Methodologies to Measure and Quantify Transportation Management Center Benefits: Final Synthesis Report

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U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
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FOREWORD

The Federal Highway Administration, in support of the Transportation Operation Center Pooled Fund Study, initiated this study to identify and quantify Transportation Management Center (TMC) benefits. In a time of shrinking budgets, government officials must select from a multitude of projects competing for the limited available resources. Many benefits of TMC have been intuitively understood by managers but now need to be quantified in order to justify the initial cost as well as the ongoing annual operations and maintenance costs. This report provides a means to identify and quantify TMC benefits. It presents direction, guidance, methodologies, and procedures to agencies associated with monitoring, evaluating, and reporting on the values and benefits of TMC operations. This report is directed toward professionals working in State transportation departments and other agencies that are responsible for the construction and operation of TMCs.

Joseph I. Peters
Director, Office of Operations
Research and Development

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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-cost analysis, including those that may be employed for freeway TMCs, traffic signal system TMCs, and corridor TMCs. This document describes the algorithms and processes used to compute many of the measures. In the case of system measures, 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.</td></tr>
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF ABBREVIATIONS

AADT	Average annual daily traffic
ACC/MEV	Accidents per million vehicles entering an intersection
ADCS	Automated data collection station
ADMS	Archived data management system
ADOT	Arizona Department of Transportation
AVL	Automatic vehicle locator
CAD	Computer-aided dispatch
Caltrans	California Department of Transportation
DMS	Dynamic message sign
EVSP	Emergency vehicle signal preemption
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
FMS	Freeway management system
FYTD	Fiscal year to date
GDOT	Georgia Department of Transportation
GPS	Global Positioning System
HAR	Highway advisory radio
HCRS	Highway Condition and Reporting System
HOV	High occupancy vehicle
ITS	Intelligent transportation system
LOS	Level of service
MAG	Maricopa Association of Governments
MOVES	Motor Vehicle Emission Simulator
NO_X	Oxides of nitrogen
NYSDOT	New York State Department of Transportation
PeMS	Performance Measurement System
PDO	Property damage only
PMT	Person miles traveled
RTMS	Remote traffic microwave sensor
SO_2	Sulfur dioxide
SPI	Safety performance index

STEWARD	Statewide Traffic Engineering Warehouse for Regional Traffic Data
TMC	Transportation Management Center
TRIPS	Travel-Time Reporting and Integrated Performance System
TxDOT	Texas Department of Transportation
VMT	Vehicle miles traveled
VOC	Volatile organic compound
WSDOT	Washington State Department of Transportation

EXECUTIVE SUMMARY

This project provides a useable means to identify and quantify Transportation Management Center (TMC) benefits. It presents 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-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 following classes of measures were identified during the literature review:

- 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 use input data from freeway management systems (FMSs) 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 revealed little commonality among TMCs in the spatial references 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 research has shown that most freeway TMCs use a similar data structure characterized by data storage by 5-min, 15-min, hourly, daily, and yearly periods, the findings of the project recommend this temporal structure for the freeway evaluation methodologies. Signal system measures use a 15-min span for the earliest data storage period.

This report describes the algorithms and processes used 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.

This report also discusses the effects of bias errors and random errors. Bias errors are most significant in conducting initial evaluations, such as before-after studies, for significant intelligent transportation system (ITS) improvements. Random errors, which are 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-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 in this report.

The methodologies described in this 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

TMCs 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. The purpose of this project was to identify key measures that can be used to execute operational strategies and 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 (ADMSs) that provide a key element for this project support the following TMC functions:(1)

- Operational strategy development.
- Operations planning.
- Long-term planning.
- Policy investment decisionmaking.

When coupled with performance measures that use these data, the results from applying the methodologies addressed provide the basis for developing reports and presentations that justify project investment to decisionmakers 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 ITSs that they manage.

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

The content of this report is organized as follows:

- Section 1 provides an introduction to the report.
- Section 2 describes TMC functions and examples of systems for performance evaluation.
- Section 3 provides a representative set of performance measures.
- Section 4 describes the spatial and temporal data structures to be employed by the processes used for the development and computation of the measures.
- Section 5 identifies recommended measures and the algorithms and processes for their computation.

- Section 6 describes technologies for collecting data, data quality control, automation of surface street data collection, and standards.

- Section 7 provides algorithms and other methodologies for obtaining travel time and delay, throughput, safety, fuel consumption, emissions, service quality and user perceptions, characteristics of incidents, service patrol measures, responses to weather situations, and an evaluation of motorist information databases.

- Section 8 describes a methodology to develop the benefit-cost ratio and techniques for alternative presentations of benefit-cost data.

- Three appendices support these sections.

2. TMC FUNCTIONS AND EXAMPLES OF PERFORMANCE EVALUATION

2.1 TMC FUNCTIONS

The goals and initiatives established by agencies 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 of this report, these functions are 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 many agency TMCs and traffic management systems.

Performance evaluation systems may include the archived data user service functions of the National ITS Architecture.(2)

Table 2 provides key functional characteristics for several performance evaluation systems.

Table 1. TMC functions.

	Facilities Managed by TMC				
TMC Functions	**Freeways**	**Signal Systems and Surface Streets**	**Corridors[a]**	**Special Facilities[b]**	**Comments**
Active Traffic Management[c]	X		X	X	See reference 3.
Speed harmonization	X			X	
Temporary shoulder use	X			X	
Queue warning	X			X	
Dynamic truck restrictions	X			X	
Dynamic routing	X		X	X	
Dynamic lane markings	X			X	
Data Analysis and Warehousing	X	X	X	X	These are support functions. They relate to outputs rather than to outcomes. No measures are provided for these functions in section 3.
Incident Response					
Development of incident management plans	X	X	X	X	
Selection of incident management plan	X	Where TMCs have this responsibility	X	X	
Assistance to emergency service providers	X		X	X	
Maintenance					These are support functions. They relate to outputs rather than to outcomes. No measures are provided for these functions in section 3.
Maintenance of TMC facilities	X	X	X	X	
Management of field equipment maintenance	X	X		X	Field equipment maintenance management for corridors depends on division of responsibilities.

Configuration management of TMC and ITS facilities	X	X	X	X	
Coordination of roadway maintenance and construction	X	X		X	
Motorist Information					
Management of information for ITS field devices	X	Where agency operates devices	X	X	
Provision of information to external services		Sometimes			
Planning	X	X	X	X	These are support functions. They relate to outputs rather than to outcomes. No measures are provided for these functions in section 3.
Ramp Management and Conventional Lane Management					
Ramp metering	X		X	X	
Ramp closure	X		X	X	
Conventional lane controls	X	X	X	X	
Security					These are support functions. They relate to outputs rather than to outcomes. No measures are provided for these functions in section 3.
Security in TMC	X	X	X	X	
Security of ITS field devices	Possibly	Not often	Possibly	Usually	
Other security functions	Possibly	Not often	Possibly	Usually	Security monitoring of other transportation department facilities.
Service Patrol	X			X	
Signal Timing					
Signal timing plan development		X	See[d]		
Signal timing operations management		X	See[d]		

Emergency vehicle signal preemption		X	See[d]		
Special Functions					These are support functions. They relate to outputs rather than to outcomes. No measures are provided for these functions in section 3.
Roadway ventilation				X	See reference 4.
Roadway fire detection and suppression				X	See reference 4.
Other Supervisory Control and Data Acquisition Functions				X	May include pumping, electrical system control, and motorist telephone system.(4)
Training and Support	X	X	X	X	These are support functions. They relate to outputs rather than to outcomes. No measures are provided for these functions in section 3.
Transit Assists					
High occupancy vehicle (HOV) bypass of metered lanes	X		X	X	
Transit signal priority		X	See[d]		
Weather Monitoring	X	Not usually	X	X	

[a] Includes TMCs with responsibility for operations on alternate routes.
[b] Includes bridges and tunnels.
[c] Active traffic management includes speed harmonization, temporary shoulder use, queue warning, dynamic merge control, construction site management (active traffic management methodologies), dynamic truck restrictions, dynamic routing and traveler information, and dynamic lane markings. Separate lines will be provided for each strategy.
[d] Responsibility for timing plan development and operations rests with the agency responsible for traffic signal systems. This function is applicable when freeway and signal system TMCs share a common facility.
Note: Blank cells in the comments field indicates no comment was provided.

Table 2. Characteristics of representative ITS performance evaluation systems.

System	Key Data Processing Features	Data Collection Periods	Data Source	Key Measures Provided
California Department of Transportation (Caltrans) Freeway Performance Measurement System (PeMS)[5,6]	• Detects and corrects missing and bad data through imputation techniques. • Computes speed by means of *g* factor calculations.[a] • Estimates truck volumes.	Collects data at 30-s intervals, then aggregates to 5-min 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 (VMT), and travel times.
Washington State Traffic Data Acquisition and Distribution System	• Contains flags to alert users to suspect data. • Uses ladder algorithm to compute travel time.[b]	Collects data at 20-s intervals, then aggregates to 5-min 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, and travel time reliability.
Minnesota TMC[7]	• Contains flags to alert users to suspect data.	Collects data at 20-s intervals, then aggregates to 5-min data.	Single inductive loop detectors in each lane.	
Florida Statewide Traffic Engineering Warehouse for Regional Traffic Data (STEWARD); designed as a statewide system that links to each district[8]	• Strong integration with roadway and detector characteristics. • Data completeness test. • Data threshold checks.	Collects data at 20-s intervals, aggregates to 5-, 15-, and 60-min periods.	• Mainline and ramp detectors. • Adaptable to all detector types.	Volume, occupancy speed, lane volume balance, effective vehicle length (see section 5.1.2.1), input/output balance, VMT, vehicle hours, delay, kinetic energy, and level of service.

[a] Additional information is provided in table 22.
[b] The *g* factor represents the effective length of the vehicle at the tuning of the loop detector. It varies over the course of time. An algorithm is in PeMS to calculate the *g* factor as a function of time.
Note: Blank cell indicates no key measures were provided.

3. PERFORMANCE MEASURES

Two general types of measures may be considered: outcome-oriented and output-oriented.

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

Output-oriented measures are the direct result 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.(9)

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

Park and Shaw are key sources for descriptions of numerous measures.(9,10) For this study, researchers selected measures that were considered to be most useful. 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 a benefit-cost analysis, the measures must not be redundant to avoid double-counting a benefit.
- The measure should be intuitively credible.

Table 3 describes criteria that may be used to evaluate measures.(10)

Table 3. Comparison of performance measures 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 conditions. 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 Department of Transportation's (TxDOT) balanced scorecard approach to developing performance measures.(10) Agencies often define measures for highway system operations. While these operations may include TMCs, they usually cover the more general functions of the highway network, such as the measures used by the Florida Department of Transportation (FDOT), which are shown in table 4.(9)

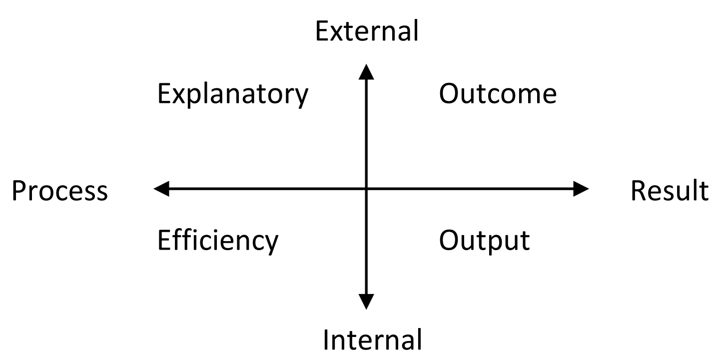

Figure 1. Illustration. TxDOT balanced scorecard approach.

Shaw and Park provide extensive discussions of measures used by agencies as well as the equations and computational procedures that may be used to develop several of these measures.(10,9) While many agencies employ these general techniques, the specific schemes used often differ.

Table 4. Measures used by FDOT.

Dimension of Mobility	Mobility Performance Measures	State Highway System	Florida Intrastate Highway System	Florida Intrastate Highway System Corridors	Metropolitan Highway Systems	Definition[a]
Quantity of travel	Person miles traveled (PMT)	X	X	X	X	Average annual daily traffic (AADT) × length × vehicle occupancy
	Truck miles traveled	X	X	X	X	AADT × length × percent trucks
	VMT	X	X	X	X	AADT × length
	Person trips					Total person trips
Quality of travel	Average speed	X	X	X		Average speed[2] weighted by PMT
	Delay	X	X	X	X	Average delay
	Average travel time			X		Distance ÷ speed[b]
	Average trip time				X	Door to door trip travel time
	Reliability			X	X	Percent of travel times that are acceptable
	Maneuverability			X		Vehicles per hour per lane
Accessibility	Connectivity to intermodal facilities	X	X	X	X	Percent within 5 mi (1 mi for metropolitan)
	Dwelling unit proximity		X	X	X	Percent within 5 mi (1 mi for metropolitan)
	Employment proximity		X	X	X	Percent within 5 mi (1 mi for metropolitan)
	Industrial/warehouse facility proximity		X			Percent within 5 mi
	Percent miles bicycle accommodations	X			X	Percent miles with bike lane ÷ shoulder coverage

	Percent miles pedestrian accommodations	X			X	Percent miles with sidewalk coverage
Utilization	Percent system heavily congested	X	X	X	X	Percent miles at level of service (LOS) E or F[c]
	Percent travel heavily congested	X	X	X	X	Percent daily VMT at LOS E or F
	Vehicles per lane mile	X	X	X	X	AADT × length ÷ lane miles
	Duration of congestion	X	X	X	X	Lane-mile hours at LOS E or F

[a] Definitions shown are generally for daily analysis. Calculations for the peak are based on prevailing conditions during the typical weekday 5 to 6 p.m. peak.
[b] Speed based on models using the *Highway Capacity Manual* or field data.[(4)]
[c] LOS ratings are determined using the *Highway Capacity Manual*.[(4)]

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.[1] Therefore, this report 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.

This 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.

Table 5. Example of percentage of ITS monetary benefits for benefits classes.[(11)]

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 an ITS performance evaluation. Table 7 relates the outcome-oriented TMC functions in table 1 to the measures in table 6.

[1] Review the scope of work for this report for additional information.

Table 6. Measures of effectiveness.

Type of Measure	Sub-Measure	Identifier	Quantity Measures or Description	Benefit-cost Analysis	Traffic Flow Quality and Safety Measures	Benefits Perceived by the Public	Measure for TMC Operations Performance
System delay measures	Vehicle system delay*	D.1	Vehicle hours per year; archived on a link, ramp, and intersection basis and aggregated to the system level	X	X	X	X
	Private passenger vehicle occupant delay*	D.2	Person hours per year	X	X	X	
	Commercial vehicle occupant delay*	D.3	Person hours per year	X	X	X	
	Goods inventory delay*	D.4	Ton hours per year	X			
	Transit vehicle occupant delay	D.5	Person hours per year	X		X	
Safety	Freeway crashes*	S.1	Crashes per million VMT per year; archived on a link and ramp basis and aggregated to the system level	X	X		X
	Secondary crashes	S.2	Crashes per million VMT per year		X		X
	Crashes at intersections*	S.3	Crashes per million vehicles entering intersection	X	X		X
	Property damage only (PDO) crashes	S.4	Crashes per million VMT per year	X	X		X

Safety (continued)	Fatal crashes	S.5	Fatal crashes per million, VMT, and fatal crashes per 1 million vehicles entering intersection	X	X		X
	Injuries resulting from crashes	S.6	Injury crashes per million, VMT, and injury crashes per 1 million vehicles entering intersection	X	X		X
	Work zone related crashes	S.7	Work zone crashes for the TMC coverage region		X		X
	Pedestrian crashes	S.8	Pedestrian injuries/deaths per 1 million vehicles entering intersection		X		X
	Safety performance index	S.9	Weighted crash frequency and severity		X		X
Fuel consumption*		F	Gallons per year	X		X	
Throughput	Freeway throughput	T.1	VMT per year during peak hour		X		
	Intersection throughput	T.2	Vehicles per peak hour at an intersection		X		
Emissions		E	Kilograms per year for each emission constituent				
Service quality/user perceptions	Route travel time	Q.1	Peak hour route travel time (hours)		X	X	X
	Route travel time reliability	Q.2	Buffer index, planning time index		X	X	X
	User satisfaction	Q.3	User satisfaction scales and surveys			X	X
	User satisfaction	Q.4	Complaints received by agency			X	X

Equity	User perception	U.1	User complaints received by agency			X	X
	Gini coefficient or Lorenz curve	U.2	Users relatively disbenefitted per total users				
Service patrol measures	Service patrol assists	M.1	Assists per year			X	X
	Quality of service	M.2	Patrol coverage periods (hours per year)			X	X
	Quality of service	M.3	Average motorist waiting time (minutes)			X	X
	Quality of service	M.4	Extent of roadway serviced (centerline miles)			X	X
	Rating by public	M.5	Rating scale			X	X
Incident clearance time	Average incident clearance time	C	Annual average incident clearance time for moving lanes minutes	X			X
Response to weather situations	Response time to provide actionable information to motorists	W	Average time in minutes from receipt of information by Road Weather Information Systems or other means to provide motorist information and to provide information to other response services		X	X	X
Life-cycle cost*		P	Dollars per year	X			X
Database to provide motorist information	See section 5.9	I	Rating scales		X	X	X

* Indicates measures used for benefit-cost analysis.
Note: Blank cells in the "Sub-Measure" column indicate that no sub-measure was identified.

