI, LG, N15) = 0.25 \cdot PA(PO) \cdot V(LI, LG, N15) \cdot LCD(LI, LG, N15) \quad \text{(B-2)}$$

Where:

POLA = Arterial Pollutant Emission (grams)
PO = Pollutant Identification
LI = Intersection ID
LG = Traffic signal lane group
PA = Idling emissions generation rate (grams/hr)
V = Volume (vph)
LCD = Control delay for the lane group for a vehicle

Table B.3 provides the values for the idling emission rates.

Table B.3
Idling Emission Rates

Pollutant	2011 Emission Rate (gm/hr)	2016 Emission Rate (gm/hr)
NO_X	5.858	3.500
SO2	0.0708	0.0669
VOC	3.404	1.642
PM 2.5	0.305	0.213
PM 10	0.318	0.222

REFERENCE

MOVES, Environmental Protection Agency, 2010 online http://www.epa.gov/otaq/models/moves/index.htm February 21, 2011.

Appendix C. Georgia DOT Motorist Survey

Georgia State University conducted a motorist survey for Georgia DOT. The report (Georgia State University (2006) describes the survey methodology, questions and results. While the survey primarily concentrates on performance, it also considered the importance of various physical and operational improvements. This appendix provides some of the material relevant to ITS evaluations.

Figures C.1 and C.2 show traffic flow performance ratings for freeways and Figures C.3 and C.4 show these ratings for non-freeway routes. Results are also provided in the report for each GDOT district. Figure C.5 illustrates the priorities chosen by survey respondents, and Figure C.6 is a presentation of performance versus importance that may assist in resource allocation.

REFERENCE

Georgia State University, *2006 Motorist Survey Pilot Statewide Results,* available: http://www2.gsu.edu/~padthp/gdot_reports/2006_statewide_motorist_report.pdf, [accessed December 22, 2010].

