Influence of Operations Strategies on Third Performance Management Rulemaking (PM3) and Other Travel Time-Based Measures Primer Part One

Recurring Congestion Strategies

November 2024

U.S. Department of Transportation
Federal Highway Administration

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TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA-HOP-24-001	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Influence of Operations Strategies on Third Performance Management Rulemaking (PM3) and Other Travel Time-Based Measures Primer Part One Recurring Congestion Strategies		5. Report Date November 2024
		6. Performing Organization Code
7. Author(s) Richard A. Margiotta, Mark E. Hallenbeck, Darcy Bullock, and Mathew J. Kulathintekizhakethil		8. Performing Organization Report No.
9. Performing Organization Name and Address Cambridge Systematics, Inc. 101 Station Landing, Suite 410 Medford, MA 02155		10. Work Unit No. (TRAIS)
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Highway Administration Office of Operations 1200 New Jersey Avenue, SE Washington, DC 20590		13. Type of Report and Period Covered
		14. Sponsoring Agency Code HOP

15. Supplementary Notes
The Task order contracting officer's representative (TOCOR) was Rich Taylor.

16. Abstract

The purpose of this Primer is to: 1) summarize previous methods used to evaluate operations strategies, 2) document the recurring congestion operational strategy implementation evaluation methodology developed for the project, including the performance measures needed to characterize benefits and costs and how to relate to third performance management rule (PM3) measures; 3) report the results of the seven real-world evaluations conducted with the methodology; and 4) provide examples for successful application of the methodology and highlight their relationship to PM3 measures.

The methodology uses empirical data to track changes in travel times and influencing factors: incidents, weather, and demand. Where indicated, traffic modeling is used to control large variations in the influencing factors. Application of the methodology to seven case studies revealed that six cases achieved a notable improvement in performance; in the seventh case, congestion in the "before" period was marginal, so little change was noted. Depending on the conditions of each case, the PM3 measures will not always track with traditional congestion mobility measures. In several instances, traditional measures showed a performance improvement, but no improvement manifested in the PM3 measures for two reasons: (1) the binary nature of the PM3 measure (reliable/not reliable); and (2) components of the PM3 metric changing at different rates from the before period to the after period (e.g., the 50th and 80th percentile travel times in the level of travel time reliability metric).

17. Key Words Operations, evaluation, performance measures, performance management, transportation systems management and operations, strategic, data, data-driven, policy, investment, PM3		18. Distribution Statement No restrictions	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 126	22. Price N/A

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

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 fl	foot-candles	10.76	lux	lx
	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf lbf/in^2	poundforce	4.45	newtons	N
	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 m^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^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 cd/m^2	lux	0.0929	foot-candles	fc
	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

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LIST OF ACRONYMS

AADT	average annual daily traffic
AASHTO	American Association of State Highway and Transportation Officials
ADM	active demand management
AOG	arrivals on green
ASOS	Automated Surface Observing System
ATDM	active transportation and demand management
ATM	active traffic management
ATR	automatic traffic recorder
B/C	benefit-cost
BCA	benefit-cost analysis
Caltrans	California Department of Transportation
CBD	central business district
CCTV	closed-circuit television
CMAQ	Congestion Mitigation and Air Quality Improvement Program
DMS	dynamic message sign
DOT	Department of Transportation
EB	Empirical Bayes
ESS	environmental sensor station
FHWA	Federal Highway Administration
GIS	geographic information system
GNB	Gray Notebook
GP	general purpose
GPS	Global Positioning System
HCM	*Highway Capacity Manual*
HOT	high-occupancy toll
HOV	high-occupancy vehicle
ICM	integrated corridor management
ILHL	incident lane-hours lost
ITS	intelligent transportation systems
LHL	lane hours lost
LOTTR	level of travel time reliability
MAP-21	Moving Ahead for Progress in the 21st Century Act
MPO	metropolitan planning organization
MTTI	mean travel time index
NCDOT	North Carolina Department of Transportation
NOAA	National Oceanic and Atmospheric Administration
NPMRDS	National Performance Management Research Data Set
PHED	peak hour excessive delay
PM3	Third Performance Management Rule
POG	percent arrivals on green
PP&E	preliminary planning and engineering
PTI	planning time index
SCOOT	Split Cycle Offset Optimization Technique
SHRP 2	Strategic Highway Research Program 2

SR	State Route
TDM	travel demand model
TMC	traffic message channel
TOC	transit-oriented community
TOPS-BC	Tool for Operations Benefit/Cost Analysis
TTI	travel time index
TTTR	truck travel time reliability
USDOT	U. S. Department of Transportation
VDF	volume-delay function
VMT	vehicle-miles traveled
VSL	variable speed limit
WSDOT	Washington State Department of Transportation

EXECUTIVE SUMMARY

This Primer presents an empirically based method for conducting before and after analyses of implemented operations strategies that deal with recurring congestion. These strategies include active transportation and demand management (ATDM), arterial management, congestion pricing, integrated corridor management (ICM), and freeway management. The method is based on using probe vehicle-based travel-time data; the National Performance Management Research Data Set (NPMRDS) is highlighted, but other probe vehicle data sources can be used. The method presented in the Primer also uses additional data for incidents, weather, and demand. The method assesses the effect that strategies have on the third performance management rule measures for system reliability, truck travel time reliability (TTTR), and peak hour excessive delay (PHED) as well as other travel time-based performance measures. Examples of how the method is applied are given.

The method was tested in seven case studies of completed operations projects. The mobility performance effects of the operational improvements were positive, except in one case in which the initial congestion level was mild. Other results from the case studies analyses show that the system reliability measure can be insensitive to changes in performance in two scenarios: (1) when other measures show only a small change in performance; and (2) when the “before” condition is severely congested. The reason for these findings is twofold. First, the measure is based on a “pass or fail” test, so small positive changes may not shift a facility from being unreliable to reliable. Second, the underlying metrics—the 80th and 50th percentiles—can change at different rates from the before to after periods. The result of the research was a recommended suite of performance measures for evaluations.

Another Primer, *Influence of Operations Strategies on Third Performance Management Rulemaking (PM3) and Other Travel Time-Based Measures Primer Part Two—Nonrecurring Congestion Strategies* (FHWA-HOP-23-060), addressed operations strategies that deal with nonrecurring congestion.

CHAPTER 1. INTRODUCTION

PURPOSE OF THIS PRIMER

The purpose of this Primer is to provide methods for conducting before and after evaluations of operational strategies implemented to address recurring traffic congestion. The focus is how these types of operational strategies affect the third performance management rule (PM3) metrics and measures and other travel time-based performance measures. This Primer documents: (1) evaluation methodology developed for the project; (2) the results of seven case studies for which the methodology was applied; and (3) examples of how agencies can apply the methodology for their own evaluations. Another Primer, *Influence of Operations Strategies on Third Performance Management Rulemaking (PM3) and Other Travel Time-Based Measures Primer Part Two—Nonrecurring Congestion Strategies* (FHWA-HOP-23-060), addressed operations strategies that deal with nonrecurring congestion.

PRIMER OVERVIEW

In the following chapters, the Primer covers several topics:

- Chapter 1:
    - The purpose and benefits of conducting evaluations of operations strategies (especially with regard to the PM3 and other travel time-based measures).
    - Types of operational strategies covered.
    - Historical perspective on project evaluation.
- Chapter 2: Evaluation methodology developed for operational strategies.
- Chapter 3: Case studies: application of the evaluation methodology in the field.
- Chapter 4: Examples of how to implement the methodology.

BACKGROUND

Types of Operations Strategies

This Primer covers evaluation methods suitable for the following operational strategies.

Active Transportation and Demand Management

Active transportation and demand management (ATDM) is the dynamic management, control, and influence of travel demand, traffic demand, and traffic flow of transportation facilities. Through the use of available tools and assets, traffic flow is managed, and traveler behavior is influenced in realtime to achieve operational objectives, such as preventing or delaying breakdown conditions, improving safety, promoting sustainable travel modes, or maximizing system efficiency. The following components are some typical ATDM activities:

- Dynamic lane use management.
- Variable speed limits (VSLs).
- Queue warning system.
- Adaptive ramp metering.

- Dynamic junction control.
- Dynamic pricing (high-occupancy toll (HOT) lanes).
- Predictive traveler information/dynamic message signs (DMSs).
- Dynamic wayfinding.

Arterial Management

The goal of arterial management is to advance the use of objectives and performance-based approaches to traffic signal management and to improve design, operations, and maintenance practices, resulting in increased safety, mobility, and efficiency for all users. The following components are some typical arterial management activities:

- Traffic signal management (retiming).
- Adaptive signal control.
- Transit signal priority (bus impact).

Congestion Pricing

Congestion pricing—sometimes called value pricing—is a way of harnessing the power of the market to reduce the waste associated with traffic congestion. Congestion pricing recognizes that trips have different values at different times and places and for different individuals. Faced with premium charges during periods of peak demand, road users are encouraged to eliminate lower valued trips by taking trips at a different time or choosing alternative routes or transport modes where available. In cases where congestion pricing is applied to specific traffic lanes, rather than to an entire highway facility, users have the option of choosing to pay to use congestion-free priced lanes or continuing to travel on general purpose (GP) lanes without paying a toll. The following components are some typical congestion pricing activities:

- Zone-based pricing.
- Parking pricing.
- Priced vehicle sharing and dynamic ridesharing.