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	Vehicle system delay*	D.1	X	X	X	X	X	X	X	X
	Private passenger vehicle occupant delay*	D.2	X	X	X	X	X	X		X
	Commercial vehicle occupant delay*	D.3	X	X	X	X	X	X		X
	Goods inventory delay*	D.4	X	X	X	X	X	X		X
	Transit vehicle occupant delay	D.5	X	X	X	X	X	X	X	X
Safety	Freeway crashes*	S.1	X	X	X	X	X			X
	Secondary crashes	S.2	X	X	X	X	X			X
	Crashes at intersections*	S.3			X			X		X
	PDO crashes	S.4	X	X	X	X	X	X		X
	Fatal crashes	S.5	X	X	X	X	X	X		X
	Injuries resulting from crashes	S.6	X	X	X	X	X	X		X
	Work zone related crashes	S.7	X	X	X	X	X			X
	Pedestrian crashes	S.8								
	Safety performance index	S.9	X	X	X	X	X	X		X
Fuel consumption*		F	X	X	X	X	X	X	X	X
Throughput	Freeway throughput	T.1	X	X	X	X	X			X
	Intersection throughput	T.2						X		X
Emissions		E	X	X	X	X	X	X	X	X

Service quality/user perceptions	Route travel time	Q.1	X	X	X	X	X	X	X	X
	Route travel time reliability	Q.2	X	X	X	X	X	X	X	X
	User satisfaction	Q.3	X	X	X	X	X	X		X
	User satisfaction	Q.4	X	X	X	X	X	X		X
Equity	User perception	U.1				X			X	
	Gini coefficient or Lorenz curve	U.2				X			X	
Quality of assistance to motorists	Service patrol assists	M.1					X			
	Quality of service	M.2					X			
	Quality of service	M.3					X			
	Quality of service	M.4					X			
	Rating by Public	M.5					X			
Incident clearance time	Average incident clearance time	C	X	X	X	X	X			X
Response to weather situations	Response time to provide actionable information to motorists	W	X	X	X	X		X		X
Life-**c**ycle cost*		P	X	X	X	X	X	X	X	X
Database to provide motorist information	See section 5.6	I	X	X	X					X

* Indicates measures used for benefit-cost analysis.
Note: Blank cells in the "Sub-Measure" column indicate that no sub-measure was identified.

4. SPATIAL AND TEMPORAL DATA STRUCTURES

4.1 DATA CAPABILITIES OF FMSS AND TRAFFIC SIGNAL SYSTEMS

The following list describes a set of data collection, storage, and data manipulation capabilities that are common to most FMSs:

- **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 these data. Point detector data may consist of volume, speed, occupancy, and vehicle classification. Provision is usually made for the identification and correction of flawed and missing data. Probe data are 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**: Functions include 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, and equipment event or failure
Data sampling or collection period	20 s to 1 min	Traffic detector collection period for field detectors
Action periods	1 to 10 min	Data accumulation periods for TMC actions such as traffic map displays, data filter updates, system-wide ramp metering, incident management, automatic dynamic message sign (DMS) messaging, and system tuning
Common reporting and analysis interval	5 min, 15 min, 1 h	Studies of traffic patterns by TMC personnel and others
Daily reports	1 day	Daily data consolidations and planning
Annual reports	1 year	Performance evaluations and planning

An example of the general relationship between data uses and data characteristics is shown in table 9.[12]

Table 9. Data uses and characteristics.

Type of Data Use	User	Data Used	Source
Long-term planning	PSRC	AADT volume	Washington State Department of Transportation (WSDOT) *Annual Traffic Report*[13]
		Highway Performance Monitoring System VMT	WSDOT Data Office
		24-h and peak volume counts	*Ramp & Roadway Report*[14]
		24-h volume counts	City and County Tube Collections
	WSDOT Planning Office	Volume counts	*Annual Traffic Report*[13]
		Forecasted efficiency data	PSRC
Performance monitoring	PSRC	AADT volume	*Annual Traffic Report*[13]
		24-h and peak volume counts	*Ramp & Roadway*
		24-h volume counts	City and County Tube Collections
Long-range planning and project planning	WSDOT Transportation Data Office	AADT volumes	*Annual Traffic Report*[13]
		Projected volume data	PSRC
		Turning movements	Northwest Region Planning Office
		Vehicle occupancy	Northwest Region Planning Office
		Vehicle classification	Northwest Region Planning Office
		Specific volume counts	Northwest Region Planning Office
		Travel time and speed	Consultants
		Transit use	Consultant
		Pedestrian and bicycle counts	Consultants
Performance Monitoring	WSDOT Office Of Urban Mobility	Volume counts	Travel-Time Reporting and Integrated Performance System (TRIPS)
		Incident data	TRIPS
Research	Washington State Transportation Center, Transportation Northwest, and the University of Washington Researchers	20 s, 1 min, 5 min, 15 min	WSDOT Transportation System Management Center
		Volume counts and lane occupancy	*Ramp & Roadway Report*[14]
		Peak volume counts	*Annual Traffic Report*[13]
		AADT volumes	Automated data collection stations (ADCSs), autoscope
		Speed	WSDOT Data Office
		Vehicle classification	ADCS, autoscope
		Vehicle occupancy	Washington State Transportation Center

Note: PRSC denotes the region's Metropolitan Planning Organization.

This project develops methodologies for employing FMS data to generate many of the evaluation measures described in table 6. Data collected every 5 min are the building blocks 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.[15]

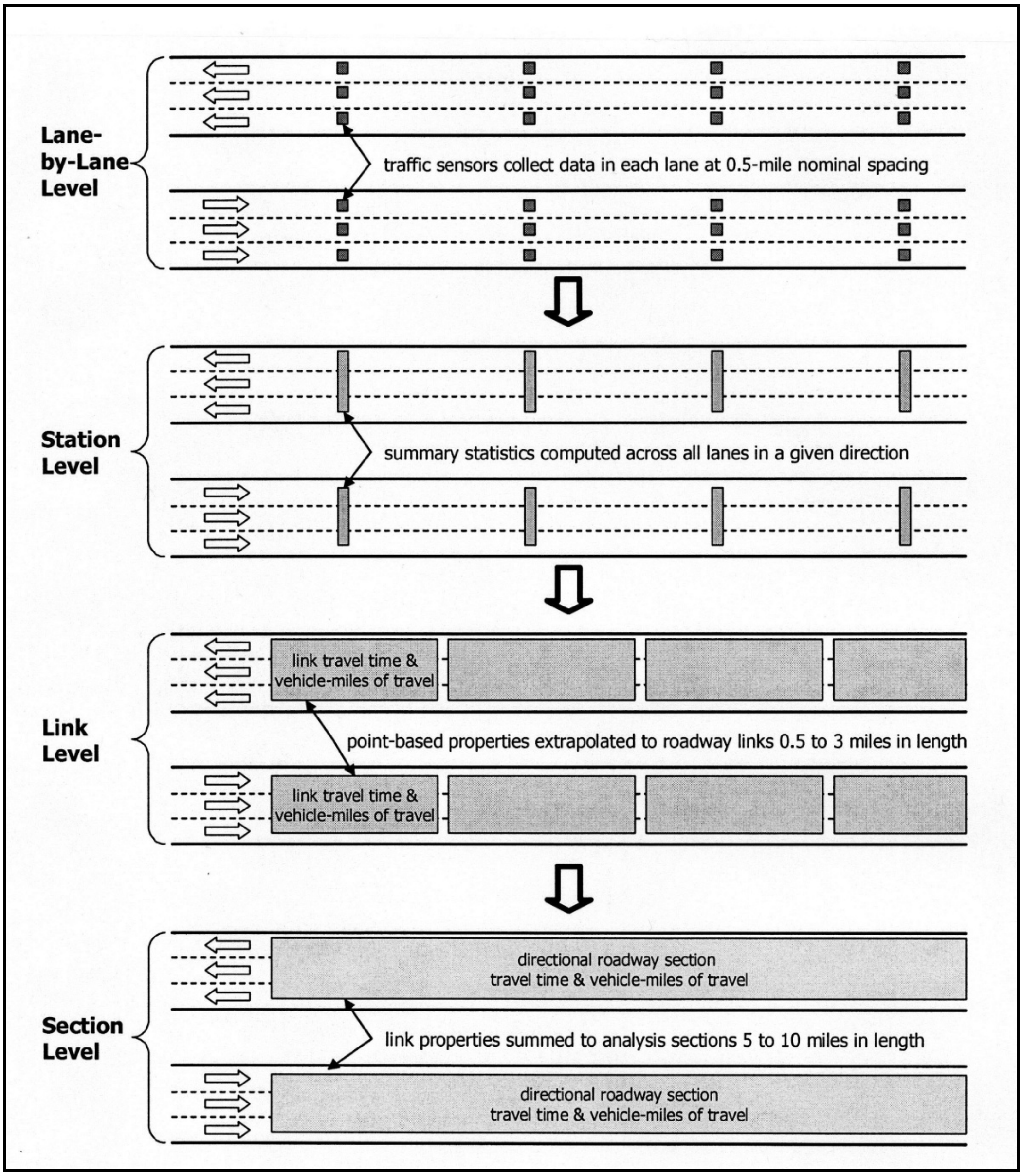

Figure 2. Illustration. Example of data aggregation structure.

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 of this report 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-min 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, and 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, etc.), a link consists of a unidirectional roadway section between entry and exit points. In some cases, sublinks may be used to denote features such 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.
- **Networ**k: 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.

FMSs generally contain a software capability to provide a reference framework to relate detectors to the link structure for the freeway network. If the FMS 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 for the following reasons:

- It simplifies the evaluation methodology. Freeway volume is discontinuous at these points, and these volume changes often result in speed changes.
- 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.[16]

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 figure 3 to relate data from freeway surveillance stations to mainline links. Domains relate links and DMSs[2] 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 the 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 none of the detectors in figure 3 exist within the physical boundaries of domain 4; that domain obtains its information from detector station 4. Section 6 of this report 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 (i.e., 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 a Global Positioning System (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 these 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 of this report.

[2]Although not strictly needed for the detector to link relationships, figure 3 includes DMS in the domain definitions to facilitate the implementation of messaging using a common reference frame.

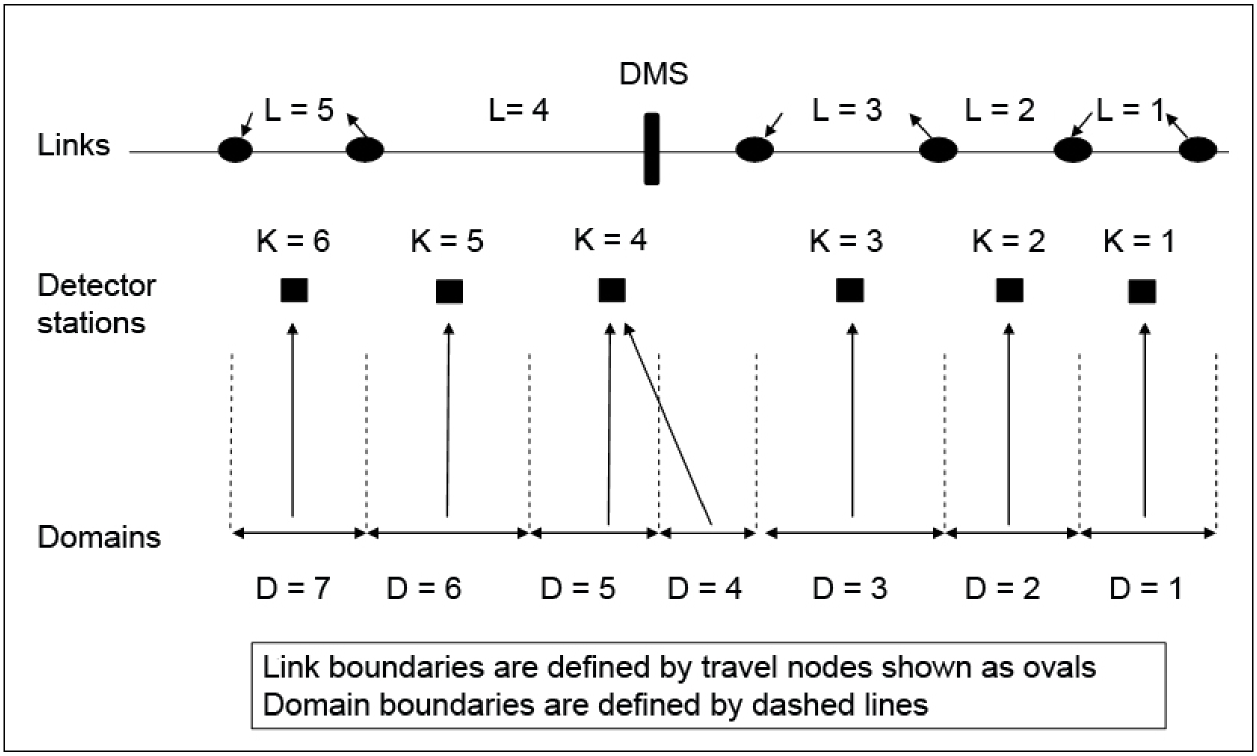

Figure 3. Illustration. Example of link, domain, and detector station relationships.

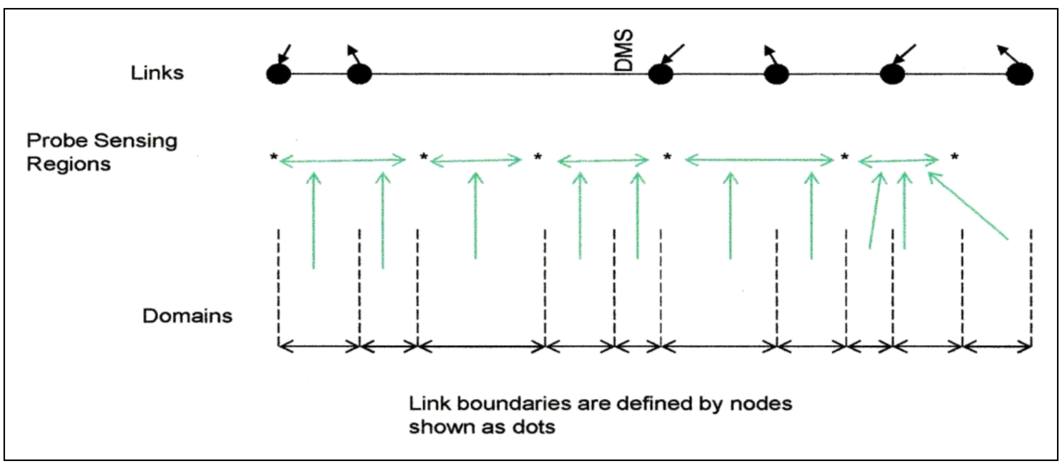

Figure 4. Illustration. Example of link, domain, and probe site relationships.

4.3 TEMPORAL RELATIONSHIPS

For archiving purposes, FMS volume, speed, and occupancy data from point detectors may be stored at 5-min intervals and aggregated into 15-min and 1-h intervals, as in the Florida STEWARD system.(8) The 5- and 15-min intervals provide convenient processing intervals for many of the delay-related computations described in section 5 of this report. Building on these concepts, a useful methodology develops these measures using the spatial/temporal relationship shown in figure 5. The methodology described uses the domain concept as the basis for freeway mainline data accumulation (see figure 3 and figure 4).