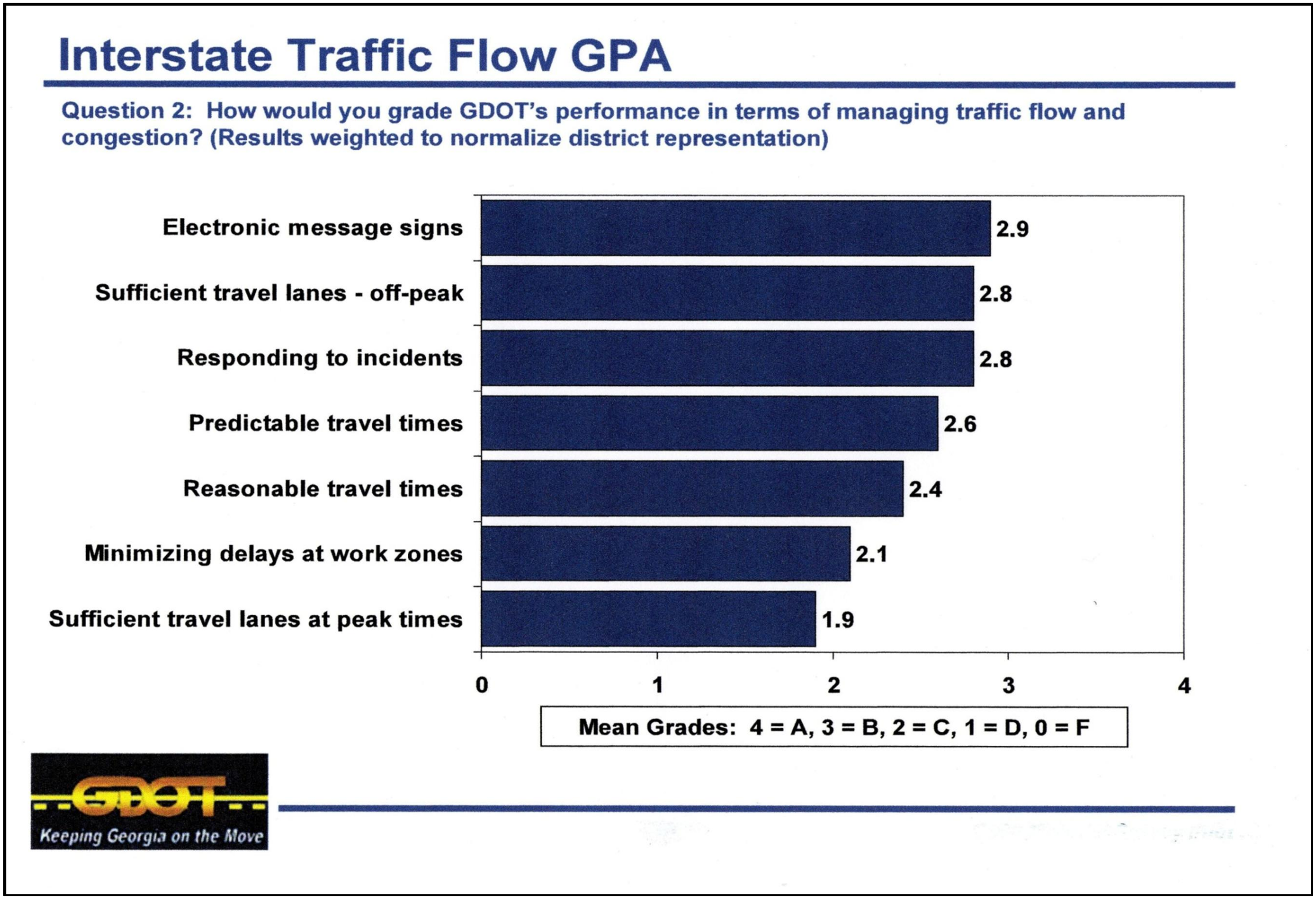

Figure C.1 Interstate Traffic Flow Scores

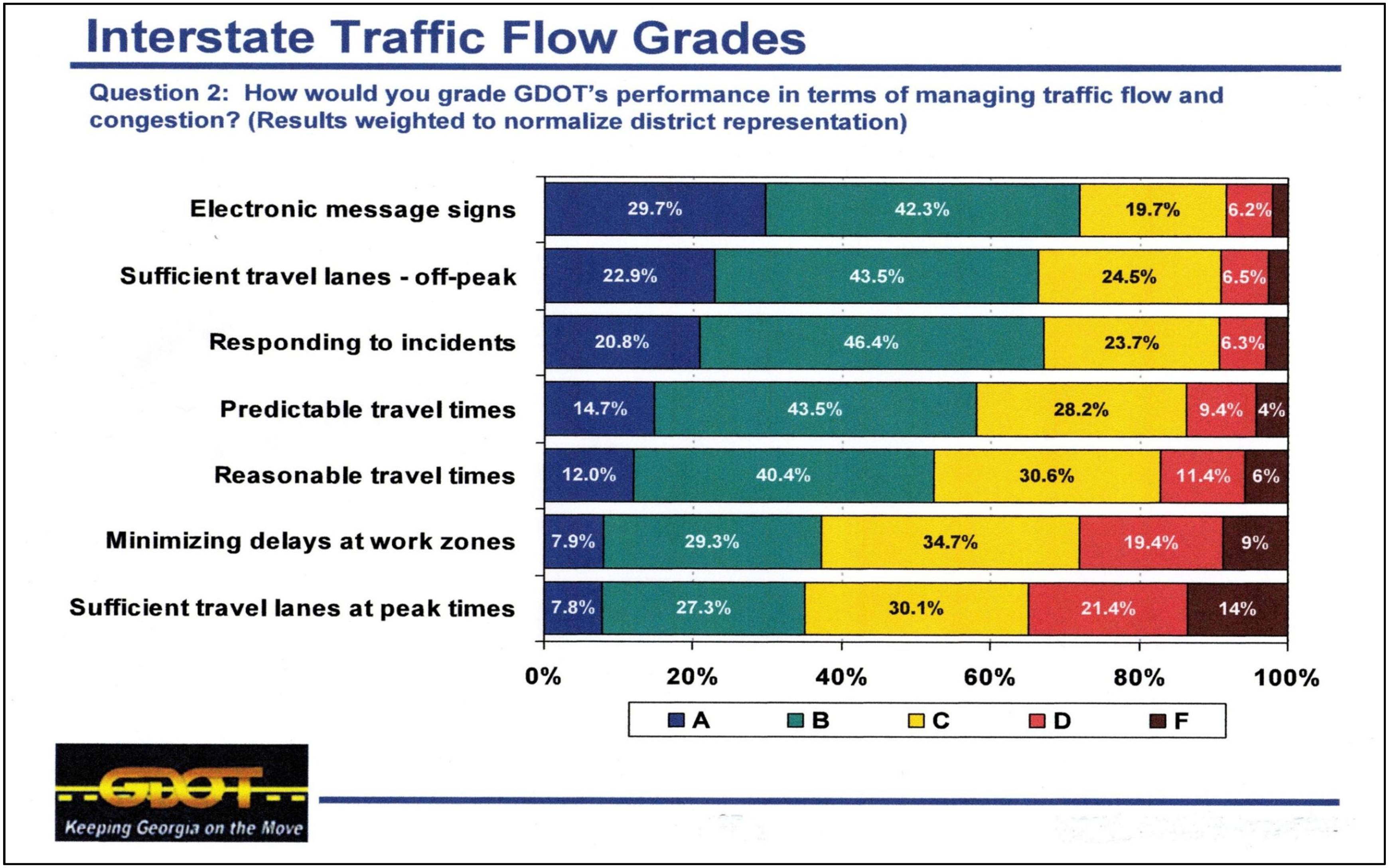