Integrated Corridor Management

As congestion occurs on a roadway, travelers respond in a variety of ways: finding an alternate route, selecting a different roadway (freeway versus surface street), adjusting their trip to another time of day, or remaining on their current route and enduring the significant delays. These disruptions range in scale, frequency, predictability, and duration and have the potential to affect a number of facilities or modes. A number of promising approaches may enhance how traffic managers currently operate the surface transportation system. The proactive use of managed-lane strategies, alternate routing of traffic, and proactively managing and controlling traffic within freeway corridors are a few potential approaches. These strategies have the potential to achieve greater levels of utilization of the existing roadway capacity, improve travel times, and enhance safety and travel reliability.

Freeway Management

Freeway management supports and promotes the use of integrated and coordinated freeway systems and proactive freeway management to improve the safety, efficiency, and reliability of travel on the Nation's freeway facilities. The following components are some typical freeway management activities:

- Hard-shoulder running.
- Reversible lanes.

Why Evaluate Operations Strategies?

Conducting evaluations of completed projects is a key element of operations performance management. Evaluating operations strategies provides valuable insight into the potential cost and benefits of investing in proposed strategies. The general value of analysis is the extent to which it assists stakeholders implementing operational strategies to:

- Invest in the right strategies—Evaluation provides information for **determining which operational strategies are likely to be most effective and under which conditions:** The evaluation helps decisionmakers identify technical and implementation gaps and invest in a combination of strategies that would produce the least congestion but the greatest benefits. Strategy evaluation provides an enhanced understanding of existing conditions and deficiencies, improving the ability to match and configure proposed strategies to the situation at hand.

- Highlight successes—Evaluations indicate if a project met its predetermined goals. When goals are met, publicizing the project will build support for future operations deployments within the agency as well as with external decisionmakers and the public.

PM3 Measures

On January 18, 2017, FHWA published the final rule that established a set of performance measures known collectively as the PM3 measures.[1] For the purpose of this Primer, four of the PM3 measures are considered because they are based on travel times:

- National Highway System Performance: Travel Time Reliability for Interstate Highways (percentage of the person-miles traveled on the Interstate that are reliable).
- National Highway System Performance: Travel Time Reliability for Non-Interstate National Highway System Highways (percentage of the person-miles traveled on the non-Interstate National Highway System highways that are reliable).
- Freight Movement on Interstate Highways: Truck Travel Time Reliability (TTTR) (truck travel time reliability index).
- Peak Hour Excessive Delay (PHED).

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[1] https://www.federalregister.gov/documents/2017/01/18/2017-00681/national-performance-management-measures-assessing-performance-of-the-national-highway-system.

FHWA has developed guidance on the calculation of the PM3 measures, and these calculations are used throughout the examples in this Primer.[2]

The immediate purpose of the PM3 measures was to implement the requirements in Title 23 of the U.S. Code §150, National goals and performance management measures, which was updated by the Moving Ahead for Progress in the 21st Century (MAP-21) legislation, Pub. L. No. 112-141. [3,4] The intent of the performance component of the legislation is for State and local transportation agencies to report highway system performance on an annual basis and to establish performance targets against which agencies can measure their progress. The agencies report performance measures at the system level, either statewide or for individual urban areas, depending on the measure.

Beyond the need to fulfill legislative requirements, the PM3 measures embody the principles of ***performance management***, whereby agencies use data to make informed investment decisions on an ongoing basis. With regard to this Primer, practitioners are concerned that, even though their operations projects are developed with improved operational performance in mind, they lack methods to demonstrate how the results of operations strategies “move the needle” on urbanized area or statewide performance measures. This Primer presents practices for quantifying the effects of operational strategy implementation and relating them to PM3 measures and investment decisionmaking. Likewise, PM3 measures may influence investment decisions. The methodology presented herein demonstrates the connection between PM3 and operations strategies.

Benefits, Costs, and Contexts of Operations Strategies

The Intelligent Transportation Systems (ITS) Benefits Database[5] contains a large body of performance information based on assessments of past evaluations.[6] These data are also the source for the benefits and costs in Tool for Operations Benefit/Cost Analysis (TOPS-BC).[7] Appendix A has more detail on the performance effects on the operations strategies covered in this primer, based on past studies.

Goals, Objectives, Strategies, Tactics, and Performance Measures for Operations Strategies

The overall vision supported by the operational strategies under consideration in this project is to improve mobility and safety. For the purpose of this report, improvement of mobility is featured.

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[2] Taylor, Rich; Purdy, Jeff; Roff, Thomas; Clarke, Justin; Vaughn, Ronald; Rozycki, Robert; and Chang, Christopher, *FHWA Computation Procedure for Travel Time Based and Percent Non-Single Occupancy Vehicle (non-SOV) Travel Performance Measures*, FHWA-HIF-18-024, April 2018, https://www.fhwa.dot.gov/tpm/guidance/hif18024.pdf

[3] 23 U.S.C. 150, https://www.govinfo.gov/content/pkg/USCODE-2019-title23/html/USCODE-2019-title23-chap1-sec150.htm

[4] https://www.fhwa.dot.gov/map21/

[5] https://www.itskrs.its.dot.gov/benefits

[6] https://ops.fhwa.dot.gov/plan4ops/topsbctool/index.htm

[7] https://ops.fhwa.dot.gov/plan4ops/topsbctool/index.htm

Table 1 shows the Goals-Objectives-Strategies-Tactics framework as applied to the operational strategies addressed in this Primer:

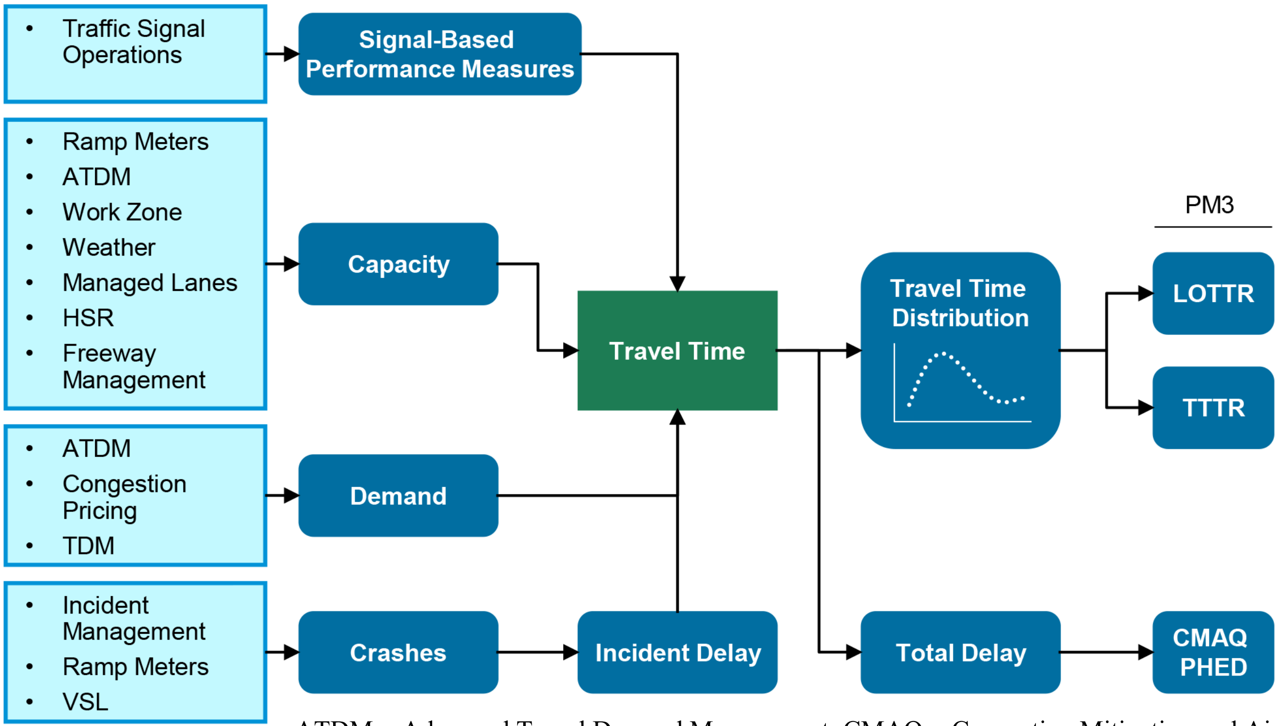
- Goals—High-level descriptors of the desired end state.
- Objectives—Achievements to be attained to demonstrate progress toward one or more goals, often capable of validation by specific quantitative measures.
- Strategies—Category, group, or program of activities that addresses one or more objectives.
- Tactics—Specific methods, devices, or activities within a category or program of activities.

Table 1 also shows the relationship of these strategies to relevant performance measures and potential impacts on the PM3 measures that all flow from the goal of improving mobility. The performance measures shown in the table are specific to each strategy. They are a mix of both output and intermediate outcome measures. Output measures describe the results of undertaking an activity (and are sometimes called activity-based measures); they answer the question "What does a program produce?" Outputs are measurable and readily determined; an example is the number of signals retimed. Outcome measures relate to the overall goals of a program; examples are measures related to travel time. Queue length and throughput are measures for some strategies. Their classification is intermediate output measures because, although they are outcomes of system performance, they are not directly based on travel time. Table 1 also presents unique characteristics of each strategy that should be considered in their evaluation.