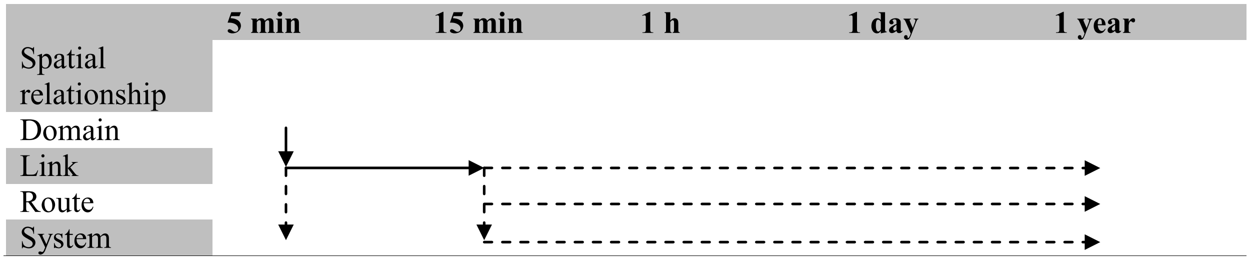

Figure 5. Illustration. Data accumulation methodology.

Detector data are used to obtain these measures at the domain level for 5-min periods and are accumulated at the link level. The 15-min period at the link level is a convenient building block for many of the evaluation measures. The path to computing this level for the 15-min period is shown by the solid trace. The dashed traces show the paths to other spatial levels and time periods. Depending on the particular measure to be computed and the purpose (reports, etc.), the 15-min 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 FMSs 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 defined as 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.

5.1.1.1 Mainline Delay and Travel Time Evaluation for Point Detectors

$$TT(DO,N5) = T5 \times V(DO,N5) \times LE(DO)/SD(DO,N5)$$

Figure 6. Equation. Domain system travel time.

Where:

TT = System mainline travel time (vehicles per hour).
DO = Domain ID.
$N5$ = 5-min evaluation period index number.
$T5$ = 5-min period for mainline and ramps.
V = Roadway volume (vehicles per hour).
LE = Length of link, domain, or probe sensing region (mi).
SD = Domain speed (mi/h).

In some systems, SD represents weighted speed.[9] Since speed and volume varies in different lanes, weighted speed is the product of lane volume and lane speed divided by the total volume.

$$\text{If } \left(TT(DO,N5) - T5 \times V(DO,N5) \times \frac{LE(DO)}{SR(DO)} \right) > 0,$$

$$\text{then } D(DO,N5) = \left(TT(DO,N5) - T5 \times V(DO,N5) \times \frac{LE(DO)}{SR(DO)} \right) \text{ else } D(DO,N5) = 0$$

Figure 7. Equation. Domain system delay.

$$TT(L,N5) = \sum_{DO=a}^{b} TT(DO,N5)$$

Figure 8. Equation. Link system travel time.

Where:

L = Link ID.

$$TT(L,P) = \sum_{NF=N5}^{NF+3} TT(L,N5)$$

Figure 9. Equation. Link system travel time for 15-min periods.

Where:

P = 15-min period index.
NF = 5-min index at the beginning of the 15-min period.

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

Figure 10. Equation. Link system delay.

Where:

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

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

Figure 11. Equation. Link system delay for 15-min periods.

$$VT(DO,N5) = T5 \times LE(DO)/SD(DO,N5)$$

Figure 12. Equation. Domain vehicle travel time.

Where:

VT = Vehicle travel time (hours).

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

Figure 13. Equation. Domain vehicle delay.

Where:

VD = Vehicle delay (hours).
SR = Reference speed for delay (mi/h).

$$VT(L,N5) = \sum_{DO=a}^{b} VT(DO,N5)$$

Figure 14. Equation. Link vehicle travel time.

$$VT(L,P) = \sum_{NF=N5}^{NF+3} VT(L,N5)$$

Figure 15. Equation. Link vehicle travel time for each 15-min period.

$$VD(L,NF) = \sum_{DO=a}^{b} VD(DO,N5)$$

Figure 16. Equation. Link vehicle delay.

$$VD(L,P) = \sum_{NF=N5}^{NF+3} VD(L,N5)$$

Figure 17. Equation. Link vehicle delay for each 15-min period.

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 (see 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 figure 18 and figure 19. *SP* represents the speed for all domains encompassed by the probe-sensing region and is used to compute domain and link vehicle travel time and delay in figure 12 through figure 17 at the 5-min level. It is also used for probe detection in place of *SD* in figure 6 and figure 12.

$$\mathrm{TP}(PR, T5) = \frac{1}{x} \times \sum_{i=1}^{x} TP(i)$$

Figure 18. Equation. Travel time as sensed by probe *PR*.

$$SP(PR) = LE(PR) / TP(PR, T5)$$

Figure 19. Equation. Probe-sensing region speed for region *PR*.

Where:

TP = Travel time as sensed by probe vehicles (hours).
PR = Probe sensing region ID.
x = Number of vehicles in 5- or 15-min probe vehicle sample.
SP = Probe sensing region speed (mi/h).
RRT = Reference ramp travel time.

Probe detection technologies are discussed in section 6 of this report.

In order to develop system delay and system travel time measures, the volume variable required by figure 6 and figure 7 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 ITSs do not provide an automatically based sensing methodology for obtaining entry ramp time and delay. Ramp data, if employed, are most conveniently accumulated on a 15-min basis when considering the ramp as a link.

5.1.1.4 Freeway System Travel Time and Delay

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

$$FT\,(\mathrm{L,P}) = TT(L,P) + T15 \times V(R) \times \sum_{R=1}^{RN} RT(R,P)$$

Figure 20. Equation. Freeway system travel time.

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

Figure 21. Equation. Freeway system delay.

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-min basis and link basis and aggregated annually on a system-wide basis, as shown in figure 22.

$$LPP(L,P) = K_1 \times FP(L,P) \times FD(L,P)$$

Figure 22. Equation. Private vehicle occupant system delay.

Where:

K_1 = Average number of travelers in a 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-min basis and link basis and aggregated annually on a system-wide basis, as shown in figure 23.

$$LPT(L,P) = K_2 \times FC(L,P) \times FD(L,P)$$

Figure 23. Equation. Commercial vehicle occupant system delay.

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-min basis and link basis and aggregated annually on a system-wide basis, as shown in figure 24.

$$LPG(L,P) = K_3 \times FR(L,P) \times FD(L,P)$$

Figure 24. Equation. Goods inventory delay.

Where:

K_3 = Average weight of load in trucks carrying goods (tons).
FR = Traffic volume fraction of trucks carrying loads, excluding 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 through Web sites. Designated routes are often provided for this purpose, and these routes are convenient to use for evaluation.[17]

Route travel time is the sum of route link travel times and may be computed as follows:

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

Figure 25. Equation. Route travel time.

Where:

RTT = Route travel time (hours).
RI = Link on start of selected route.
RO = Link on end of selected route.
VT = Route link travel time (hours).

If a trip starts at 7 a.m., the travel time for the first link on the route (designated as *RI*) becomes *VT*. *N*5 for the first link in this case is 73 (12 5-min periods for the period from midnight until 7 a.m. 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 was studied.(17) Route travel time is the sum of route link travel times and is computed for the appropriate time period for that link. The concept is described below.

If *VT* for a link is less than 5 min, then the travel time for the next link uses the same 5-min time period. If *VT* is greater than or equal to 5 min, then the travel time for the next link uses the subsequent 5-min time period. Higatani et al. indicate that this approach is more accurate than the summation of link travel times computed for a single time period.(18)

Figure 26 provides a flow chart that implements this concept.

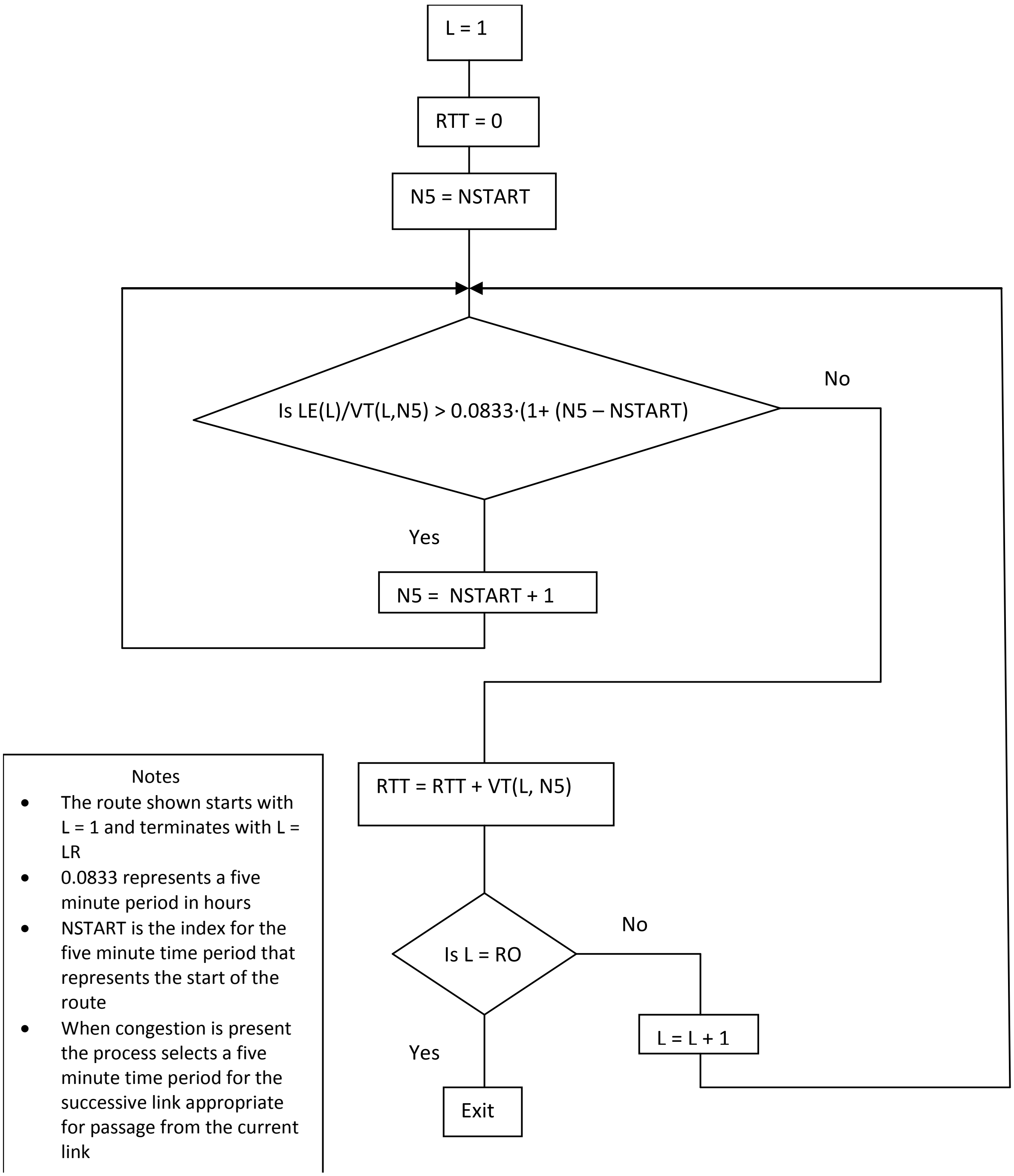

Figure 26. Flowchart. Route travel times.

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

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

Figure 27. Equation. Freeway route delay.

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 are generated per day. It may be expected during the course of 1 month that data will be available for a minimum of 15 days after eliminating weekends, holidays, and other days that may not be typical because of weather problems, special events, etc. Based on these values, the standard estimate of the mean value of route delay is approximately 7.5 percent.[19]

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 day-to-day and/or across different times of the day [20]

Travel time variability may be measured by comparing travel times for a specified route for a given time period (e.g., for a peak hour starting at 7 a.m). Shaw recommends a minimum data collection period of 4 weeks at 15-min intervals.[10] Coupling this criterion with the previous discussion of route travel time, if a "trip" is considered to be a calculation of three 5-min travel times for each 15-min period in a weekday peak hour, eliminating holidays and other non-representative days, a 1 month data collection cycle is a sufficiently representative time period.

The basis for travel time variability and the measures that are used to express it is the standard deviation of the travel time measurements. This is given by Martin and Wu as follows:[7]

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

Figure 28. Equation. Standard deviation of travel time measurements.

Where:

s = Estimate of travel time standard deviation.
T_j = Travel time of the *i*th trip on a specific route.
M = Mean travel time of a set of sample trips for the period (e.g., 15 min).
n = Number of sample trips.

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

Measures that are commonly used include the following:[20]

- **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 the equation in figure 29.

- **Planning time**: The total travel time, which includes buffer time (i.e., calculated as the 95th percentile travel time), as shown in figure 30.

- **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.

$$\text{Buffer time} = 1.64 \times s$$

Figure 29. Equation. Buffer time.

$$\text{Planning time} = \text{Route Travel Time} + \text{Buffer Time}$$

Figure 30. Equation. Planning time.

The relationship among these measures is shown in figure 31.[20]

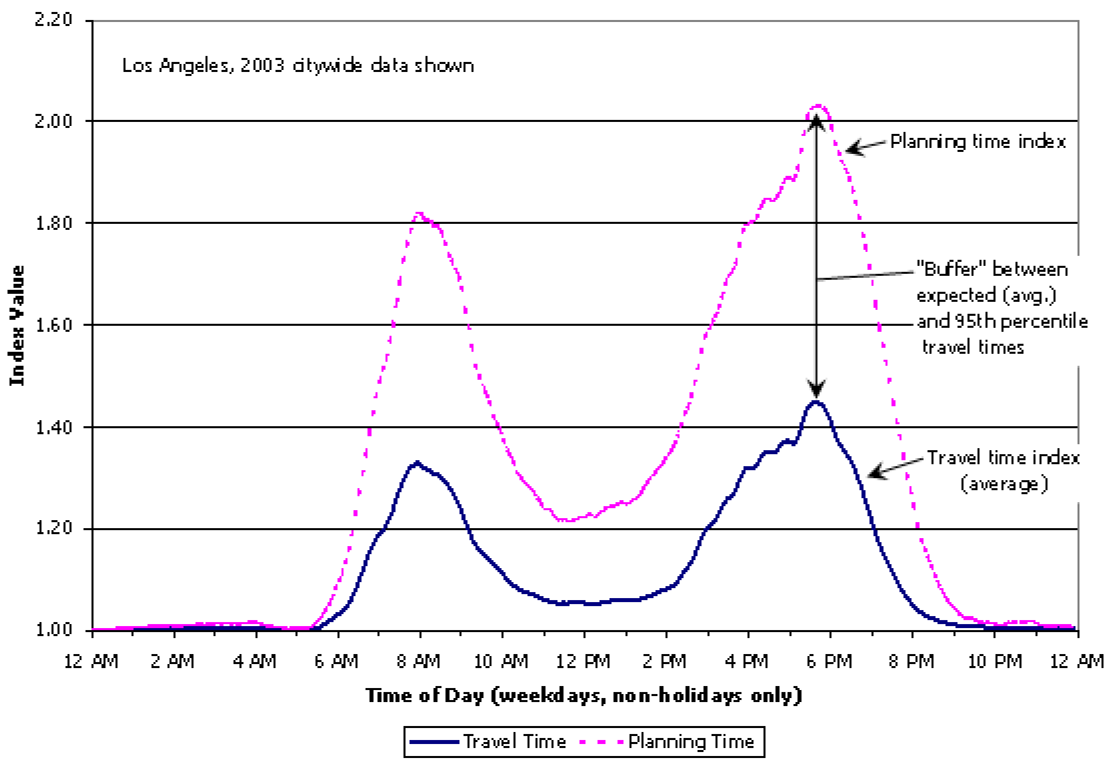

Figure 31. Graph. Relationship of travel time reliability indices.

The basis for all of the reliability measures is route or point-to-point travel times. The following lists shows the four basic ways in which these travel times can be developed:[20]

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).

4. Estimated using computer simulation, sketch planning, or demand forecasting models.

5.1.3 Throughput

Throughput may be evaluated as VMT for a link for the peak hour. For the evaluation process, for each 5 min of the peak hour, the lowest volume for each domain in the link (*LV*) is identified. Peak hour throughput (*PHT*) is provided in figure 32.

$$PHT(L) = \sum_{N5\ =\ \text{5-min period identifier for peak hour start}}^{N5+12} T5 \times LE(L) \times LV(L,N5)$$

Figure 32. Equation. Peek hour throughput.