Figure C.2 Distribution of Interstate Traffic Flow Scores

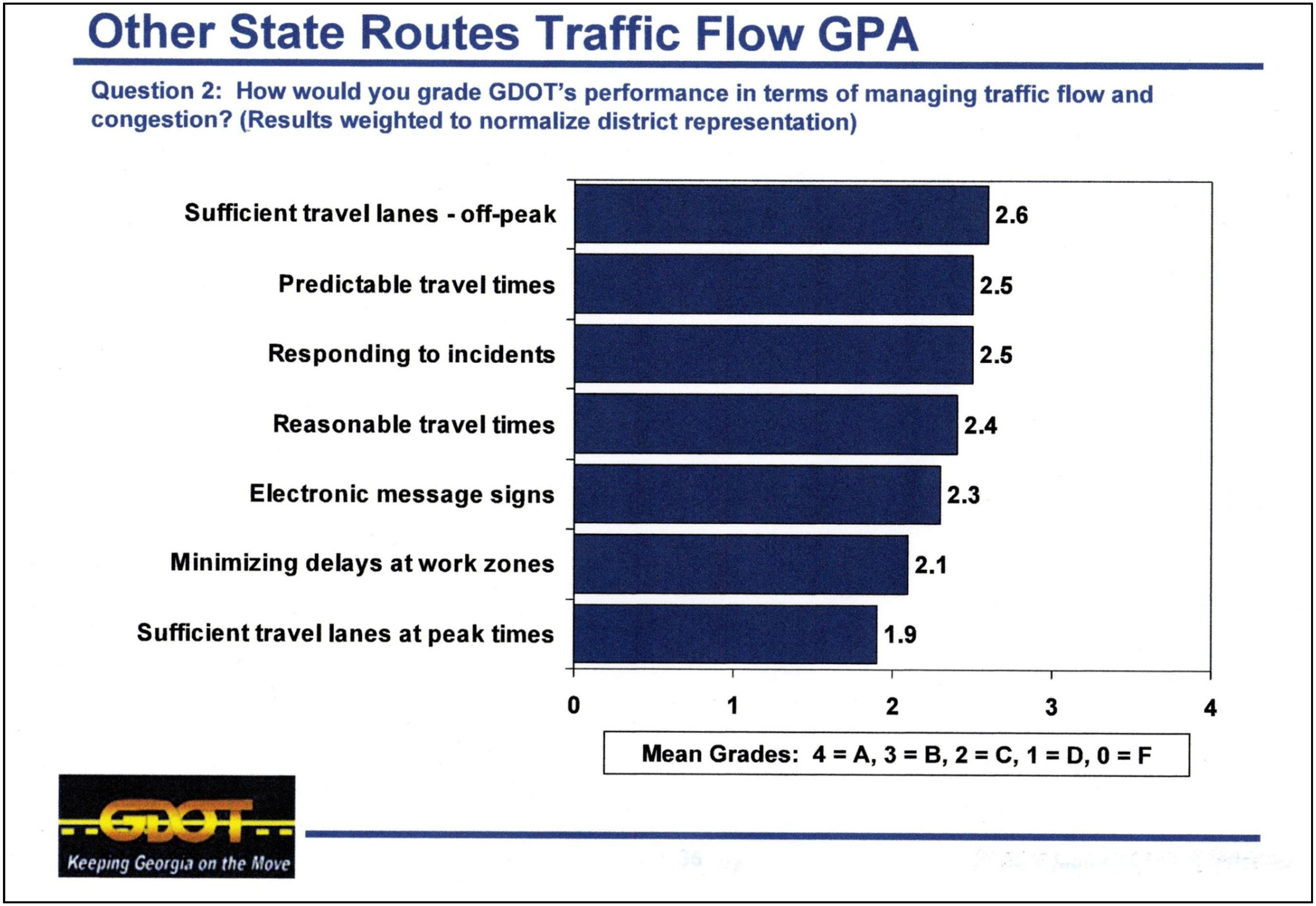