Relevance of the PM3 Measures to Operational Objectives

Figure 1 shows the mechanism, or "pathway," for relating operational strategies to travel time-based measures such as the PM3 measures. ***The effects of operational strategies are typically seen in traffic flow and safety (crashes).*** Traffic flow, in turn, is defined by increases in capacity, safety, changes in demand, and improvement in traffic signal performance (improved progression and phasing). All these factors ultimately affect travel time and, therefore, affect the PM3 measures. Put another way, if an operational strategy affects travel times on a facility, in theory, it should affect the PM3 measures. Because the PM3 measures are constructed as binary measures (pass or fail), possibly small changes in travel times will not affect the PM measures, unless the before value is close to the threshold.

Figure 1 shows that operational strategies may be evaluated using various performance measures that influence demand or capacity that can be translated to travel time. Some operational strategies not specifically targeted to demand such as active traffic management (ATM) strategies are implemented at the facility level and have an indirect demand effect. The level of control for ATM can vary from day to day in response to congestion conditions (e.g., different ramp metering rates and VSLs) and, depending on the performance outcome, will influence travelers' decisions primarily about route choice and time of departure. Active demand management (ADM) strategies affect travelers' decisions directly. Dynamic pricing has a strong demand effect, most notably on lane choice (toll or GP); but with enough advance information disseminated to travelers, pricing also can influence other components of trip planning. Predictive traveler information also has the potential for affecting trip planning.



(Source: FHWA.)

ATDM = Advanced Travel Demand Management; CMAQ = Congestion Mitigation and Air Quality Improvement Program; HSR = high-speed rail; LOTTR = level of travel time reliability; PHED = peak hour excessive delay; TDM = travel demand model; TTTR = truck travel time reliability; VSL = variable speed limit.

Figure 1. Flow chart. Changes in travel time caused by operations strategies' effect on PM3 performance measures.

Evaluation of Operations Strategies in the Project Development Continuum

Figure 2 shows the continuum of project development from initial planning through implementation, operation and management, and evaluation, and the methodologies that can be used at each stage. The figures also show that as the project moves toward implementation, more sophisticated methodologies are employed, and benefit and cost analysis (BCA) can be used at each stage of the process.

The project development continuum, through design and implementation, is driven by applying forecasting methodologies because projects have not been implemented. A variety of methodologies for predicting the traffic flow impacts of projects or packages of projects is used and are based on traffic flow theory in some form. The underlying methodologies range from very simple macroscopic traffic flow relationships for travel demand applications to microscopic simulation models that predict the movement of individual vehicles at the subsecond level.

Past Evaluation Methodologies for Operations Strategies

Estimating the effects of transportation projects—and of operations strategies specifically—can be achieved by either applying models or by conducting before and after analyses with empirically collected travel-time data, which can be collected through a variety of technologies (e.g., roadway sensors, prove vehicles). The expected impacts of proposed projects should be ascertained by using some type of forecasting model, whereas before and after analyses are best conducted using empirical data (actual measurements of the effects). Appendix B summarizes past evaluation methods reviewed for this project.

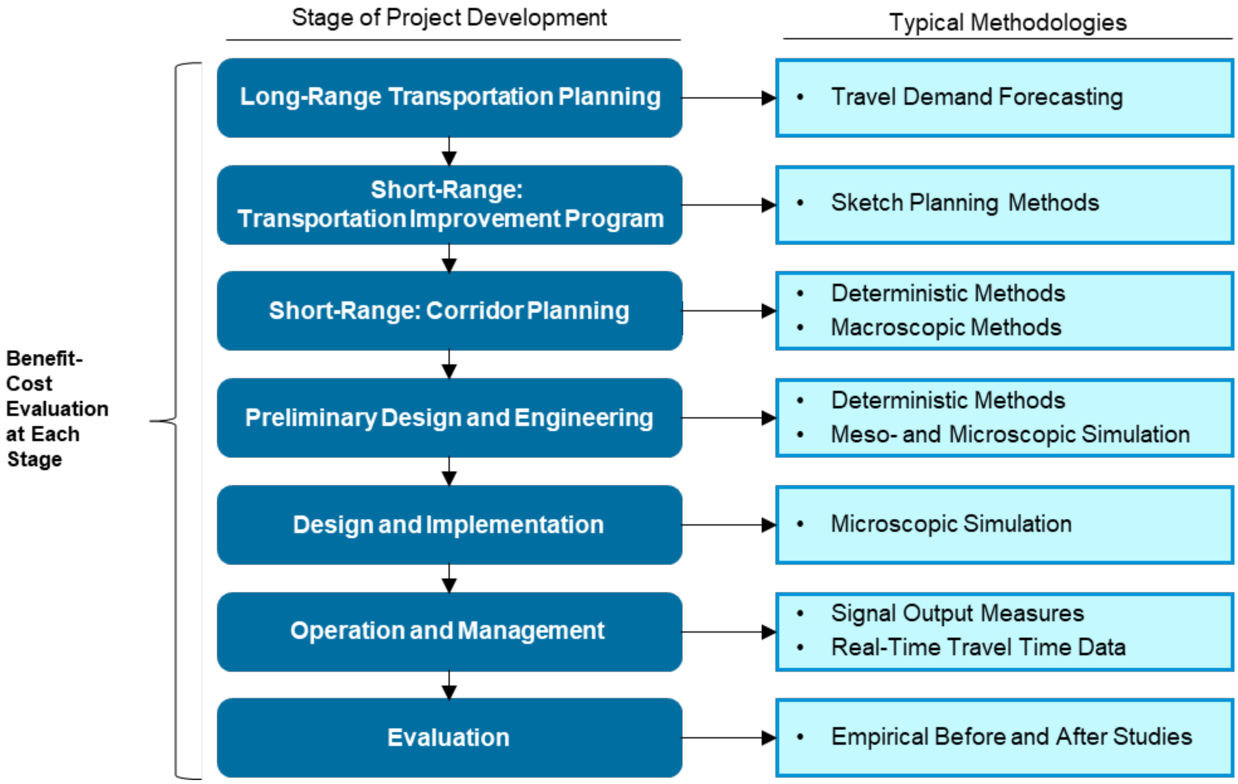


Figure 2. Diagram. Analysis of operations strategies that should occur at each stage of the project development continuum.

(Source: FHWA.)

Table 1. Operational strategies and their performance contexts.

Operational Strategy Category	Goals	Objectives	Strategies	Tactics for Implementation	Primary Effect Category	Output Performance Measures	Possible Influence on PM3 Measures	Unique Evaluation Characteristics
Active transportation and demand management (ATDM)	Reduce delay and improve reliability	Reduce perturbations in traffic flow	Dynamic lane control	Dynamic control based on level of congestion	Capacity: increase lanes available at critical merge points	Throughput: vehicles per hour	Delay reductions leads to more reliable travel	Level of enforcement, type of lane direction displays, times activated, and number of lanes closed
ATDM	Reduce delay and improve reliability	Reduce perturbations in traffic flow	Variable speed limits (VSL)	Dynamic control based on level of congestion	Capacity: Maintain existing capacity by avoiding breakdown	Throughput: vehicles per hour	Delay reductions leads to more reliable travel	Level of enforcement, type of VSL displays, times activated, and adjusted speed limits
ATDM	Reduce delay and improve reliability	Reduce perturbations in traffic flow	Queue warning system	Upstream of major bottlenecks or high crash locations	Safety	Queue length; crashes and crash rate	Minimal as delay reductions are minimal	Times activated; type of communication

Table 1. Operational strategies and their performance contexts (continuation).

Operational Strategy Category	Goals	Objectives	Strategies	Tactics for Implementation	Primary Impact Category	Output Performance Measures	Possible Influence on PM3 Measures	Unique Evaluation Characteristics
ATDM	Reduce delay and improve reliability	Increase throughput	Adaptive ramp metering	At ramp junctions known to be bottlenecks	Capacity: Increase capacity of ramp junctions where possible, otherwise adjust estimated delay	Ramp + mainline queue length; throughput: vehicles per hour	Delay reductions leads to more reliable travel	Existence of downstream bottlenecks; times activated
ATDM	Reduce delay and improve reliability	Increase throughput	Dynamic junction control	At ramp junctions known to be bottleneck	Capacity: Increase capacity of ramp junctions where possible—otherwise adjust estimated delay	Ramp + mainline queue length; throughput: vehicles per hour	Delay reductions leads to more reliable travel	Existence of downstream bottlenecks; performance of nearby arterial; times activated
ATDM	Reduce delay and improve reliability	Increase throughput	Dynamic pricing (high-occupancy toll lanes)	Congested corridors with a large number of through trips	Capacity and to a lesser degree, demand	Throughput: vehicles per hour	Delay reductions leads to more reliable travel	Times activated with pricing

Table 1. Operational strategies and their performance contexts (continuation).

Operational Strategy Category	Goals	Objectives	Strategies	Tactics for Implementation	Primary Impact Category	Output Performance Measures	Possible Influence on PM3 Measures	Unique Evaluation Characteristics
ATDM	Reduce delay and improve reliability	Balance demand (across facilities)	Predictive traveler information and dynamic message signs	At locations where alternative routes can be taken	Demand	Change in vehicles per hour on facilities	Minimal as delay reductions are minimal	Times activated; type of communication
ATDM	Reduce delay and improve reliability	Reduce unnecessary travel	Dynamic wayfinding	Central business district (CBD) parking	Demand	Change in vehicles per hour on facilities	Minimal as delay reductions are minimal	Times activated; type of communication
Arterial management	Reduce delay and improve reliability	Equitable distribution of green time, smooth flow, maximize throughput	Adaptive signal control	Modify signal timing parameters, cycle length, splits, offsets	Travel time, arrivals on green, stops, split failures, phase utilization	Number of stops; corridor delay and travel time; arrivals on green; arrival type	Delay reductions leads to more reliable travel	No special considerations for developing outcome measures; changes in signal operation parameters should be documented and related to outcome measures

Table 1. Operational strategies and their performance contexts (continuation).