Throughput may be considered a measure of system efficiency for a freeway link, particularly during the peak period. Gordon et al. suggest that plots of traveler miles versus traveler hours for various conditions may be useful for evaluating the general performance of ITS improvements.(21) This concept is shown in figure 33, where the solid curve represents improved system operation for all traffic conditions relative to the dashed curve. The slope of the line from the origin to a point on the curve represents speed for the link.

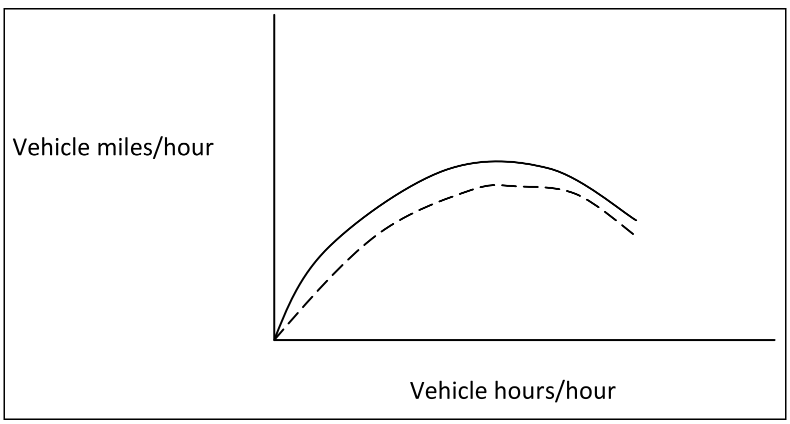

Figure 33. Graph. Link throughput.

The throughput measures originally shown in table 6 include the following:

- **Freeway throughput**: VMT 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. As a result, 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. Section 6 of this report 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 defined as the portion of delay that is attributable to the control device (i.e., 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.[22] Figure 34 shows control delay in a time-space context.[4]

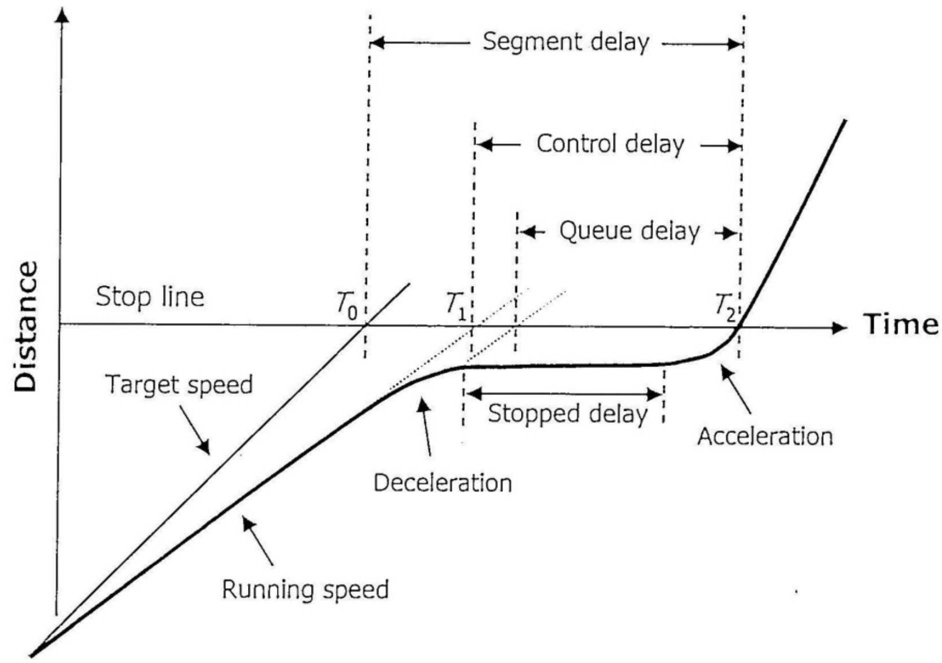

Figure 34. Graph. Control delay.

Control delay for a lane group may be obtained by observations at the intersection or by measuring the time it takes for a vehicle to traverse a path. The relationship between travel time and control delay for a lane group is given by figure 35 as follows:[4]

$$LCD\ (LI, LG) = RLTT(LI, LG) - RET(LI, LG)$$

Figure 35. Equation. The relationship between travel time and control delay.

Where:

LCD = Control delay for the intersection lane group associated with a travel link for a 15-min 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 the equation in figure 35 or measuring the link travel time and identifying the control delay using that equation.

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

Chapter 31 of the *Highway Capacity Manual* provides worksheets to assist in recording manual queue observations and computing control delay from these observations.[4]

Table 10 provides an estimate of the number of runs required to achieve a 95 percent level of confidence.[23]

Table 10. Sample size requirements.

Average Range in Running Speed (mi/h) × *R*	Minimum Number of Runs for Specified Permitted Error				
	+1.0 mi/h	+2.0 mi/h	+3.0 mi/h	+4.0 mi/h	+5.0 mi/h
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 a value other than those shown in column 1.

Figure 36 provides the basis for evaluating individual vehicle travel time and control delay for a lane group at a signalized intersection approach as well as the measures derived from them.

5.1.4.1 Surface Street System Delay

Intersection delay for a 15-min period is provided in figure 36 as follows:

$$LCD(LI) = \sum_{LG=1}^{\text{Intersection lane groups}} LCD(LI, LG) \times V(LI, LG) \times T15$$

Figure 36. Equation. Intersection delay.

Where:

LI = Intersection ID.
LG = Traffic signal lane group.
*T*15 = 15 min for intersection signals and surface streets.

System delay (*SSSD*) for a 15-min period is provided in figure 37 as follows:

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

Figure 37. Equation. System delay.

5.1.4.2 Surface Street Route Delay

Surface street route delay (*SSRD*) is provided in figure 38 as follows:

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

Figure 38. Equation. Surface street route delay.

5.1.4.3 Surface Street Route Travel Time

Surface street route travel time (RTT) is provided in figure 39 as follows:

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

Figure 39. Equation. Surface street route travel time.

5.1.4.4 Other Surface Street Delay Measures

By substituting *SSSD* for *FD*, figure 22 through figure 24 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 11 shows an example of statewide statistics for Washington State, and table 12 shows an example of a Washington State summary report of crashes by type.(24)

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 as follows:

- **Freeway crashes**: These data may be expressed in crashes per million VMT for each freeway link.

- **Crashes at intersections**: These data may be expressed in crashes per million vehicles entering the intersection.

Table 11. 2009 average collision rates by functional class in Washington—Northwest region (State routes only).

Type of Area	Principal Arterial	Minor Arterial	Collector	Interstate	All Highways
Rural Areas					
VMT (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*	1.06	1.14	1.82	0.53	0.92
PDO collisions	378	292	249	347	1,266
PDO collision rate*	0.68	0.64	1.15	0.37	0.58
Injury collisions	205	219	143	145	712
Injury collision rate*	0.37	0.48	0.66	0.15	0.33
Fatal collisions	4	7	2	2	15
Fatal collision rate**	0.72	1.54	0.92	0.21	0.69
Urban Areas					
VMT (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*	2.19	2.98	0.00	1.36	1.73
PDO collisions	5,981	943	0	6,351	13,275
PDO collision rate*	1.45	1.87	0.00	0.93	1.16
Injury collisions	3,034	551	0	2,898	6,483
Injury collision rate*	0.74	1.09	0.00	0.42	0.57
Fatal collisions	17	7	0	17	41
Fatal collision rate**	0.41	1.39	0.00	0.25	0.36
All Areas					
VMT (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*	2.06	2.11	1.82	1.26	1.60
PDO collisions	6,359	1,235	249	6,698	14,541
PDO collision rate*	1.36	1.29	1.15	0.86	1.07
Injury collisions	3,239	770	143	3,043	7,195
Injury collision rate*	0.69	0.80	0.66	0.39	0.53
Fatal collisions	21	14	2	19	56
Fatal collision rate**	0.45	1.46	0.92	0.24	0.41

* Indicates per 1 million VMT.

** Indicates per 100 million VMT.

Table 12. 2009 leading collision type for all collisions in Washington (State routes only).

First Collision Type	Eastern Region		North Central Region		Northwest Region		Olympic Region		South Central Region		Southwest Region	
	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent
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 the benefit-cost analysis. These components include the following:

- **PDO crashes**: Crashes per 1 million VMT.
- **Fatal crashes**: Freeway crashes per 100 million VMT or, alternatively, crashes per 1 million VMT and intersection crashes per 1 million entering vehicles.
- **Injury crashes**: Freeway crashes per 100 million VMT or alternatively crashes per 1 million VMT and intersection crashes per 1 million entering vehicles.

An example of data from the New York State Department of Transportation (NYSDOT) crash record database that was used for a benefit-cost analysis is shown in table 13 and table 14.[25] The tables show 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 FMS, TMC-generated data may be used to supplement crash record data.

Table 13. Crash rates for selected links in Rochester, NY, during the accident period from March 1, 2000, to February 28, 2002.

Roadway Link	Link Description	Total Accidents	Average AADT	Link Length (mi)	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 Total	**465**	**64,257**	**10.21**	**0.96**	**1.94**
Interstate 490	Route 390 interchange	141	90,000	1.46	1.38	1.94
	Mount Read interchange	60	100,000	0.47	1.44	2.26
	Mount 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 Total	**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 Total	**273**	**50,725**	**3.70**	**1.94**	**1.94**

*Average accident rate is higher than the statewide average rate for similar facility types.

Table 14. Crash classification by link in Rochester, NY, during accident period from March 1, 2000, to February 28, 2002.

Roadway Link	Link Description	Severity						Total Accidents
		Fatality		Injury		PDO		
		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, and Route 250 interchanges	0	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	6
	Route 104 total accidents and severity distribution	1	0.22	125	26.88	339	72.90	465
	NYSDOT average severity distribution	N/A	0.35	N/A	33.12	N/A	66.53	N/A
Interstate 490	Route 390 interchange	0	0.00	38	25.95	103	73.05	141
	Mount Read interchange	0	0.00	18	30.00	42	70.00	60
	Mount Read Boulevard to inner loop area	0	0.00	58	25.33	171	74.67	229
	Inner loop area	0	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	N/A	1.35	N/A	33.12	N/A	66.53	N/A
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	N/A	0.35	N/A	33.12	N/A	66.53	N/A

N/A = Not applicable.

While freeway crash data are generally best organized by links for benefit-cost analyses and when trying to identify locations requiring increased attention, crash data on surface streets are 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 1 million vehicles entering the intersection or freeway ramp. Table 15 is an example of average values provided by NYSDOT.(26)

Table 15. Average intersection accident rates for State highways by intersection type based on accident data from January 1, 2007, to December 31, 2008.

Intersection Type	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
Three-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
Four-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 with one lane	0.07	0	—	—	—	—	—	—	—
Merge with two+ lanes	0.04	0.01	—	—	—	—	—	—	—
Off Ramp (All Control)									
Merge with one lane	0.08	0.08	—	—	—	—	—	—	—
Merge with two+ lanes	0.04	0.01	—	—	—	—	—	—	—

ACC/MEV = Accidents per million vehicles entering the intersection.
— Indicates accident information was not collected.
Note: NYSDOT stopped processing most non-reportable accidents beginning with 2002 accident data. Therefore, the rates are based primarily on just reportable accidents from NYSDOT.

Kar and Datta describe a complex weighting of PDO, injury, and fatality crash costs, as well as crash frequency to develop a safety performance index (SPI).(27) Their findings indicate that 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, WSDOT maintains a database that reports on the details of a number of factors, including the following:[(24)]

- Work zone crashes.
- Speed-related crashes.
- Alcohol-related crashes.
- Weather-related crashes, including type of weather occurrence.
- Type of object struck.
- Driver contributing circumstances (see table 16).
  - Five leading contributing circumstances in all collisions (see figure 40).
  - Five leading contributing circumstances in fatal collisions (see figure 41).

Because ITS has different impacts on these factors and agencies collect and report crash causality data using different formats with varying levels of detail and different importance scales, researchers in this project have 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. Therefore, measures are included in table 6 and table 7 for work zone crashes.

Table 16. WSDOT crash data for contributing circumstances.[(24)]

Driver Contributing Circumstances	Fata Collisions	Serious Injury Collisions	Minor Injury Collisions	PDO 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 close	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/pedal cyclist	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

The *Work Zone Safety Performance Measures Guidance Booklet* suggests the safety measures shown in table 17.(28)

Table 17. Safety work zone performance measures.

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

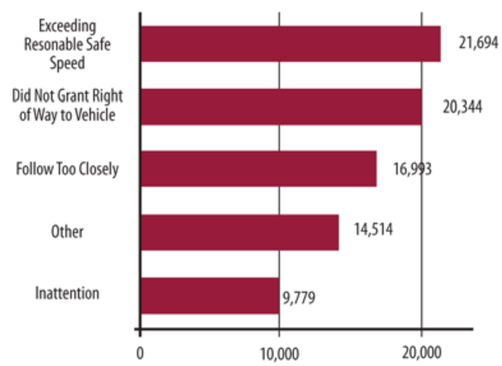

Figure 40. Graph. Five leading contributing circumstances in all collisions.

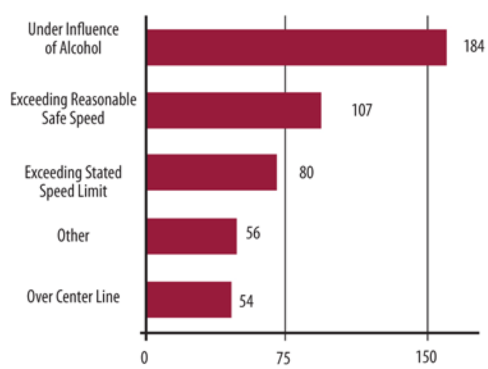

Figure 41. Graph. Five leading contributing circumstances in fatal collisions.

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 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.[29,30]

Secondary crashes are often not identified as such by many of the accident reporting and classification systems. 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. These data are best obtained by ensuring that secondary crashes are included as a crash classification parameter in FMS. 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 VMT. The fuel consumption rates in table 18 were computed using the Motor Vehicle Emission Simulator (MOVES) model.[31] The model employs a representative vehicle class mix. The speeds listed 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.

Table 18. Fuel consumption rates in gallons per VMT.

Speed Range	Year	
	2011	**2016**
10 mi/h > s	0.175	0.167
20 mi/h > $s \geq$ 10 mi/h	0.077	0.073
30 mi/h > $s \geq$ 20 mi/h	0.059	0.056
40 mi/h > $s \geq$ 30 mi/h	0.052	0.050
50 mi/h > $s \geq$ 40 mi/h	0.050	0.048
60 mi/h > $s \geq$ 50 mi/h	0.048	0.046
s > 60 mi/h	0.049	0.046

Note: *s* represents the speed range.

Fuel consumption (*FUF*) in gallons for a domain for a 5-min period is computed as follows:

$$FUF(DO, \mathrm{T5}) = 0.0833 \times G \times LE(DO) \times V(DO)$$

Figure 42. Equation. Fuel consumption.

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.

Federal Highway Administration (FHWA) data developed for this project provide the following conservative fuel consumption rates when intersections experience control delay:

- A total of 0.67 gallons per hour per vehicle in 2011.
- A total of 0.61 gallons per hour per vehicle in 2016.

Fuel consumption resulting from control delay for each lane group for a 15-min evaluation period is given by the following equation:

$$FUP(LI, LG, N15) = 0.25 \times GA \times V(LI, LG, N15) \times LCD(LI, LG, N15)$$

Figure 43. Equation. Fuel consumption due to control delay.

Where:

GA = Fuel consumption rate.
FUP = Fuel consumption for intersections for a 15-min period (gallons).
$N15$ = 15-min 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 as well as 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 minus the travel time for a reference speed. For surface streets, it is provided by the equation in figure 38. Freeway route delay is the sum of link delay for the links comprising the route (see figure 16).

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 LOS

LOS is a commonly used measure for quality of service.[10] The characteristics for freeway LOS are summarized in table 19.[32]

Table 19. Freeway LOS characteristics.

LOS	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, and forced flow.

While the American Association of State Highway and Transportation Officials publication, *A Policy on Geometric Design of Highway and Streets*, suggests a level C LOS for urban and suburban freeways, the decision is based on a number of factors for the local agency to consider.[33] Agencies may also consider the availability of transit alternatives in the selection of a design LOS.[34]

The recommended measure includes LOSs worse than level C as well as a grouping of levels A, B, and C. Table 20 defines LOS in terms of traffic density LOS.[4]

Table 20. LOS criteria for freeway facilities.