Figure C.3 Non-Interstate Traffic Flow Scores

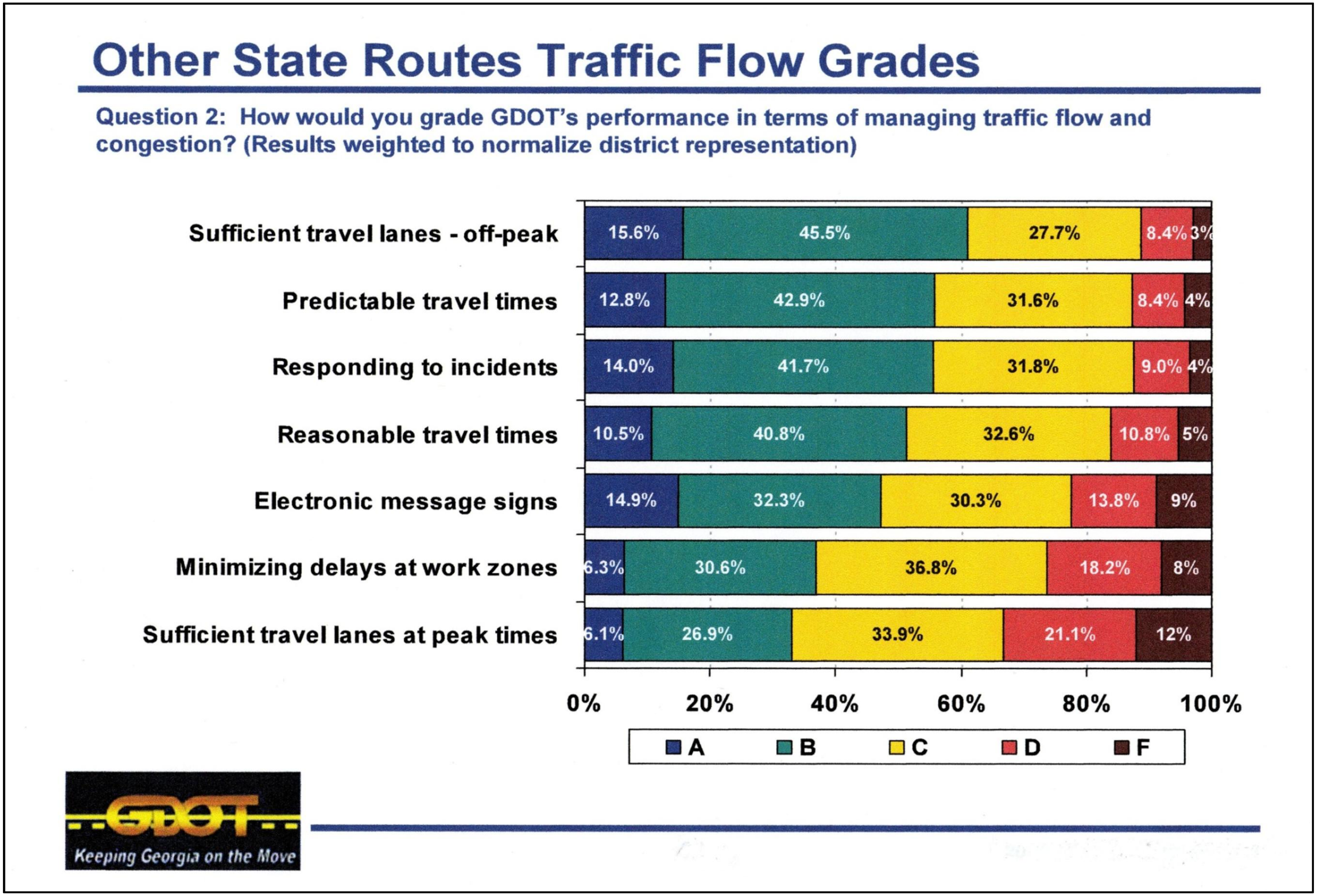