Operational Strategy Category	Goals	Objectives	Strategies	Tactics for Implementation	Primary Impact Category	Output Performance Measures	Possible Influence on PM3 Measures	Unique Evaluation Characteristics
Arterial management	Reduce delay and improve reliability	Improve transit schedule adherence	Transit signal priority	Corridors heavily used by transit	Transit travel times	Buses receiving priority	Almost no effect	No special considerations for developing outcome measures; changes in signal operation parameters should be documented and related to outcome measures
Arterial management	Reduce delay and improve reliability	Equitable distribution of green time, smooth flow, maximize throughput queue management	Traffic signal management and operations	Signal timing optimization apply performance measurement	Travel time, delay	Volume-to-capacity, green and red occupancy ratios; queue length	Delay reductions lead to more reliable travel	No special considerations for developing outcome measures; changes in signal operation parameters should be documented and related to outcome measures

Table 1. Operational strategies and their performance contexts (continuation).

Operational Strategy Category	**Goals**	**Objectives**	**Strategies**	**Tactics for Implementation**	**Primary Impact Category**	**Output Performance Measures**	**Possible Influence on PM3 Measures**	**Unique Evaluation Characteristics**
Arterial management	Reduce delay and improve reliability	Reduce delay of trucks at signals, the impact of slow truck acceleration on other traffic, and red light running by trucks	Truck signal priority	Corridors heavily used by trucks	Truck travel times and reliability	Trucks receiving priority	Delay reductions, truck travel time reliability on arterials (N/A to Interstate TTTR)	Corridors with high truck volumes, intersections with high truck turning movements, intersection approaches with steep downgrade
Congestion pricing	Reduce delay and improve reliability	Balance demand (across facilities and times of day)	Zone-based pricing	Corridors and subareas experiencing heavy congestion (e.g., CBDs)	Demand	Vehicles per hour and vehicle miles traveled (VMT) across network	Minimal as delay reductions are minimal	Times activated with pricing
Congestion pricing	Reduce delay and improve reliability	Balance demand (across facilities and times of day)	Parking pricing	Corridors and subareas experiencing heavy congestion (e.g., CBDs)	Demand	Vehicles per hour and VMT across network	Minimal as delay reductions are minimal	Times activated with pricing

Operational Strategy Category	Goals	Objectives	Strategies	Tactics for Implementation	Primary Impact Category	Output Performance Measures	Possible Influence on PM3 Measures	Unique Evaluation Characteristics
Congestion Pricing	Reduce delay and improve reliability	Balance demand (across facilities and times of day)	Priced vehicle sharing		Congestion pricing	Reduce delay and improve reliability	Balance demand (across facilities and times of day)	Priced vehicle sharing
Corridor Traffic Management	Reduce delay and improve reliability	Balance demand (across facilities and times of day); increase throughput	Integrated corridor management (ICM)	Ramp meter/signal coordination; diversion plans	Capacity and demand	Throughput: Vehicles per hour and VMT across network; output failures for implemented strategies	Delay reductions leads to more reliable travel	Times activated; as ICM bundles individual strategies; their unique characteristics should be considered
Freeway Management	Reduce delay and improve reliability	Increase throughput	Hard shoulder running	Congested corridors with no major safety problems; times of day when traffic speeds are slow due to congestion.	Capacity	Throughput: Vehicles per hour and VMT by lane; crashes and crash rate	Delay reductions; also should lead to more reliable travel	Times activated; impact on incident management (duration, blockage) should be considered
Freeway management	Reduce delay and improve reliability	Increase throughput	Reversible lane	Congested corridors with no major safety problems	Capacity	Throughput: Vehicles per hour and VMT by lane; crashes and crash rate	Delay reductions leads to more reliable travel	Times activated; effects on incident management should be considered

CHAPTER 2. BEFORE AND AFTER EVALUATION METHODOLOGY FOR OPERATIONAL STRATEGIES

OVERVIEW

The study reviewed several past methods for conducting empirical before and after analyses. Based on that review, a methodology was developed keyed to operations strategies and the types of data that are generally available. Figure 3 outlines this 12-step methodology for conducting empirical before and after evaluations for operations strategies. It is based on expanding simple (naïve) before and after studies using only travel time-based observations. The methodology has been extended from the approach originally developed for the Strategic Highway Research Program 2 (SHRP 2) program.[1]

An important feature of the 12-step process is the implementation of controls to adjust for the influence of external factors on the travel time measurements. The following define the two-stage approach to implementing controls in the method:

- The first stage of control uses classic definitions of control groups typically used in safety analysis (step 7). These controls are relevant not just for the safety portion of a Transportation Systems Management and Operations (TSMO) (operations strategies) evaluation, but also for the congestion analysis portion.
- The second stage tracks trends in the underlying causes of congestion to check if those causes could be influencing the primary congestion measurement, for example, changes in travel times (steps 11 and 12). If a check of the underlying causes of congestion reveals that the causes are substantially dissimilar, then modeling is used so that the congestion effect can be isolated. Even without defining control groups, tracking trends in the contributing causes of congestion can reveal whether the observed changes in travel times were unduly influenced by external causes.

The methodology can be used with or without controls. The decision to use controls should be based on data availability for external factors such as incidents, weather, demand, the existence of suitable control sites, and if traffic modeling is feasible. If controls are not used, steps 1–4, step 6 (considering just travel time) and step 10 are used. Figure 3 shows details of the methodology.

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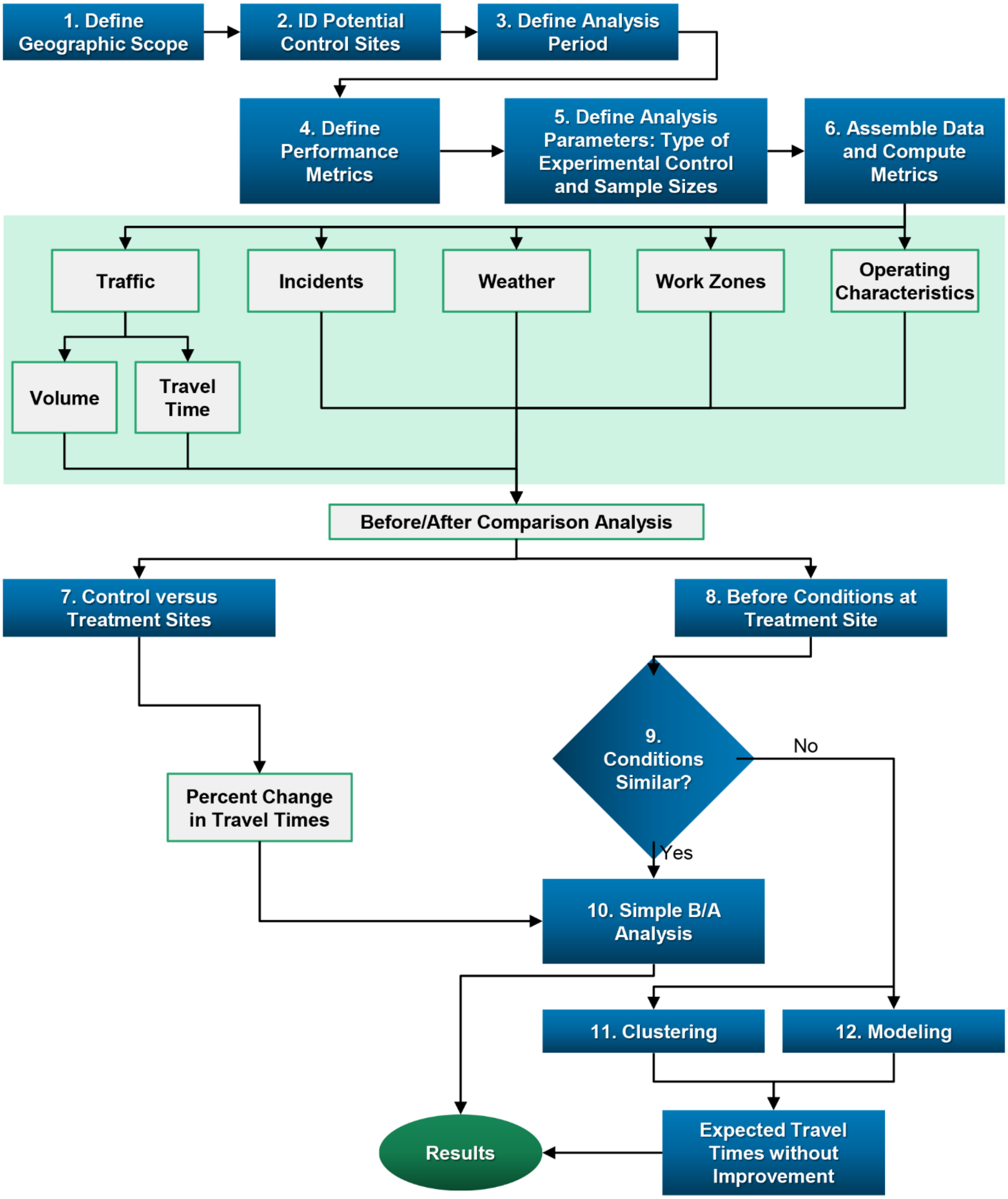
[1] Cambridge Systematics and Kittelson Associates, *A Guidebook for Standard Reporting and Evaluation Procedures for TSM&O Strategies*, 2014, https://transops.s3.amazonaws.com/uploaded_files/SHRP2_L17_Gap-Filling_Project_4_GuidebookForStandardReportingAndEvaluationProceduresFor_TSM%26O_Strategies.pdf.