LOS	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 as follows:

$$DD(DO,N5) = \frac{V(DO,N5)}{SD(DO,N5)}$$

Figure 44. Equation. Density.

Commonly used LOS measures include the following:

- **Peak hour LOS for a link**: The weighted average link density (*DWL*) for a 5-min period during the peak hour may be computed by figure 45. In figure 46, these 5-min link speeds are averaged over the peak hour to provide the peak hour weighted average link density (*DWLP*). LOS for the peak hour is obtained from table 20.

- **Signalized Intersection LOS**: Table 21 provides the *Highway Capacity Manual* LOS description for signalized intersections.[4] Level F applies if the volume-capacity ratio exceeds 1.0 for any row in the table. Control delay measurements for the intersections may be used to identify LOS. Figure 36 provides the intersection control delay (*LCD*) for 15-min periods. When *LCD* is divided by 15-min intersection volume, LOS may be obtained from table 21.

$$DWL(L,N5) = \frac{\sum_{DO=1}^{\text{Domains in link}} DD(DO) \times V(DO) \times LE(DO)}{\sum_{DO=1}^{\text{Domains in link}} V(DO) \times LE(DO)}$$

Figure 45. Equation. 5-min weighted average link density.

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

Figure 46. Equation. Peak hour weighted average link density.

Table 21. LOS for signalized intersections.

LOS	Description
A	Control delay ≤ 10 s/vehicle
B	20 s/vehicle ≥ control delay > 10 s
C	35 s/vehicle ≥ control delay > 20 s
D	55 s/vehicle ≥ control delay > 35 s
E	80 s/vehicle ≥ control delay > 55 s
F	Control delay > 80 s/vehicle

5.5.2.2 User Satisfaction

Commonly used measures include the following:

- **Rating scales**: Rating scales are used 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, the Georgia Department of Transportation (GDOT) conducted a detailed motorist mail survey.[35] 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 an 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 improvements 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 the following:

- Ramp metering.

- HOV and high occupancy toll lanes.

- Signal phasing to enhance pedestrian safety.

Measures for equity include the following:

- **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. describe an approach to measuring equity.[36] The Lorenz curve (i.e., the heavy line in figure 47) 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, the area between the thin line and the heavy line (AD) in the figure identifies the users that are relatively disbenefitted by the treatment. The area below the Lorenz curve (AT) is also used in the calculation of the Gini coefficient. The Gini coefficient is computed in figure 48.

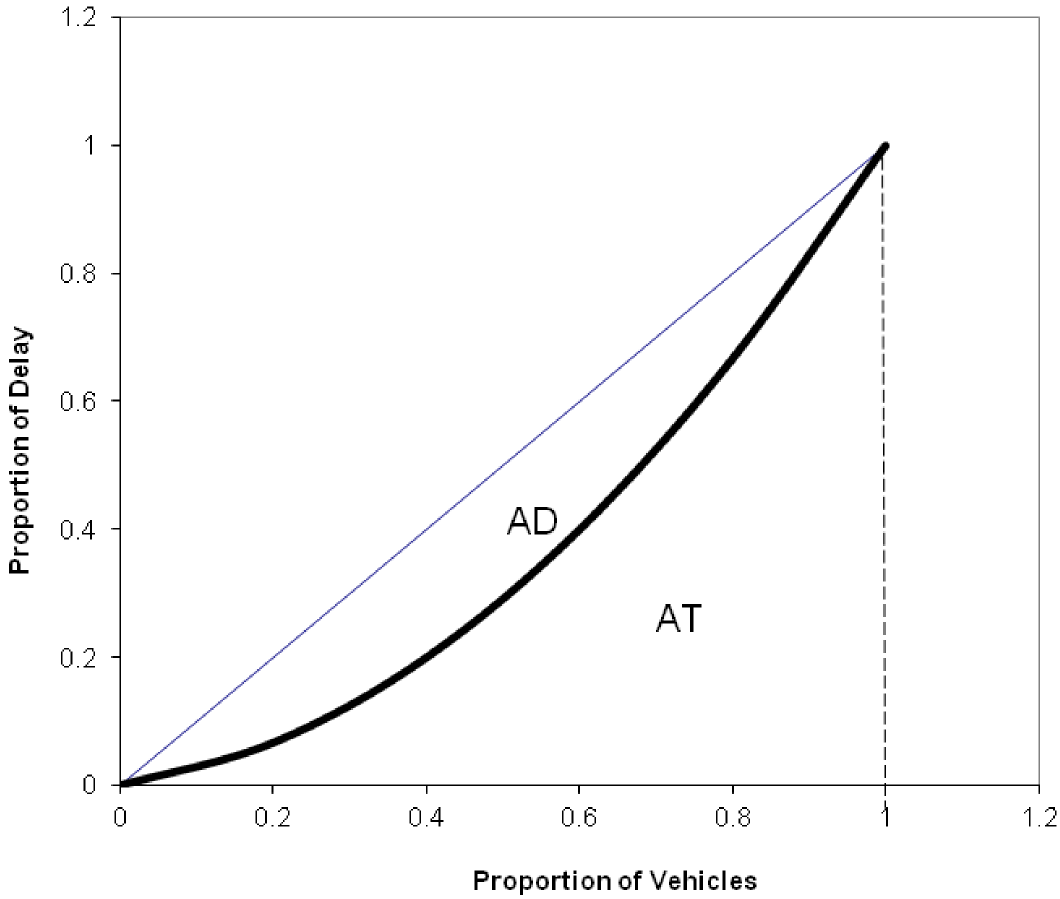

Figure 47. Graph. Example of Lorenz curve for a metered freeway entrance ramp.

$$G = AD/(AD + AT)$$

Figure 48. Equation. Gini coefficient.

5.5.3 Incident Clearance Time

A major benefit of using ITS to reduce delay is the ability it provides operations managers to reduce incident clearance time. Although this benefit is included in section 5.1, "Delay and Travel Time Measures," its importance to the evaluation of TMC operations may merit special attention.

Gordon describes the following simplistic model for the total system delay from the time an incident occurs until the queue clears:[21]

$$D_T = (q_2 - q_3) \times T^2/2 + (q_2 - q_3)^2 \times T^2/(2 \times (q_1 - q_2))$$

Figure 49. Equation. Total system delay.

Where:

D_T = Total system delay from the time an incident occurs until the queue clears.
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 figure 49 as figure 50, Gordon shows that the ratio of change in delay as a result of reduced incident clearance time to incident clearance time is given by figure 51.[21]

$$D_T = K \times T^2$$

Figure 50. Equation. Rewriting total system delay.

$$\frac{\frac{dD_T}{dT}}{T} = 2 \times K$$

Figure 51. Equation. Relationship between change in delay and reduced incident clearance time.

Where:

T = Incident clearance time.
K = Percentage of delay.

From figure 51, it is observed that a small percentage of reduction in the time needed to clear an incident results in twice the percentage of delay reduced.

Measures to consider include the recording of the time needed to clear an incident and the total delay resulting from the incident. A number of evaluation studies 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.[37,38]

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. These data, along with the classification of incidents, are 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 6 h are deleted from the average (or are limited to 6 h) 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 hazardous materials situations.

5.5.4 Service Patrol Measures

Motorist service patrols have proved popular with the public.[39,37] Measures for evaluation include the service patrol assists, quality of service, and rating by public, as outlined in the following sections.

5.5.4.1 Service Patrol Assists

Most agencies that operate service patrol 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, such as that used by WSDOT (see figure 52).[37] 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 53 shows a survey form used by WSDOT. The public's rating on service is shown in figure 54.

WSDOT Service Patrol Assist Form

Your Name	Agency/Company	Month	Day	Year

Location of Disabled Vehicle:

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

Time logs for your response:

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

Check all that apply:

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

Description of disabled vehicle:

	License No.	State	Color	Make	
Vehicle I					
Vehicle II					

Figure 52. Illustration. Washington service patrol assist form.

WSDOT Service Patrol Survey

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 53. Illustration. WSDOT service patrol survey.

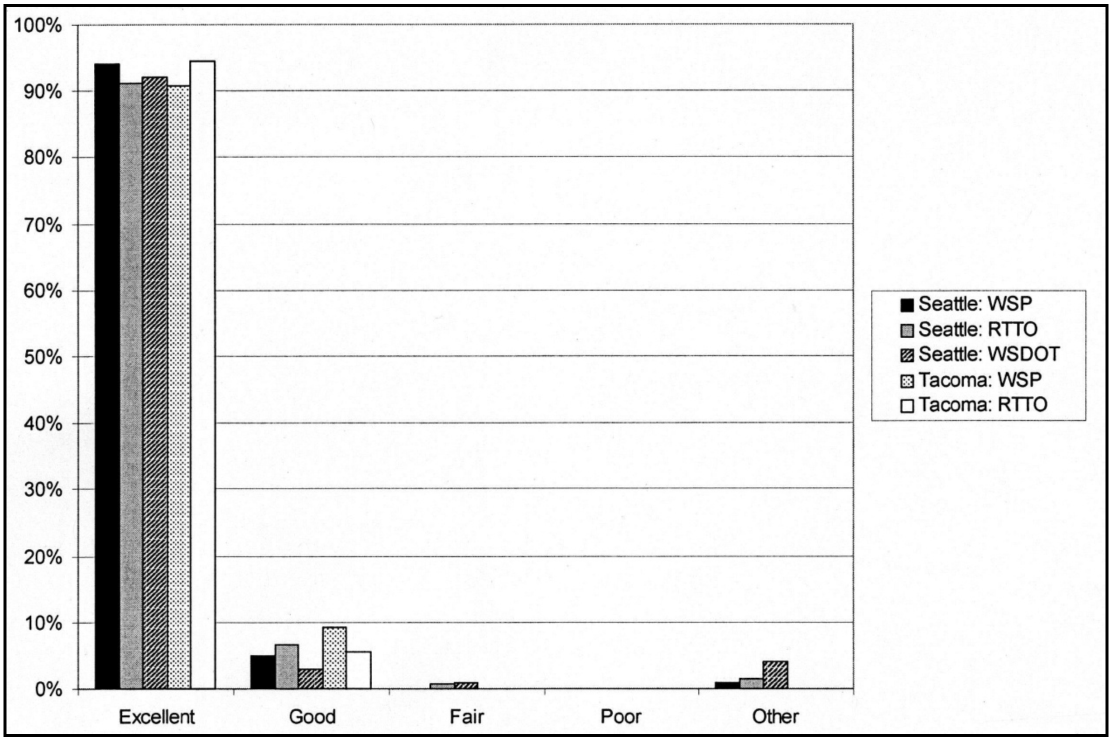

Figure 54. Graph. Public rating on WSDOT service patrol program.

5.5.5 Response to Weather Situations

ITS may provide motorist information and other information to police and highway maintenance agencies to assist in responding to weather situations that affect travelling conditions. These conditions include snow/ice, fog, high winds, and 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.

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 the following:

- Devices on the roadway such as DMSs 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 ADMS FOR FREEWAYS

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

6.1.1 Point Detection and Generation of Traffic Data

Many agencies currently have the capability to provide evaluations. Table 22 describes the data collection characteristics for several agencies. These data are initially generally aggregated to 5-min periods before they are 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 s to 1 min. 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.

When loop traps are not available, speed may be estimated at the TMC from loop detector occupancy and volume measurements. A relationship employed by WSDOT is provided in figure 55.[17]

$$v = \frac{q}{o \times g}$$

Figure 55. Equation. Estimated speed.

Where:

v = Estimated speed.
g = Factor that incorporates vehicle length and loop detector length.

o = Percentage occupancy.
q = Volume in vehicles per hour.

The Caltrans PeMS system accomplishes this function by using a continuously computed g factor.[(6)] Table 22 provides basic data generation for representative performance monitoring systems.

Table 22. Basic data generation for representative performance monitoring systems.

System	Reference	Principal Data Source	Volume	Occupancy	Speed	Basic Spatial Definition	Short Period Time Data Organization	Notes
PeMS	5	Single loop detectors in each lane reported every 20 s; spacing approximately 0.5 mi	From loop detectors	From loop detectors	Computed from volume and occupancy by developing *g* factor in real time for each lane	Segment—region between detector stations	5 min	Statewide system that collects data from individual TMCs
Florida STEWARD System	40	Example installation uses remote traffic microwave sensor (RTMS) radar detectors at approximately 0.25- to 0.5-mi spacing; data reported every 20 s	From RTMS detectors		From RTMS detectors	Segment—region between detector stations	5, 15, and 60 min	Statewide system that collects data from individual TMCs
Minnesota	36	Single loop detectors in each lane reported every 20 s; spacing approximately 0.5 mi	From loop detectors	From loop detectors	Computed from volume and occupancy assuming an average effective vehicle length (vehicle length plus loop length) of 22 ft	Segment—region between detector stations	5 min	
Oregon PORTAL Archived Data User Service	41	Loop traps in each lane reporting data every 20 s	From loop detectors	From loop detectors	From loop detectors	Segment—region halfway between detector stations	5 min, 1-min data recoverable from 20-s data	
Washington State	17	Single loop detectors in each lane reported every 20 s; spacing approximately 0.5 mi	From loop detectors	From loop detectors	Computed from volume and occupancy by use of *g* factor	Segments defined by analyst reviewing spaces between detector locations	1 and 5 min	

Where loop detector traps are employed, vehicle length and speed may also be obtained, providing the potential to classify vehicles by length.

In recent years, point detectors are more common than inductive loop detectors. The most commonly used technologies include frequency modulated continuous wave, microwave radar detectors, passive acoustic detectors, and video processor-based detectors. While these technologies may offer advantages in terms of installation and maintenance cost as well as the ease of conveying data to a communications node point, they are generally considered to be less accurate than inductive loop detectors. Examples of these technologies and errors as reported by Hagemann are shown in table 23.(42) 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 beyond the roadway shoulder.

Table 23. Error rate of different surveillance technologies in field tests.

Technology	Technology	Mounting	Count Error (Percent)	Speed Error (Percent)
Inductive loop		Pavement saw-cut	0.1–3	1.2–3.3
Pneumatic road tube		Pavement	0.92–30	
Microwave radar	WHELEN® TDN 30	Overhead	2.5–13.8	1
	EIS® Remote Traffic Microwafe Sensor	Overhead	2	7.9
Active infrared	Schwartz Electro-Optics Inc. Autosense II®	Overhead	0.7	5.8
Passive infrared	ASIM Technology Ltd IR 254 sensor	Overhead	10	10.8
Video image processing	Econolite Control Products Inc. Autoscope Solo®	Side-fire	5	8
	Econolite Control Products Inc. Autoscope Solo®	Overhead	5	2.5–7
Ultrasonic	Novax Industries Corp. Lane King®	Overhead	1.2	
Passive acoustic	SmarTek Systems, Inc. SAS-1	Side-fire	8–16	4.8–6.3
Wireless sensor networks	Sensys Networks Inc. VSN240	Pavement	1–3	

Note: Blank cells indicate no data were provided.

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 benefit evaluation purposes, the addition of supplementary detector stations may, in some cases, be required 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 in the following sections.

Data Screening

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

Smith and Venkatanarayana divide data screening tests into the following categories:(43)

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

Turner et al. provide the following thresholds for acceptable data for thresholds on a single variable:(15)

- Maximum volume < 250 vehicles per hour for 5 min.
- Maximum occupancy < 90 percent for 5 min.
- Maximum speed > 3 mi/h.
- 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-min time periods (e.g., speeds fluctuating from 60 to 20 mi/h and back to 60 mi/h in consecutive time periods) imply faulty data.

6.1.3.1 Data Imputation

Imputation is the process of filling in the gaps that occur from missing data due to equipment, software, or communication failures.(9) A number of techniques including 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 many 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 (which 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 to zero each other out as the number of sample points increases. 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-to-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 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 these 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 have become increasingly popular for obtaining speed and travel time information. In order to provide estimates for the system oriented measures described in section 3 of this report, volume information is 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 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 24.(44) 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 addresses, these vehicles can be tracked. The I-95 Corridor Coalition tested this technology in conjunction with the testing of INRIX® data.(16) An example of the comparative results (with several floating vehicle tests performed by the University of Maryland) is shown in figure 56 for a morning peak period.(44)

- **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.(45) This technology is effective in determining travel time in 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, which is a service provided by some private firms. While this technology is being improved, results to date have not been sufficiently consistent, particularly at low speeds, to warrant its employment for evaluation purposes.(42)

Table 24. I-95 corridor coalition probe detection test results.