Figure C.4 Distribution of Non-Interstate Traffic Flow Scores

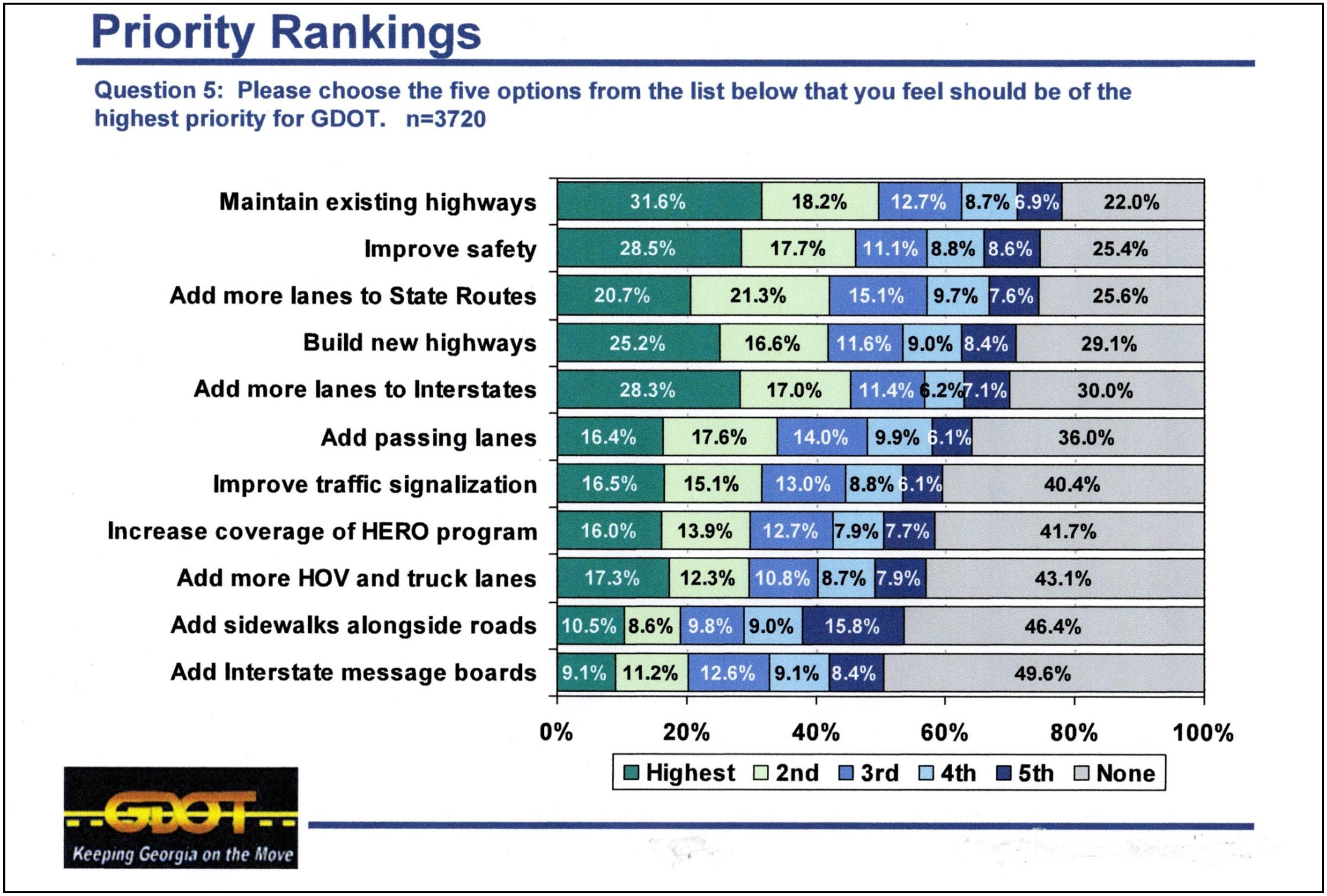