Note: B/A = before and after; ID = identification.

Figure 3. Flow chart. Outline of the evaluation methodology.

(Source: FHWA.)

PROCESS STEPS

Step 1: Define Geographic Scope

Operations strategies are generally confined to short sections of the highway system. An open question is how focused improvements affect longer corridors (including nearby routes), subareas, regions, and an entire State. As the geographic scope expands beyond the immediate roadways affected by an improvement, the effects of a single project may become diluted. As a result, the effect of operations strategies on areawide performance is not known because methods to determine the effect of completed projects are lacking.

The geographic scope needs to include the facility where the changes are being made, as well as—at a minimum—upstream and downstream roadway segments to the changed road section. Because improvements usually result in a change in travel patterns, additional highways that could possibly be influenced by demand changes should be included in the analysis. The upstream and downstream segments are used to understand how improvements in the segment affects nearby road segments' performance. For example, did the improvement activate new bottlenecks downstream of the original bottleneck? The geographic scope also should include parallel facilities that serve the same travel shed. The main roadway's improvement can draw traffic from parallel facilities, improving the performance of those roads, while increasing the use of the improved facility and potentially limiting the performance improvements observed through the improved section. Measuring performance on these facilities allows the before and after study to account for the improvements on these parallel facilities.

To maintain homogeneity, the beginning and end points of analysis sections are typically selected to coincide with major interchanges and intersections or other locations where traffic conditions were expected to change because of traffic or roadway characteristics. Roadway sections also should represent the typical commute travel patterns so that the measures such as travel times collected from these sections echo typical travelers' experiences.

In summary, the geographic scope should consider the following topographies:

- Improved facility.
- Upstream and downstream of the improved facility (1–2 miles) to capture off-section influences such as incidents (downstream) and queues (upstream).
- Nearby and adjacent major roadways likely to be affected by demand shifts.
- Control sites (if used; see Step 2).

Step 2: Identify Potential Control Sites

In addition to test sections (i.e., sections that receive the operational strategy or "treatment"), operations evaluations also can include control sections if they are available to the analyst. The control sections should have similar traffic and roadway characteristics as test sections and follow the same selection criteria as the test sections, with the exception that operations strategies would have no effect on control sections. Using the following procedures adopted from the *Highway Safety Evaluation Procedural Guide* is helpful in selecting control sites:[1]

1. Identify and list candidate control sites. Candidate sites must have operation and geometric characteristics similar to the test sites. Variables to be considered include roadway functional class, adjacent land use, horizontal and vertical alignment, number of lanes, lane width, access control traffic volume, peak direction, peak period, traffic composition, traffic control and law enforcement, roadway geometric, incident/work zone occurrence, and climate condition.

2. Select the candidate sites with performance that is within ± 10 percent of the test site in terms of the following measures:

    a. AADT for all segments on the site.
    b. Travel time index (TTI) for the entire facility.
    c. Total crash rate.

3. Select the final control sites based on judgment.

Step 3: Define Analysis Period

The following temporal aspects that should be considered in the evaluation of operations strategies are:

- Because of the need to compute reliability, at least 1 year's worth of data in each of the before and after periods is needed. Six months is suggested as an absolute minimum, but seasonal effects are likely to occur unless the same months of different years are used.

- In addition to the 6–12 months for the before and after periods, analysts should consider the construction and implementation time between the two. The after period should not start immediately after construction but at least 1 month later to provide enough time for demand to stabilize.

- The time periods should include user-defined peak periods (a.m. and p.m.), midday, and offpeak periods. The peak periods should be defined for weekday nonholidays. At a minimum, analysts should analyze peak periods; other periods may be added at the analyst's discretion. The peak periods should be long enough to capture the complete congestion picture, especially if queuing is significant. Alternately, the user can define two sets of peak periods with short and long durations. Note that in some cases, the period of interest may be different from those mentioned above, for example, weekends in rural recreational areas may be the focus of an operational treatment. The time periods for the PM3 measures are already established and consider many more hours of the day and days of the week than typical peak period analyses.

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[1] https://www.fhwa.dot.gov/publications/research/safety/81219/81219.pdf.

Step 4: Define Performance Metrics

Outcome measures relate directly to the goals and objectives of a program, such as the improvement of mobility for travelers. In this methodology, travelers' experience is defined in terms of mobility. Therefore, ***outcome measures for operational strategies are based on travel times and reflect how users experience the system.*** Table 2 shows the recommended travel time- and queue-based performance outcome measures. All of these measures are relevant for evaluating the operations strategies covered in this report. Structurally, the measures can be defined by two categories:

- Continuous (or nominal)—These measures are interval scale measurements that sometimes take the form of an index.
- Binary—These measures are sometimes called "failure" or "pass/fail" measures as they set a threshold for an acceptable level of performance and count the instances that either exceed or are below the threshold.

Table 2. Travel time-related outcome performance measures for operations strategies.

Performance Measure	Type of Measure	Continuous or Binary?	Definition
Planning Time Index	Reliability	Continuous	95th percentile travel time index (TTI) (95th percentile travel time divided by the free flow travel time).
80th Percentile TTI	Reliability	Continuous	80th percentile TTI (80th percentile travel time divided by the free flow travel time).
PM3 System Reliability (Level of Travel Time Reliability)	Reliability	Binary	Percentage of person-miles deemed to be reliable, wherein "reliable" is travel below the ratio of the 80th percentile travel time and the median travel time for four time periods.
PM3 Truck Reliability (Truck Travel Time Reliability)	Reliability	Continuous	Index based on the ratio of truck travel times: 95th percentile divided by the median for 5 time periods; the index is the maximum of the ratio of the 5 periods.
Delay	Average/ Typical Condition	Continuous	Vehicle- or person-hours that occur above a threshold travel time; also may be computed as a rate, e.g., hours per vehicle-mile.
PM3 Peak Hour Excessive Delay	Average/ Typical Condition	Continuous	Person-hours that occur above a threshold, when the threshold is either 60 percent of the speed limit or 20 mph, whichever is higher.
TTI	Average/ Typical Condition	Continuous	Ratio of average travel time to the free flow travel time.
Average Speed	Average/ Typical Condition	Continuous	Space mean speed, calculated as the vehicle-miles traveled (VMT)-weighted harmonic mean speed.
Congestion Duration	Average/ Typical Condition	Binary	Percentage of time when speeds fall below a threshold value.
Congestion Extent	Average/ Typical Condition	Binary	Percentage of highway miles, person-miles, trips, or VMT when speeds fall below a threshold value.

Additional performance metrics also are needed to conduct evaluations. These measures are used to describe the underlying causal factors for congestion. Specifically, they are used to interpret the outcome results properly and to identify if an observed change in travel times is due, at least in part, to a change in the underlying conditions. Many operational strategies specifically target the causal factors (e.g., incident management, work zone management, weather mitigation), and understanding the change in a targeted factor can provide insight for future deployments. Table 3 presents these measures, which must be developed for the analysis periods selected in Step 3 (e.g., peak period).

Lane-hours lost (LHL) due to incidents and work zones is a key metric for comparing conditions in the before and after periods. Some incident and work zone datasets allow direct calculation of LHL. These data identify the number of lanes lost and the duration of that loss for each incident. Because the number of lanes blocked can change over the course of an incident, changes in lane blockage should be tracked over the course of an individual incident. If these data are not available, the following procedure can be used for incidents:

$$\text{ILHL} = \text{NumberIncidents} \times \text{LanesBlocked} \times \text{IncidentDuration}$$

Where: ILHL = Incident lane-hours lost

NumberIncidents = Number of annual incidents

= IncidentRate × VMT

LanesBlocked = Lanes blocked per incident

IncidentDuration = Average incident duration (hours), defined as the time between when the incident started and the last lane or shoulder has been cleared.

If the incident rate is unavailable locally, it may be estimated by multiplying the crash rate by 4.5, which assumes that crashes are 22 percent of all incidents (remaining incidents are primarily vehicles breakdowns and debris on the roadway). If lanes blocked per incident data are unavailable locally, the incident rate can be estimated using the following factors, which were developed from 2 years of incident data from Atlanta:[2]

- If a usable shoulder is present and it is the local policy to move lane-blocking incidents to the shoulder as rapidly as possible, the incident rate is 0.476. (In Atlanta, for example, a usable shoulder is considered as being capable of safely storing disabled and emergency vehicles.)
- If lane-blocking incidents are not moved to the shoulder, the incident rate is 0.580. (Developed by considering lane-blocking incidents that were moved to the shoulder and reassigning them to lane-blocking status.)
- If usable shoulders are unavailable, the incident rate is 1.140.

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[2] Mariotta, R., T. Lomax, M. Hallenbeck. 2012. *Analytic Procedures for Determining the Impacts of Reliability Mitigation Strategies.* SHRP 2 Report L03. https://rosap.ntl.bts.gov/view/dot/3619, last accessed December 27, 2023.

Step 5: Define Analysis Parameters: Type(s) of Experimental Control and Sample Sizes

A two-stage experimental control plan is used for operations strategy evaluations. The plan is based on combining a classical control group analysis with examining the causal factors for congestion. At this point, it is recommended conducting both stages to provide additional insight into the effect of the operational treatment, but testing with the case studies may change this recommendation.