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

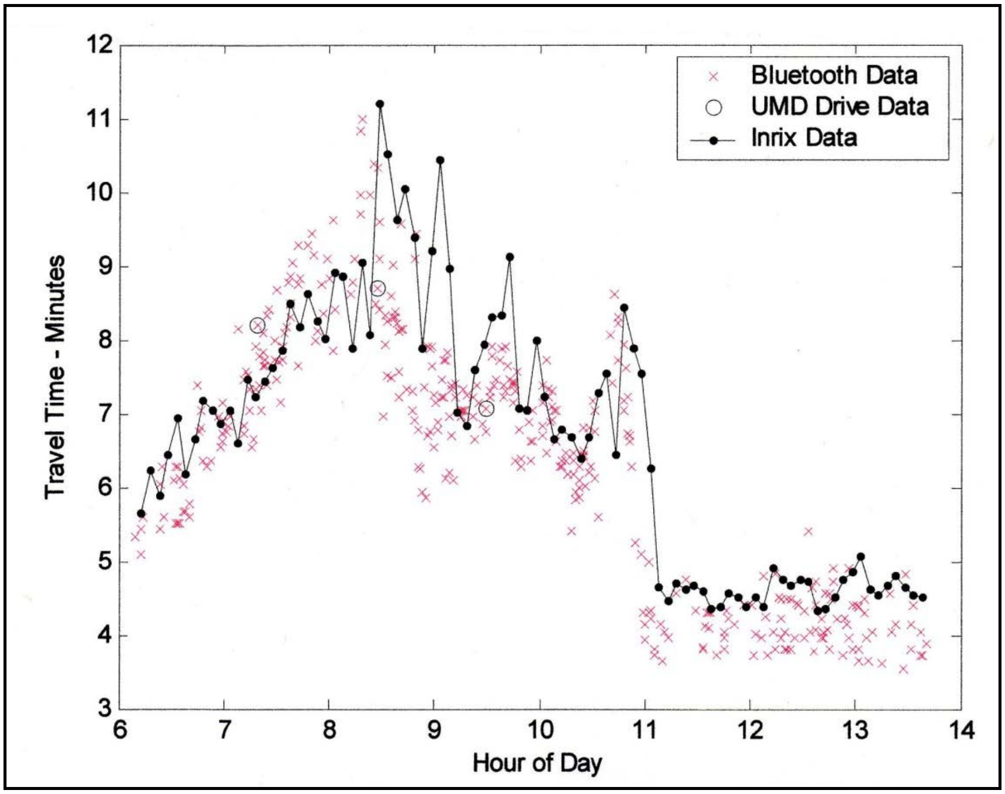

Figure 56. Graph. Comparison of INRIX® data with Bluetooth® data and measured travel time.

6.3.2 Use of Probes for Benefits Evaluation

At the time this report was written, 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 results are 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 is not sufficiently equipped with point detectors to meet this requirement but are equipped with closed circuit television 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. As a result, it will be possible to develop only a limited dataset for this situation.

6.4 AUTOMATION OF DATA COLLECTION FOR SURFACE STREET MEASURES

As indicated in section 5.1.4 in this report, signal timing evaluation is traditionally performed using manual techniques. Specifically, 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 et al. describe the Traffic Signal Performance Monitoring System, which develops measures for isolated intersections.(46) Liu and Ma reported on the SMART-SIGNAL system.(47) Figure 57 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, LOS, queue length, and corridor travel time.

- **Modification of software in traffic controllers**: Using detectors at the intersection and upstream of the intersection, Sharma et al. describe a data logger added to the intersection controller software that enables it to be downloaded to a central facility for processing.(48) 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.

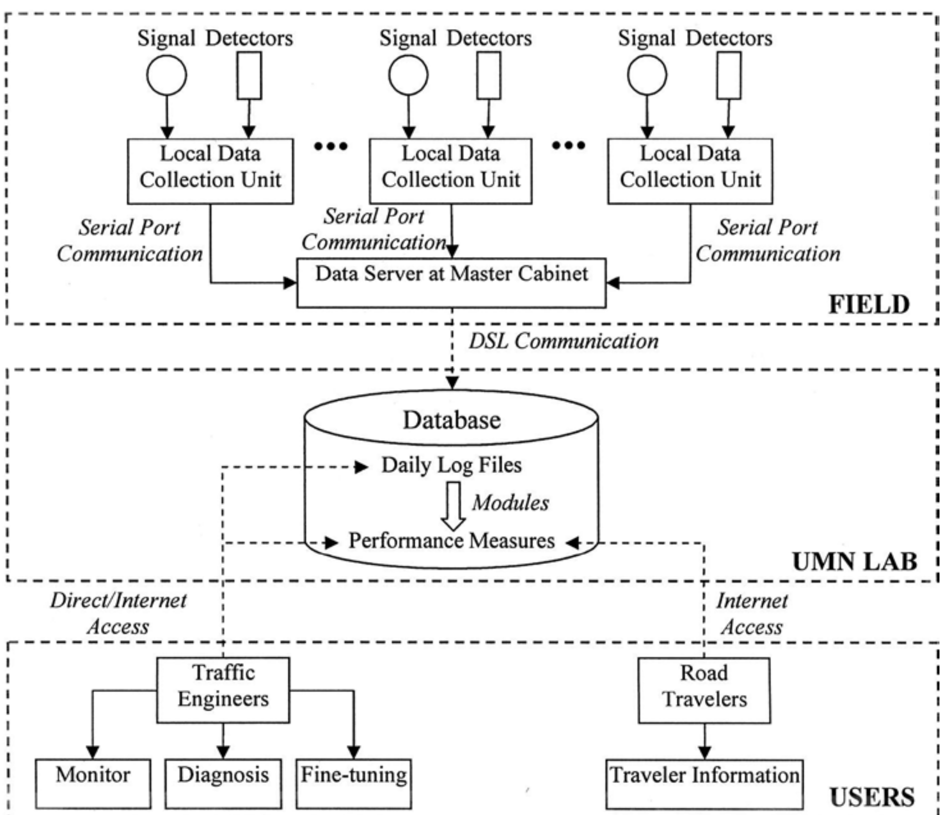

Figure 57. Flowchart. The SMART-SIGNAL system architecture.

6.5 STANDARDS

The National ITS Architecture provides general guidelines regarding archived data user services. The development of standards was assigned to ASTM subcommittee E17.54. The following relevant standards have been developed:

- ASTM E2259-03a: "Standard Guide for Archiving and Retrieving Intelligent Transportation System-Generated Data."(49) 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."(50) 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."(51) 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 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-after context. As time progresses, interest becomes more focused on the year-to-year benefit changes achieved by improvements to TMC operations as well as demand changes. Table 25 identifies general approaches that may be employed as the evaluation emphasis changes.

Table 25. Evaluation approaches.

Evaluation Objective	Project Phase	Possible Evaluation Approach
Continuous year-to-year evaluation	Project operational	Use methodologies as described in this report. Consider adding supplementary surveillance to correct deficiencies in providing automated data.
Before-after evaluation followed by year-to-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-after evaluation followed by year-to-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:

1. 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-cost analysis such as system delay require volume detection, as well. The level of accuracy required for the evaluation should also be identified.

2. Define the evaluation network and the time period of the evaluation. These include the physical boundaries of the network to be evaluated and the time periods or function (e.g., before-after analysis).

3. 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.

4. Compute the measures. Section 5 of this report describes algorithms and computational procedures for evaluating the measures.

5. 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**: These reports may assist officials in assigning resources among agencies in the jurisdiction or in assessing the overall worth of the project.

An example of a report includes the *Houston TranStar 2009 Annual Report*.(52) 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 the following outcome-oriented measures:

- o Average incident clearance time (see figure 58).
- o Motorist cost savings (see figure 59).
- o Benefit-cost ratio (see figure 60).

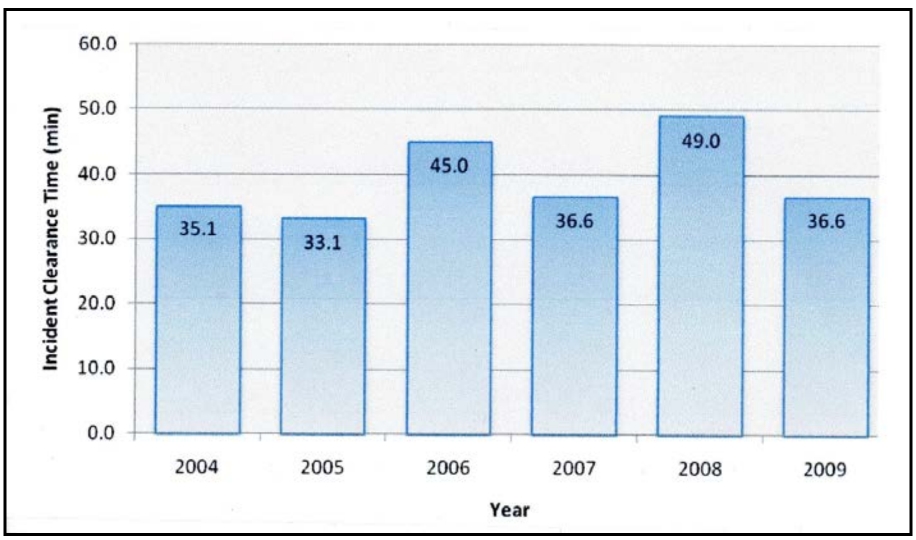

Figure 58. Graph. Annual average incident clearance time.

Agencies might consider the addition of a band in the columns shown in figure 59 and figure 60, which represents the standard error of the estimate or some other measure of error.

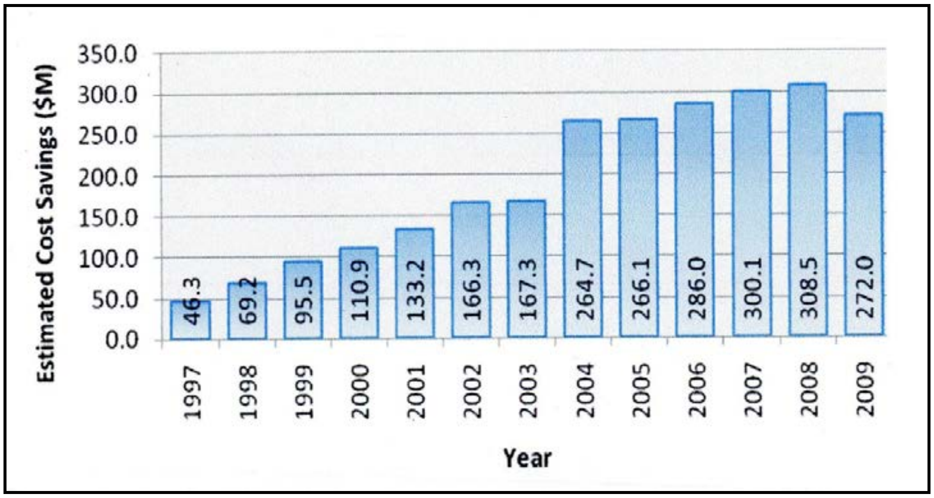

Figure 59. Graph. Estimated annual motorist cost savings attributed to Houston TranStar operation.(52)

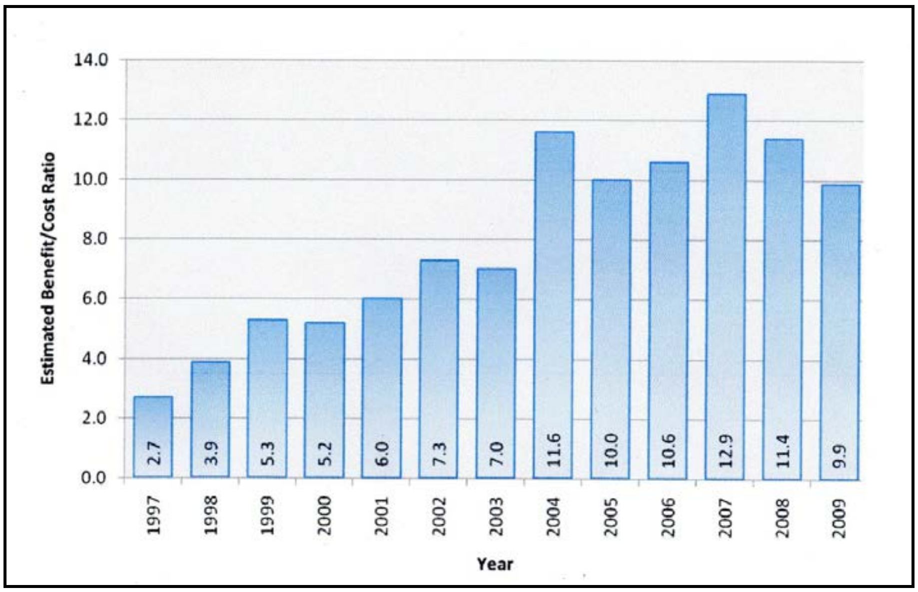

Figure 60. Graph. Houston TranStar benefit-cost ratio.(52)

7.1 MICHIGAN ITS CENTER

The monthly report developed by the Michigan ITS Center provides a detailed overview of performance.(53) In addition to providing measures such as the number of motorist messages, it includes outcome-oriented statistics such as freeway service patrol response and clear times (see table 26).

Table 26. Freeway service patrol performance statistics.

Freeway Segment	(Miles)	Total Assists		Assist Density		Average Response Time (min)		Average Clear Time	
		Sept. 2010	FYTD Average	Sept. 2010	FYTD Average	Sept. 2010	FYTD Average	Sept. 2010	FYTD Average
I-75									
Oakland County Line to I-696	37.0	42.0	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
I-75 Total	**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
I-94 Total	**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	127	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
I-96 Total	**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
I-275 Total	**37.5**	**304**	**335.8**	**8.1**	**10.7.5**	**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
I-696 Total	**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**						

Note: FYTD = Fiscal year to date.

7.2 NAPERVILLE, IL (WEBSITE)

New timing plans were implemented based on periodic examination of traffic conditions. Formal evaluations were conducted in conjunction with signal retiming projects. An example of such a study is shown in table 27 through table 29.[54]

Table 27. Example of Naperville, IL, travel time/delay summary.

Time Period	Travel Direction	Condition	Travel Time (s)	Delay (s)	Stops	Average Speed (mi/h)
Morning 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
		Percent change	24.2 percent	48.2 percent	40.2 percent	32.0 percent
	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
		Percent change	15.9 percent	29.5 percent	41.3 percent	18.7 percent
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
		Percent change	13.0 percent	42.8 percent	16.7 percent	15.4 percent
	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
		Percent change	19.7 percent	39.4 percent	55.2 percent	24.2 percent
Afternoon 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
		Percent change	13.2 percent	33.5 percent	38.3 percent	15.2 percent
	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
		Percent change	19.7 percent	35.8 percent	21.5 percent	24.9 percent

Table 28. Naperville, IL, vehicle emmisions summary—percent reduction.

Time Period	Travel Direction	Hydrocarbons (Percent grams/day)	Carbon Monoxide (Percent grams/day)	Nitrogen Ovide (Percent grams/day)
Morning peak	Eastbound	7	2	-11
	Westbound	5	-5	-1
Midday	Eastbound	5	2	-2
	Westbound	13	1	12
Afternoon peak	Eastbound	9	8	5
	Westbound	10	2	3

Table 29. Naperville, IL, vehicle emmisions summary—annual emission reduction.

Time Period	Hydrocarbons (tons/year)	Carbon Monoxide (tons/year)	Nitrogen Oxide (tons/year)
Morning peak	-16	10	10
Midday	-40	-71	-13
Afternoon peak	-28	-140	-6

8. BENEFIT-COST ANALYSIS

8.1 LIFE CYCLE COST

Several different formulations may be used to relate the value of money and the annual cost of a project. Because project costs and benefits are incurred annually, life-cycle cost is conveniently expressed as annualized cost.[55] The computation of life-cycle cost is described in NYSDOT's *Intelligent Transportation Systems Scoping Guidance*.[56]

The value of design cost and construction cost (*PDC*) is shown in figure 61.

$$PDC = Design\ cost + Construction\ cost$$

Figure 61. Equation. Value of design and construction cost.

The capital recovery factor (*CRF*) relates the interest rate (*I*) and system operational life (*NL*) to these capital costs, as shown in figure 62.

$$CRF = \frac{I \times (1 + I)^{NL}}{(1 + I)^{NL} - 1}$$

Figure 62. Equation. Capital recovery factor.