Figure C.5 Motorist Priority Rankings

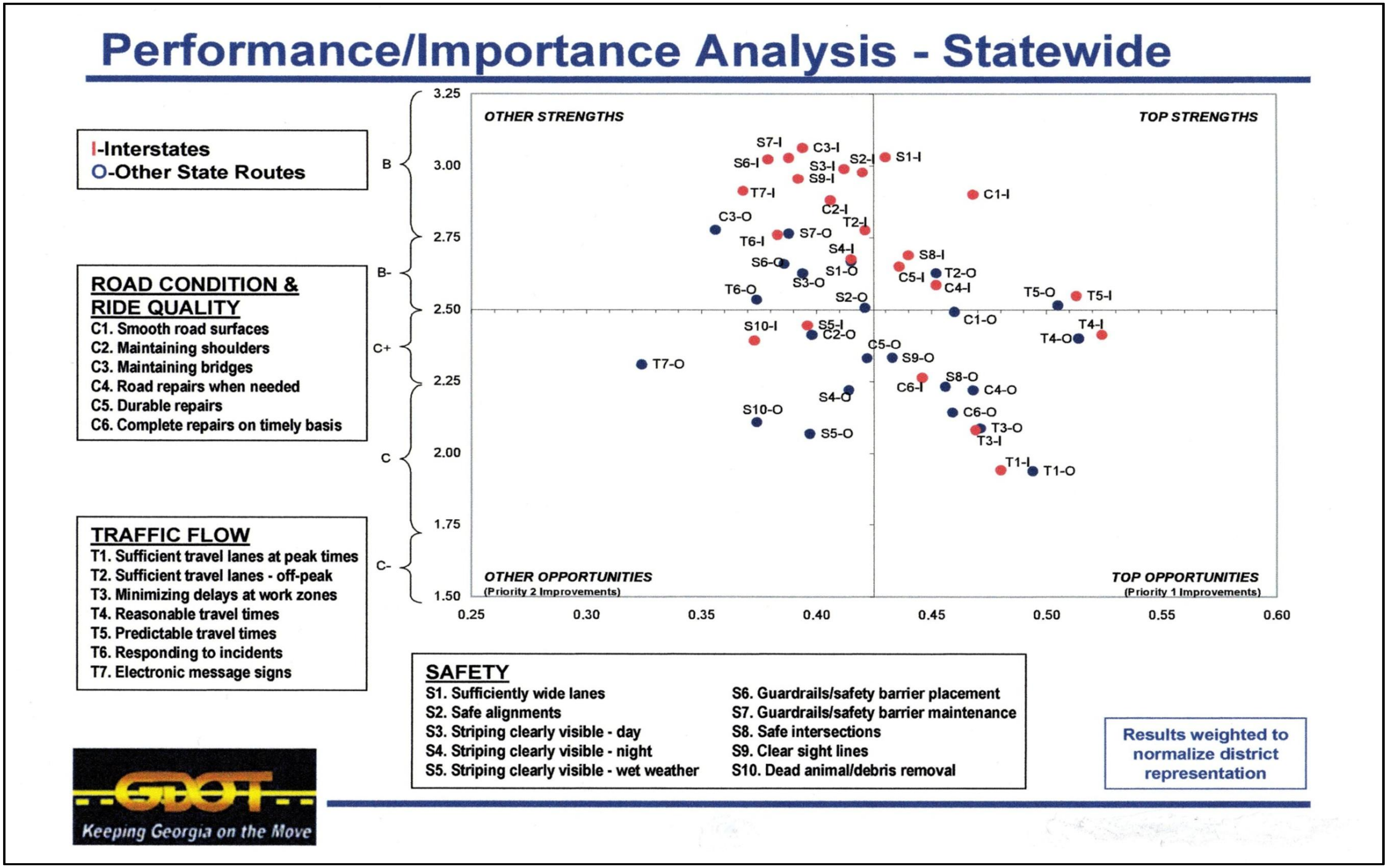

Figure C.6 Performance vs. Importance Plot