Step 6: Assemble Data and Compute Metrics

For the treatment and control sites, all the performance measures are computed. Researchers at FHWA developed guidance on how to calculate the PM3 measures.[3] Appendix C contains calculation procedures for the other travel time-based measures.

Visual inspection to determine whether the selected control sites are similar to the test sites during the period before the improvement and the behavior of travel times after the improvement is implemented. It also is useful to track measures as a time series (figure 4) in addition to computing the measures for the entire before and after periods. Visualization can be used to compare the travel time distributions in the before and after periods on the treated facility. Additional information can be added to the graph of the distributions if they are available (figure 5). Developing cumulative distribution functions and displaying travel times for the before and after periods on the same graph are useful in highlighting changes.

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[3] Margiotta, Richard A., Shawn Turner, Rich Taylor, Christoper Chang. *National Performance Measures for Congestion, Reliability, and Freight, and CMAQ Traffic Congestion: General Guidance and Step-by-Step Metric Calculation Procedures*, FHWA-HIF-18-040, June 2018, https://www.fhwa.dot.gov/tpm/guidance/hif18040.pdf, last accessed October 8, 2023.

Table 3. Performance measures for tracking the causal factors of congestion.

Category	Data Items
Incident/crash characteristics	Total incidents by type: crashes, stalls, and debris
	Incident and crash rates (incidents/crashes per 100 million vehicle-miles traveled (VMT)
	Incident duration: mean and standard deviation
	Lane-hours lost (LHL) due to incidents[1]
	Shoulder-hours lost due to incidents[1]
Work zone characteristics	Number of work zones
	LHL due to work zones[1]
	Shoulder-hours lost due to work zones[1]
Weather	Hours with rainfall ≥ 0.1”
	Hours with frozen precipitation
	Hours with visibility restricted
Demand	VMT (total, passenger vehicles, large trucks)
	Person-miles traveled

[1] The number of lanes closed multiplied by the number of hours they were closed. As a reference for future studies, LHL and shoulder-hours lost ***indices*** also should be computed: These are the LHL and shoulder-hours lost divided by the original number of lanes.

Step 7: Control Versus Treatment Sites

If the evaluation is using control sites and if the previous steps all show that the observations at treatment sites can be trusted, then this step is applied for the travel time-based measures. After the standard computations are conducted on the test sites and control sites during the before and after periods, the next step is to calculate the expected values of performance measures and the expected percentage changes in those measures. The expected values at the test sites (as if no improvements are implemented) can be from the control sites.

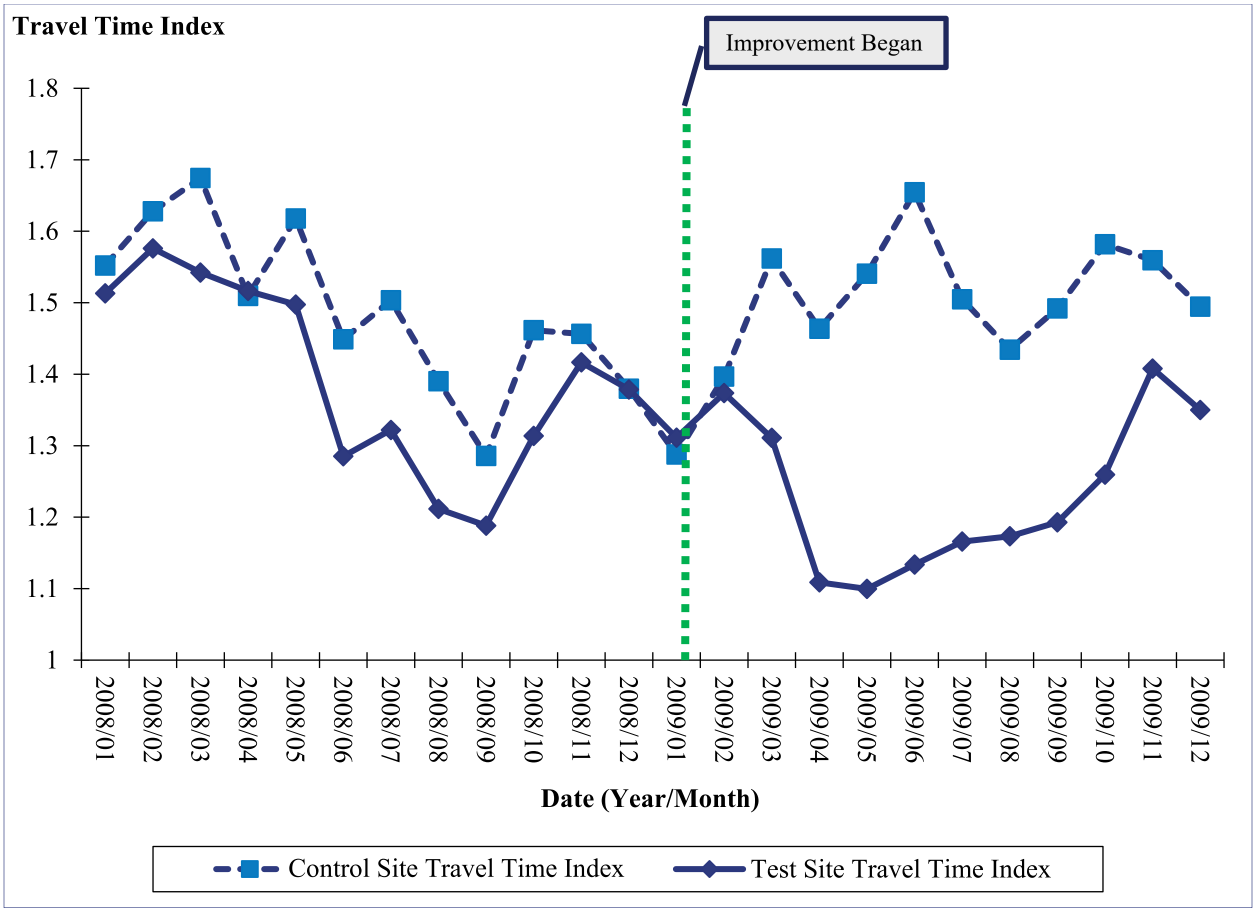

Figure 4. Graph. Example time series plot of mean travel time index on test sites and control sites.

(Source: FHWA.)

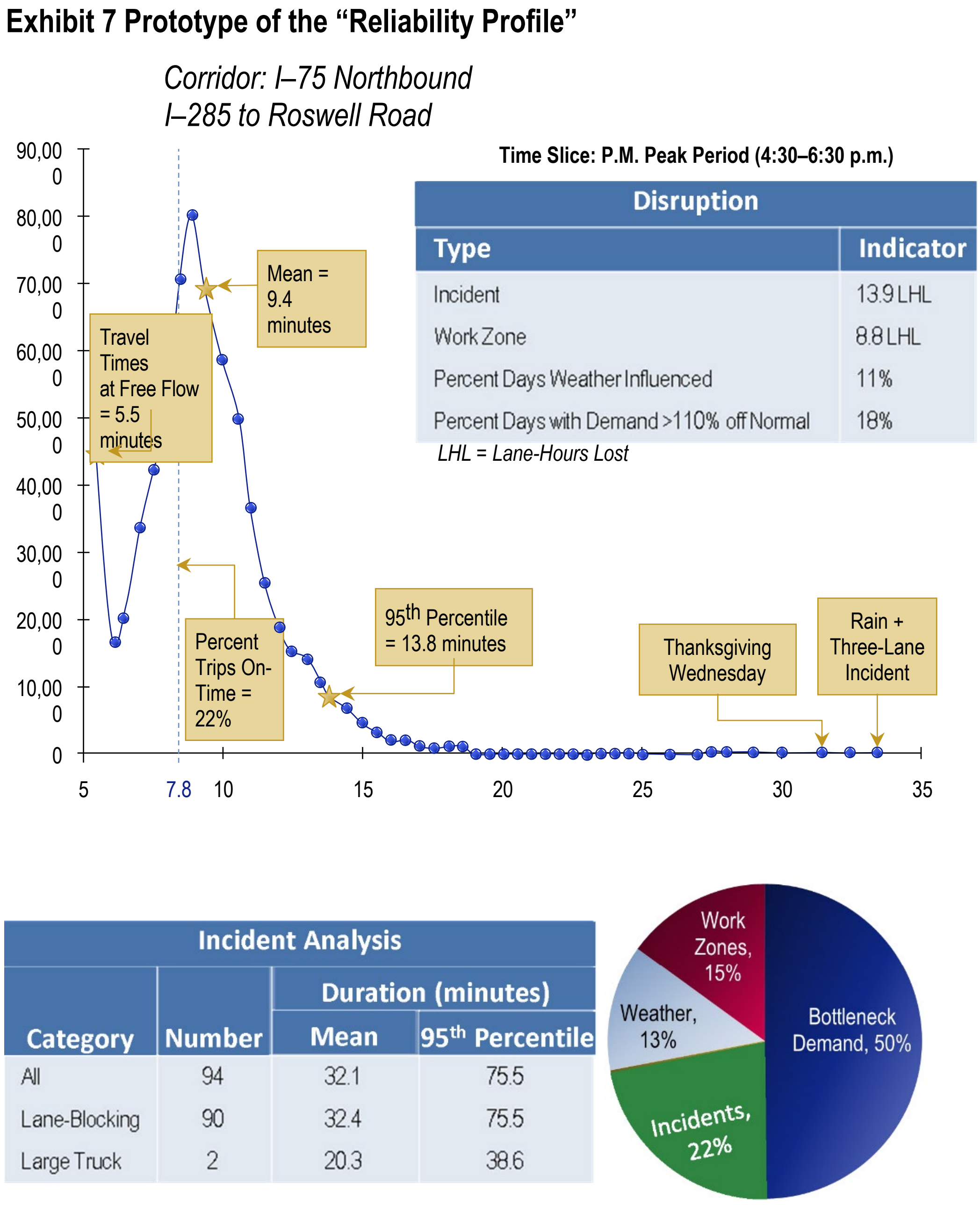

Exhibit 7 Prototype of the “Reliability Profile”

Corridor: I–75 Northbound
I–285 to Roswell Road

Time Slice: P.M. Peak Period (4:30–6:30 p.m.)