Tables for *CRF* are also provided in standard economics texts. Historical interest rates for 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 in figure 63 as follows:

$$REI = PDC \times CRF$$

Figure 63. Equation. Uniform annual equivalent investment cost.

Annualized life-cycle cost (*LCC*) is provided in figure 64 as follows:

$$LCC = REI + Annual\ operating\ cost + Annual\ maintenance\ cost$$

Figure 64. Equation. Annualized life-cycle cost.

In figure 62, the system operational life (*NL*) may be considered to be the average life of a component weighted by the furnish and the installation 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

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 of this report discusses evaluation alternatives when prior evaluations have not been performed. Table 30 identifies the monetary performance components included in each of these evaluations.

Table 30. Performance component for benefit-cost analysis.

Component	Expression	Reference for Key Parameters
Private vehicle occupant system delay	$PVOSD = H1 \times LPP$	Figure 22
Commercial vehicle occupant system delay	$CVOSD = H2 \times LPT$	Figure 23
Goods inventory delay	$GID = H3 \times LPG$	Figure 24
Cost of crashes	$CC = H4 \times CRA$	None
Cost of fuel	$CF = H5 \times \sum_{\text{Domains}} \sum_{\text{5-min periods}} FUF(DO,T5)$	Figure 42

Representative values for coefficients $H1$ through $H5$ in table 30 are provided in table 31.

Table 31. Representative values for coefficients.

Coefficient	Definition	Representative Value in 2010	Reference for Value
$H1$	Private vehicle occupant system delay ($ per vehicle occupant)	17.02	Average of references 37, 50, and 54 adjusted to 2010
$H2$	Commercial vehicle occupant system delay ($ per vehicle occupant)	27.49	Reference 37 adjusted to 2010
$H3$	Goods inventory delay ($ per ton hour)	30.81	Reference 56 adjusted to 2010
$H4$	Cost of crashes ($ per crash)	45,585.00	Average of references 37, 52, and 56 adjusted to 2010
$H5$	Cost of fuel ($ per gallon)	Average of past 3 years	N/A

N/A = Not applicable.

Crash costs are the cost of fatality, injury, and PDO crashes weighted by the frequency of the accident class.

Costs were adjusted to 2010 levels by using the relationship in figure 65 as follows:

$$CPIR = \frac{CPI\ for\ year\ 2010}{CPI\ for\ year\ data\ obtained}$$

Figure 65. Equation. Cost adjusted to 2010 levels.

The Consumer Price Index may be obtained from the Bureau of Labor Statistics Web site at 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 31.

The annualized monetary performance for the project is provided by figure 66.

$$MP = H1 + H2 + H3 + H4 + H5$$

Figure 66. Equation. Monetary performance.

The annualized monetary benefit for the project is provided by figure 67.

$$MB(E) = MP(BA) - MP(E)$$

Figure 67. Equation. Monetary benefit.

Where:

BA = Baseline year.
E = Year for which the evaluation is performed.
MB = Monetary benefit.
MP = Monetary performance.

Note that the values for $H1$ through $H5$ for the evaluation year should also be used for the base year.

8.3 BENEFIT-COST RELATIONSHIPS

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

8.3.1 Benefit-Cost Ratio

The benefit-cost ratio provided in figure 68 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-cost ratio greater than 1.0 is required for viable projects, projects with higher benefit-cost ratios often provide decisionmakers with preferred rationales for project funding. Note that values for both *MB* and *LCC* are in evaluation-year dollars.

$$\frac{B}{C} = \frac{MB}{LCC}$$

Figure 68. Equation. Benefit-cost ratio.

8.3.2 Other Benefit-Cost Relationships

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

Figure 69 shows several possible system design or operation alternatives. The slopes of the dotted lines (when the axes scales are considered) are the benefit-cost ratios. Although alternative A has the higher benefit-cost, alternative B provides significantly greater benefits. The slope from alternative A to alternative B shows the marginal benefit-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.

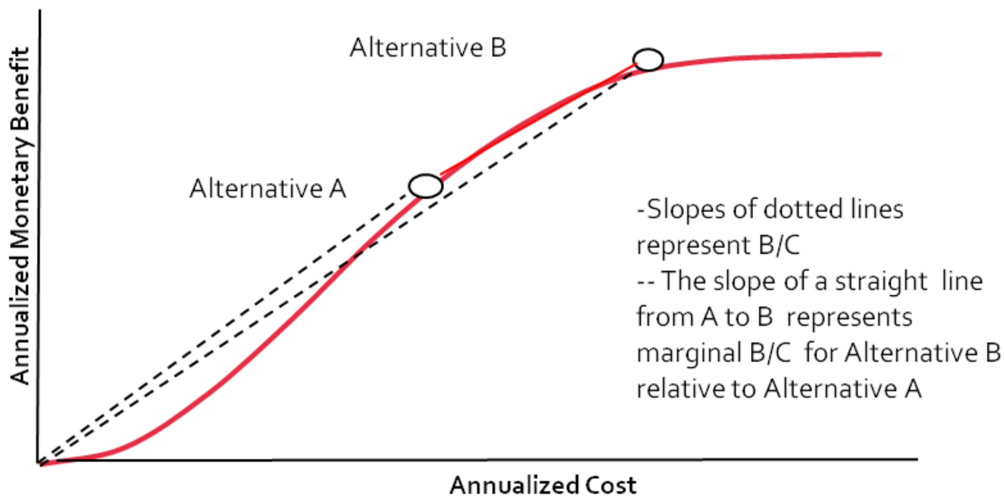

Figure 69. Graph. Monetary benefits and costs for project alternatives.

APPENDIX A. EXAMPLE OF PROGRESSION TO PERFORMANCE MEASURES

The following appendix illustrates the process used by the Maricopa Association of Governments (MAG).[57] The process starts with the development of goals (see table 32) and progresses to the development of initiatives to achieve these goals and the functions required (see table 33). Figure 70 shows the measures used to evaluate the goals.

Table 32. Development of goals.

Operational Categories	3-Year Goal	5-Year Goal
Freeway mobility	Limit the percent increase in average travel time to less than the percent increase in traffic volume.	Same as 3-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 2 years or when traffic volumes through the interchange change by more than 5 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.	Deploy transit signal priority to bus rapid transit routes where beneficial.

Computer system reliability	• Operate the system with up time of 95 percent—no more than 450 h down time per year. Allows for approximately 8 h of system maintenance per week. Maintenance is preferably conducted in off-peak periods. • Minimize system down time to an average of 1 h per system failure.	No 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, 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 Arizona Department of Transportation (ADOT)/Maricopa County Department of Transportation/ City of Scottsdale Web-based Highway Condition and Reporting System (HCRS) pilot project for local closure and restriction information to include five additional MAG member agencies (phase 2). • Incorporate transit status information from automatic vehicle locator (AVL) data from buses into travel information services. • Develop Web-based arterial maps for 100 percent 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 percent of instrumental arterial roadways and post this information to the Web, 511, and variable message signs.

Table 33. Development of initiatives.

Operational Categories	Initiatives	Functions
Regional Traffic Signal Optimization Program	Improved traffic signal timing within cities and across jurisdiction 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 preset traffic signal timing structure and criteria for traffic signal timing plan changes during incidents.
Arterial and freeway incident	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. • Improve the prequalified list of towing and recovery vehicles. • Facilitate agreements between agencies to extract computer-aided dispatch (CAD) information for travel information services and ADOT Traffic Operations Center. • 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 preventative maintenance and prompt repair of locally owned ITS field devices and central systems. • Improve preventative 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.
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 interagency 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 variable message sign. • Market travel information services.
Performance Measurement	The effectiveness of all the initiatives can be measured through a performance measurement program.	Develop performance measurement program.

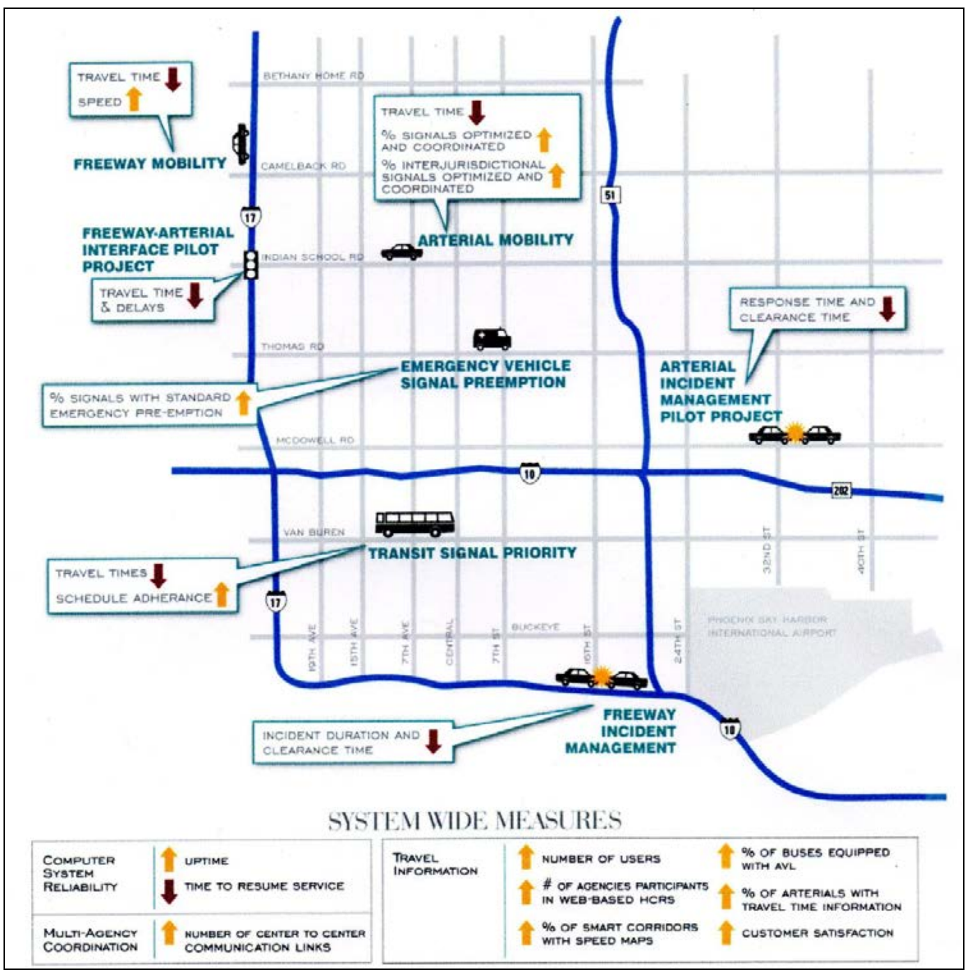

Figure 70. Illustration. Performance measures.

APPENDIX B. POLLUTANT EMISSIONS

This appendix describes the computations for pollutant emissions. The pollutants discussed are provided in table 34.

Table 34. Pollutant index identification.

Pollutant	Pollutant Index Identification
Volatile organic compound (VOC)	PO = 1
Sulfur dioxide (SO_2)	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

1 µm = 0.039 mil

The emission data in this appendix were provided by FHWA using the MOVES model.(31)

B.1 FREEWAYS

Emission rates in terms of grams per VMT are typically relatively low at high speeds (e.g., 75 mi/h). The rates reduce somewhat as speed decreases and then increase significantly as speed continues to decrease. Emissions for each pollutant for 5-min time periods are modeled by figure 71.

$$POL\,(PO,N5) = V\,(DO,N5) \times LE(DO) \times \frac{ER\,(PO,SD\,(PO,N5))}{12}$$

Figure 71. Equation. Emissions.

Where:

POL = Emissions.
PO = Pollutant.
ER = Emission rate.

The emission rate for each pollutant as a function of speed for years 2011 and 2016 is provided in table 35 and table 36.

Table 35. Emission rates for 2011.

Speed (mi/h)	Emission Rate (g/mi)				
	NO_X	SO_2	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	1.028	0.00821	0.1434	0.0370	0.0387
25	1.105	0.00913	0.1638	0.0395	0.0413
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 36. Emission rates for 2016.

Speed (mi/h)	Emission Rate (g/mi)				
	NO_X	SO_2	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.

B.2 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 are 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-min-period emission levels is provided in figure 72.

$$POLA(PO,LI,LG,N15) = 0.25 \times PA(PO) \times V(LI,LG,N15) \times LCD(LI,LG,N15)$$

Figure 72. Equation. Arterial pollutant emission.

Where:

POLA = Arterial pollutant emission (g).
PO = Pollutant identification.
LI = Intersection ID.
LG = Traffic signal lane group.
PA = Idling emissions generation rate (g/h).
V = Volume (v/h).
LCD = Control delay for the lane group for a vehicle.

Table 37 provides the values for the idling emission rates.

Table 37. Idling emission rates.

Pollutant	2011 Emission Rate (g/h)	2016 Emission Rate (g/h)
NO_X	5.858	3.500
SO_2	0.0708	0.0669
VOC	3.404	1.642
PM 2.5	0.305	0.213
PM 10	0.318	0.222

APPENDIX C. GDOT MOTORIST SURVEY

Georgia State University conducted a motorist survey for GDOT. The report, *2006 Motorist Survey Pilot Statewide Results*, describes the survey methodology, questions, and results.(35) 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.

Figure 73 and figure 74 show traffic flow performance ratings for freeways, and figure 75 and figure 76 show these ratings for non-freeway routes. Results are also provided in the report for each GDOT district. Figure 77 illustrates the priorities chosen by survey respondents, and figure 78 presents performance versus importance that may assist in resource allocation.

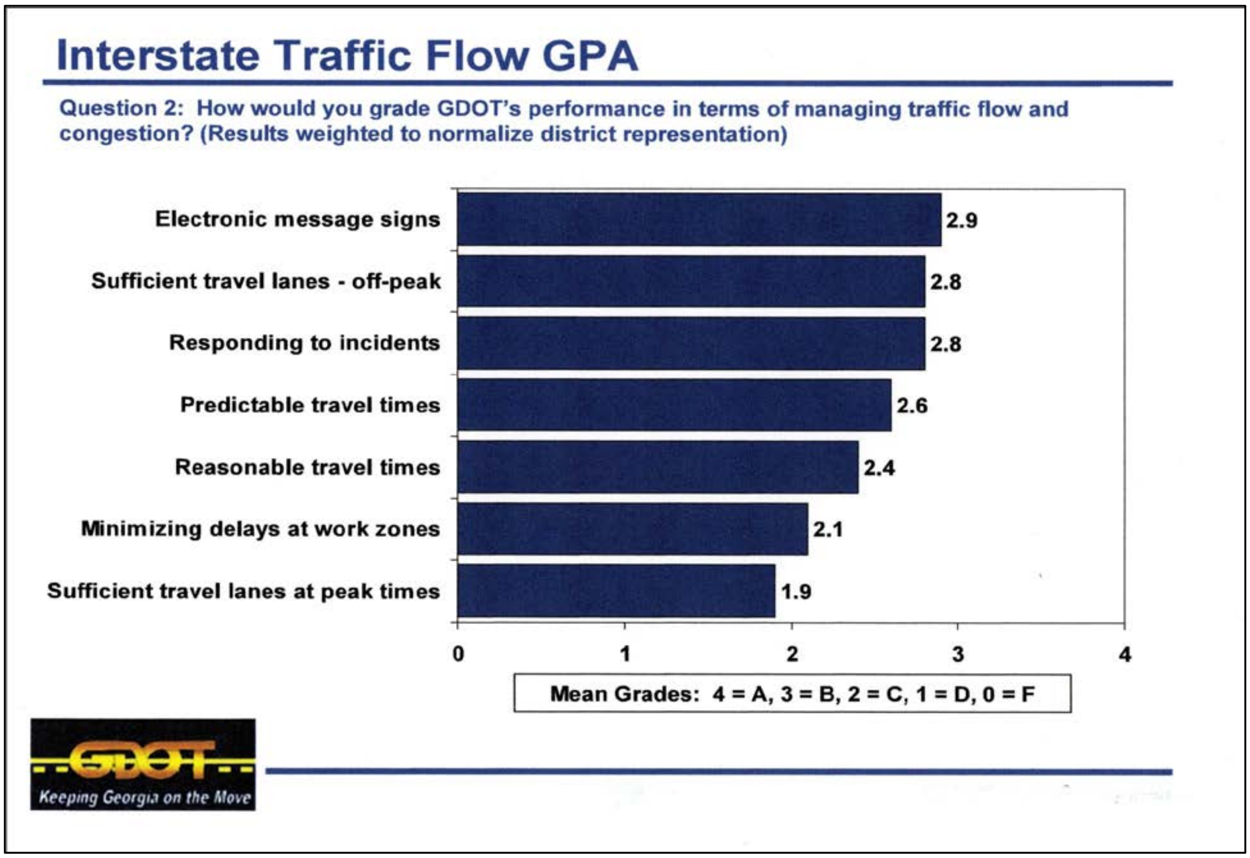

Figure 73. Illustration. Interstate traffic flow scores.