Disruption	
Type	**Indicator**
Incident	13.9 LHL
Work Zone	8.8 LHL
Percent Days Weather Influenced	11%
Percent Days with Demand >110% off Normal	18%

LHL = Lane-Hours Lost

Incident Analysis			
		Duration (minutes)	
Category	**Number**	**Mean**	**95th Percentile**
All	94	32.1	75.5
Lane-Blocking	90	32.4	75.5
Large Truck	2	20.3	38.6

Figure 5. Screenshot. Enhanced travel time distribution graphic.

(Source: FHWA.)

Expected Values

The performance measures are averaged for the before period and after period, respectively. Before and after periods for the control and test sites should be the same. Figure 6 shows the calculation for expected values:

$$E_t = B_t\left(\frac{A_c}{B_c}\right)$$

Figure 6. Equation. Formula for expected performance measures based on control sites.

(Source: FHWA.)

Where:

E_t = Expected performance measures at the test sites if the improvement project had not been implemented

B_t = Before period performance measures at the test sites

A_c = After period performance measures at the control sites

B_c = Before period performance measures at the control sites

Percentage Change in Performance

The effectiveness of the improvement on the test sites can be calculated as the percentage change:

Percentage Change = $[(A_t—E_t)/E_t]/100$

Where:

E_t = Expected performance measures at the test sites if the improvement project had not been implemented

A_t = After period performance measures at the test sites

Steps 8 and 9: Compare Before Conditions at Treatment Site

These are key steps in the evaluation methodology as they will determine whether a simple comparison of travel time measures in the before and after periods can be used or if a modeling-based adjustment needs to be made. The conditions compared relate to the factors that influence travel times: demand, incidents, work zones, and weather. To make this determination, the tolerances must be set for the key indicators shown in table 3. The case studies in chapter 3 will help to determine these tolerances. Likely, tolerances cannot be reasonably determined, so the modeling adjustments in tasks 11 and 12 should be conducted regardless of the comparisons.

Step 10: Conduct Simple Before and After Analysis.

If the expected values from the control sites closely match those that are observed at the treatment site and if the background conditions at the treatment site are the same in the before and after periods, then a direct comparison of the travel time-based measures can be made. If not, both or either steps 11 and 12 need to be conducted to adjust the observed measures in the after period at the treatment site.

Step 11. Conduct Cluster Analysis.

In updating the *Traffic Analysis Toolbox Volume III,* FHWA researchers recommend that a statistically based cluster analysis be undertaken when modeling the expected impacts of transportation improvements, including operations:

> To make wise, cost-effective investment decisions, identifying and categorizing days by travel conditions is beneficial to better understanding the sources of variability in the system and identifying conditions when one alternative outperforms another or under what conditions an alternative is most effective. For example, an increase in corridor delays during the post implementation period might be attributed to poor performance of the adaptive traffic signal control strategy. However, this might have been caused by some confounding factor, such as a series of severe weather events during the post implementation period.[4]

A simple method for addressing the variability issue is to create categories (or bins) based on ranges for the influencing factors. For example, one could bin the observations (days) based on predetermined ranges—such as low, medium, and high incident blockage and duration scores—and do the same for weather conditions and demand levels. For each bin, the probability of occurrence is calculated from the data so that the results can be properly weighted; figure 7 shows an example.

However, the *Toolbox* states that formal cluster analysis is preferred to this simple categorization of influencing factors: "Cluster analysis helps to partition data into groups, or clusters, to minimize the variance within each cluster (so that days within each cluster are similar) and maximize the variance between clusters (so that days in different clusters are dissimilar)."[5] The *Toolbox* offers guidance on how to apply cluster analysis to the evaluation of alternatives.

The concept from the *Toolbox* can be extended to before and after analysis. The approach is to compare the travel time-based measures in the before and after periods for each defined cluster, where a cluster is a group of days from the analysis periods that are statistically similar based on several influencing factors. The numeric variables shown in table 3 should be used in the cluster analysis as influencing factors, especially the lane- and shoulder-hours lost for incidents and work zones as well as for demand level and weather conditions. Cluster analysis is the preferred method for conducting this type of analysis based on categorization of the influencing factors. However, for the case studies in this report, the project team will evaluate the utilities of both the binning and clustering methods.

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[4] U.S. Department of Transportation, Federal Highway Administration (FHWA). 2019. "Data Collection and Analysis." Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Modeling Software 2019 update to the 20024 Version. Washington, DC, FHWA. https://ops.fhwa.dot.gov/publications/fhwahop18036/chapter2.htm, last accessed December 27, 2023.

[5] U.S. Department of Transportation, Federal Highway Administration (FHWA). 2019. "Data Collection and Analysis." Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Modeling Software 2019 update to the 20024 Version. Washington, DC, FHWA. https://ops.fhwa.dot.gov/publications/fhwahop18036/chapter2.htm, last accessed December 27, 2023.

Step 12: Conduct Modeling Tests, if Necessary. If the comparison to control sites is inconclusive or if the demand, weather, and incident characteristics in the before and after conditions are substantially different, then modeling should be pursued as a form of control. The idea is to create before and after scenarios based on the same demand, incident, and weather conditions as in the before case. This practice enables the analyst to answer the question: "What would have happened without the treatment?"

The approach is like the empirical Bayes (EB) method for safety, except that the expected value is computed as a weighted combination of observed and expected values. The weight in the EB method is based on the amount of data and the variance in the model's estimates; the model in this case is an empirically based predictive equation (safety performance function).[6] The reliability of the data affects the "weight." The more reliable the data are, the more weight will go to the data; conversely, the less reliable the data are, the more the weight will go to the average. Whether this approach can be used verbatim in the operations evaluation methodology as the variance in the models' predictions used for this analysis is unknown. However, during the case studies, the project team will determine if the expected value will be based solely on the model output or on a combination of the modeled result and empirical observation.

Congestion-related models have been traditionally confined to measures of the average or typical condition. Because two of the three PM3 measures relate to reliability, the SHRP 2 reliability products are useful, although they would have to be adjusted to produce the PM3 measures. For this methodology, the project team recommends the *Highway Capacity Manual* (HCM) procedures for freeway facilities and urban streets (developed in SHRP 2 project L08) as they both produce reliability measures and handle queuing (freeways) and spillback (signalized highways), albeit with less rigor than the simulation models. The input data for the HCM model come from the empirical measurements for demand, incidents, weather, and physical attributes of the highway. The results of applying the HCM procedure are the expected values for the performance measures, assuming that the implementation of the operational treatment has not been implemented. Analysts compare these expected values with the observed values to note differences. In essence, analysts replace the before condition with a modeled condition.

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[6] The overdispersion parameter from a negative binomial distribution.

Table 4. Example of a binning scheme used to address influencing factors for travel time variability.

Capacity Scenarios	Demand Scenarios: Very Low Demand (%)	Low Demand (%)	Medium Demand (%)	High Demand (%)	Very High Demand (%)	Total (%)
No incidents, good weather	6.31	15.76	18.92	15.76	6.31	63.05
Single lane closure, good weather	0.13	0.32	0.39	0.32	0.13	1.29
Dual+ lane closure, good weather	0.17	0.42	0.51	0.42	0.17	1.69
No incidents, bad weather	3.24	8.11	9.73	8.11	3.24	32.44
Single lane closure, bad weather	0.07	0.17	0.20	0.17	0.07	0.66
Dual+ lane closure, bad weather	0.09	0.22	0.26	0.22	0.09	0.87
Total	10.00	25.00	30.00	25.00	10.00	100.00

A simple (sketch planning) method is the HCM's preliminary planning and engineering (PP&E) methodology.[7] While the data requirements are much smaller than for the regular HCM procedures, the methodology does consider queuing. Reliability prediction is based on the concepts produced by SHRP 2 Project L03, where empirical data are used to develop relationships to predict reliability measures as a function of the average condition (mean travel time index (MTTI)). Figure 7 shows an example of this relationship developed from the National Performance Management Research Data Set (NPMRDS) for Oregon. The TTI is used for this relationship to normalize the data for different section lengths.

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[7] Dowling, Richard et al., *Planning and Preliminary Engineering Applications Guide to the Highway Capacity Manual*, NCHRP Report 820, 2016, https://www.nap.edu/download/23632.