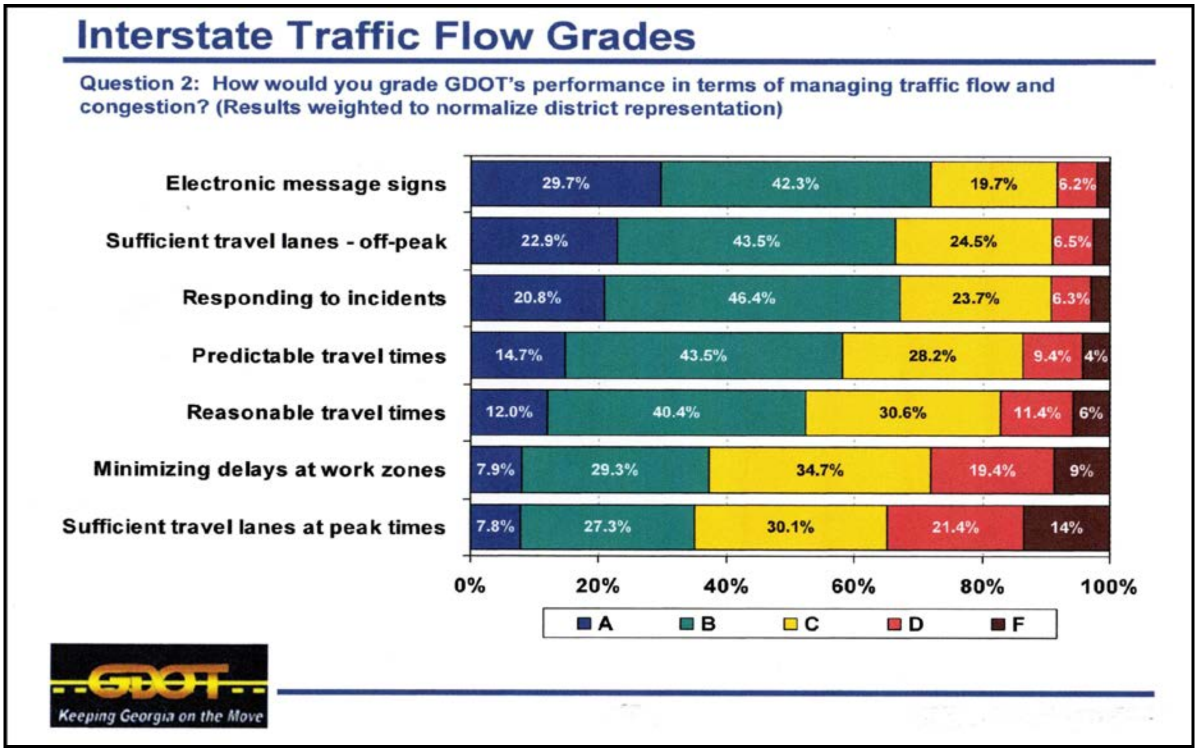

Figure 74. Illustration. Distribution of interstate traffic flow scores.

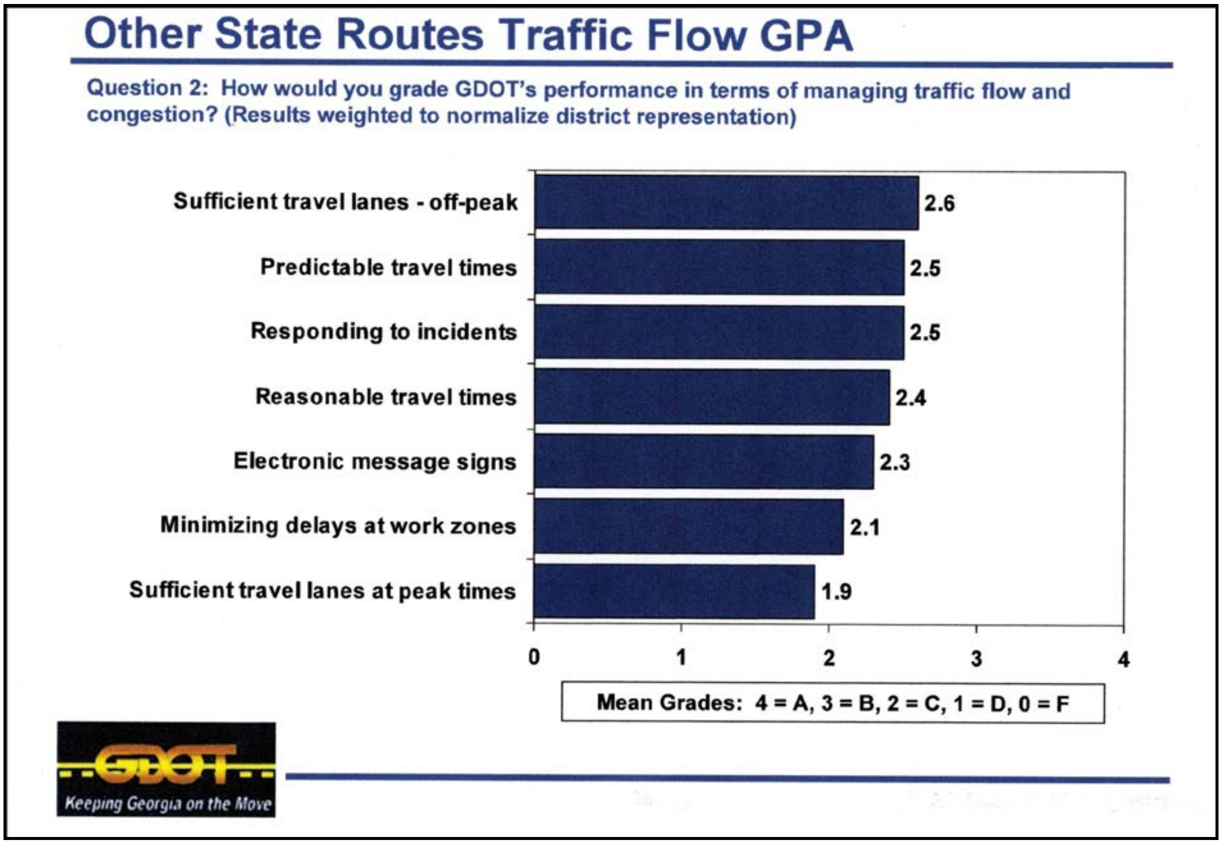

Figure 75. Illustration. Non-interstate traffic flow scores.

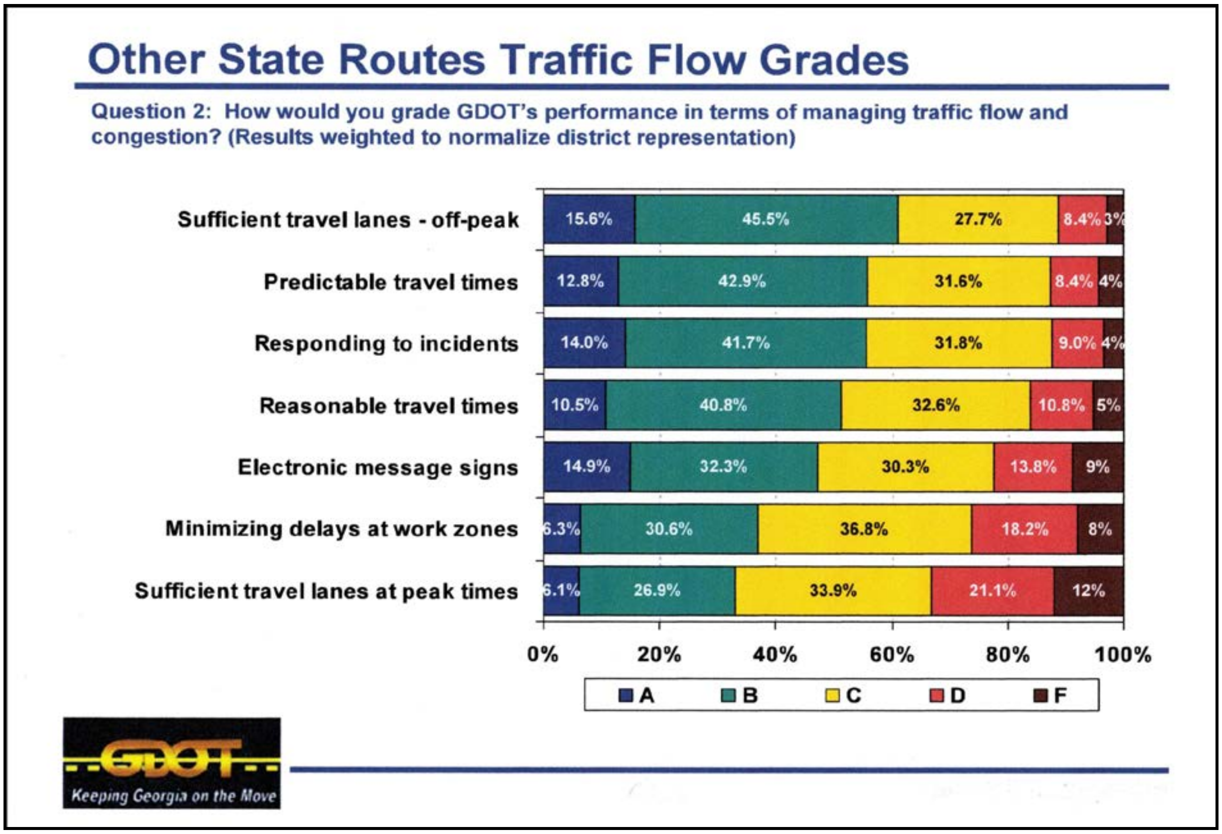

Figure 76. Illustration. Distribution of non-interstate traffic flow scores.

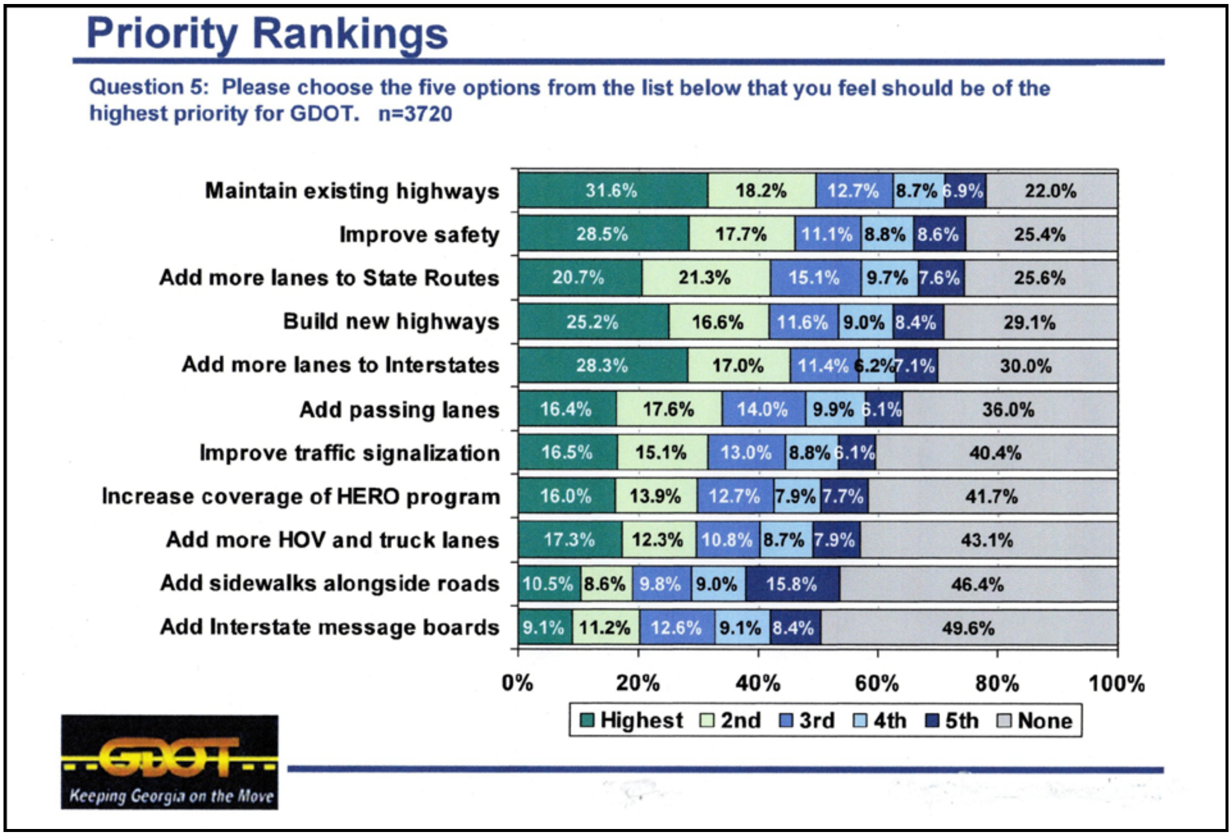

Figure 77. Illustration. Motorist priority rankings.

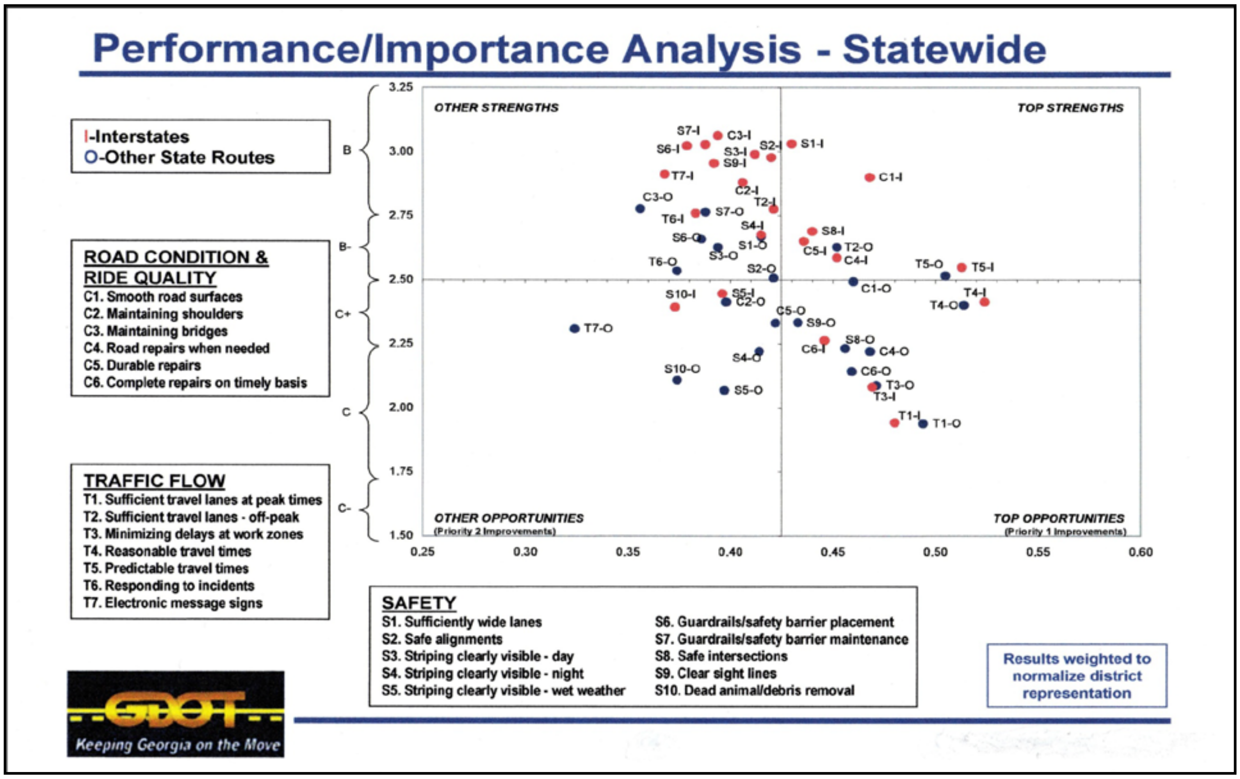

Figure 78. Illustration. Performance versus importance plot.

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