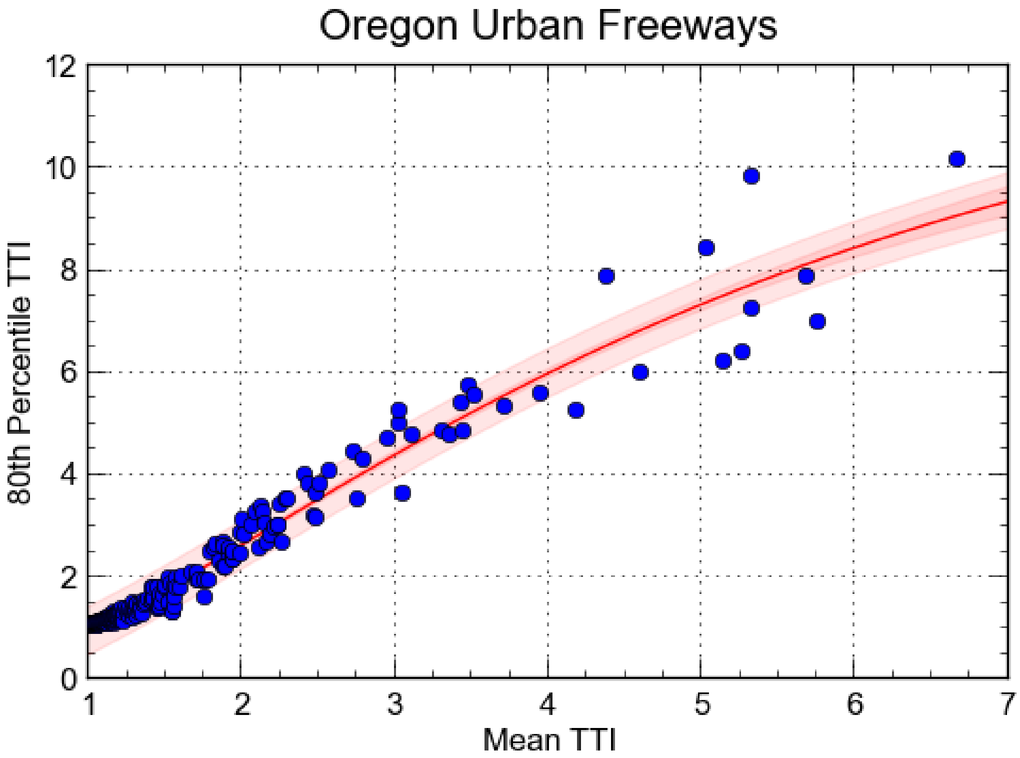

Figure 7. Graph. Empirical relationship for predicting the 80th percentile travel time index.

(Source: Cambridge Systematics, *Oregon SHRP2 C11 Reliability Analysis Implementation Plan*: *Task 2 Report*, prepared for Oregon DOT, September 2020.)

The steps in applying the PP&E process are the following.

1. Using vehicle probe data such as the NPMRDS, develop functions like the one shown in figure 7 from roadways with similar characteristics in the region where the evaluation is taking place. Note the variances in the data for each relationship.
2. Use a volume-delay function (VDF) to predict the recurring-only predicted MTTI in the after case. Use a VDF that attempts to address queuing characteristics such as modified versions of the Davidson function. Capacity is the same as for the before period.
3. Apply the travel time or delay reduction factors for the operations treatment from the values presented in the task 2 matrix to get the revised predicted MTTI.
4. Apply the relationships developed in step 2 to obtain the predicted values for the rest of the travel-time measures.

Results Compilation

At this point, before and after performance measure values from several methods have been produced. The direct empirical measurements from the simple before and after analysis will be produced regardless if controls are implemented. If controls are used, several more performance measure comparisons also will exist: expected values from control versus treatment sites, direct empirical comparisons from the cluster analysis, and predicted values for what would have occurred in the absence of the treatment from modeling. All of these values taken together provide insight into the performance changes due to implementing operations strategies.

BCA can be conducted once the performance measures are calculated. Two tools are available for conducting a BCA that consider the travel time reliability effects of operational improvements:

- SHRP 2 Project C11, Development of Tools for Assessing Wider Economic Benefits of Transportation, developed a tool to conduct a BCA that includes reliability impacts.[8,9]
- FHWA's TOPS-BC was specifically designed to consider operational strategies.[10] TOPS-BC was used for BCA in the examples shown in chapter 4.

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[8] https://onlinepubs.trb.org/onlinepubs/shrp2/RFPL38/C11ReliabilityTechnicalDocumentation.pdf.

[9] https://www.ebp-us.com/en/projects/shrp2-c11-tools-assessing-wider-economic-benefits-transportation-accessibility-intermodal.

[10] https://ops.fhwa.dot.gov/plan4ops/topsbctool/index.htm.

CHAPTER 3. CASE STUDY RESULTS

CRITERIA FOR SELECTING CASE STUDY SITES

The project team applied evaluation methodology to seven case study sites around the United States. The team used several of the following criteria in selecting the case study sites:

- The seven sites should represent a variety of operations strategies.
- The implementation of the strategies should have been completed recently to increase the chances of finding relevant data and to allow full-year before and after analysis periods.
- The implementing agency should be a willing participant in the evaluation.

The following list of PM3 measure analysis periods are defined by the Final Rule:

National Highway Performance Program Reliability (Level of Travel-Time Reliability)

1. 6 a.m.–10 a.m., weekdays.
2. 10 a.m.–4 p.m., weekdays.
3. 4 p.m.–8 p.m., weekdays.
4. 6 a.m.–8 p.m., weekends.

Freight Reliability

1. 6 a.m.–10 a.m., weekdays.
2. 10 a.m.–4 p.m., weekdays.
3. 4 p.m.–8 p.m., weekdays.
4. 8 p.m.–6 a.m., all days.
5. 6 a.m.–8 p.m., weekends.

Peak Hour Excessive Delay

1. 6 a.m.–10 a.m., weekdays.
2. 4 p.m.–8 p.m., weekdays.

All Other Performance Measures

Peak periods:

1. 7–9 a.m.
2. 4–6 p.m.

Overview of Case Study Sites

The following list of locations shows the selected case study sites:

- I–205, Vancouver, WA—Ramp meter installation (freeway).

- I–405, Seattle, WA—Addition of HOT lanes (freeway).

- U.S. 23, Ann Arbor, MI—Hard shoulder running, variable speed advisories, and queue warning system (freeway; known as the Flex Route system).

- I–540, Raleigh, NC—Ramp meter installation (freeway).

- State Route (SR) 92, Paulding County, GA—Signal retiming (signalized arterial).

- SR 22, Monroeville, PA (suburban Pittsburgh)—Signal controller upgrade (signalized arterial).

- Mercer Street, downtown Seattle, WA—Split Cycle Offset Optimization Technique (SCOOT) real-time adaptive system installation (signalized arterial).

Figures 8 through figure 13 show the locations of these case study sections.

Summary of Case Study Results: Key Takeaways

Table 5 and table 6 summarize the performance results for the seven case study locations. Based on these evaluations, several observations can be made.

- The results are context sensitive to such characteristics as network typology, demand patterns, and the level congestion in the "before" time period. This feature makes a strong case for performing empirical-based evaluations instead of using default values, which usually do not account for influencing factors or models, which will tend to regress to the mean condition.

- Ramp metering has a relatively small but positive performance effect. This finding is consistent with previous studies that determined ramp metering results in a small capacity increase (3–9 percent).[1]

- Context also plays a role in the results. On I–540 in North Carolina, a system interchange is immediately downstream of the metered section and becomes a bottleneck under high demand levels. As a result, the bottleneck queues diminish the effectiveness of ramp metering. On I–205 in Washington, no downstream bottleneck is present, and the positive effect of ramp metering is better than on I–540.

- In locations where hard shoulder running was implemented (two sites), the I–405 site in Washington State showed moderately positive performance effects, and the U.S. 23 site in Michigan showed positive performance impacts, including reliability. As with the I–540 ramp metering, the influence of a downstream bottleneck (on I–405 and I–5 interchange north of Seattle) affects the performance of the hard shoulder running section. Hard shoulder running is a method for dynamically increasing the physical

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[1] Zhang, Lei; David M. Levinson. 2010. *Ramp Metering David Freeway Bottleneck Capacity*. Elsevier. Retrieved from the University of Minnesota Digital Conservancy, https://hdl.handle.net/11299/179995.

highway capacity when conditions warrant, so large improvements in performance are to be expected. By inference, more routine capacity additions also improve reliability.

- Adaptive control signal improvements implemented on congested arterials have a moderate to strong positive effect on performance. The site with the highest level of base congestion (Mercer Street in Seattle) showed the largest performance improvements.
- The PM3 System Reliability measure can be at odds with typical reliability measures. That is, the PM3 measure may show lower performance when the other measures (e.g., 80th percentile TTI and the planning time index [PTI]) show improved performance. The project analysts observed three reasons for this anomaly:
    - Because system reliability is based on traffic message channel (TMC)-level performance, changes in 1–2 TMCs can affect the value of the final measure.
    - Conditions can improve due to a strategy implementation lowering the level of travel-time reliability (LOTTR) values, but travel time reliability can still be above the 1.5 threshold.
    - The percentiles in LOTTR formula—50th and 80th—can change at different rates.

These problems likely wash out at the system level; but at the project level, they can be present. The TTTR measure is less prone to these problems, but some discrepancies can still occur. In the sites studied, the PHED measure tracks with typical reliability measures. The project team suggests using a full suite of performance measures, including PM3 measures for evaluations.

Figure 8. Map. Location of I–540 ramp metering section, Raleigh, NC.

(Source: Adapted from *Planning Level Evaluation of the Effects of Ramp Metering on North Carolina Freeways*, NCDOT Report 2016-11.[2])

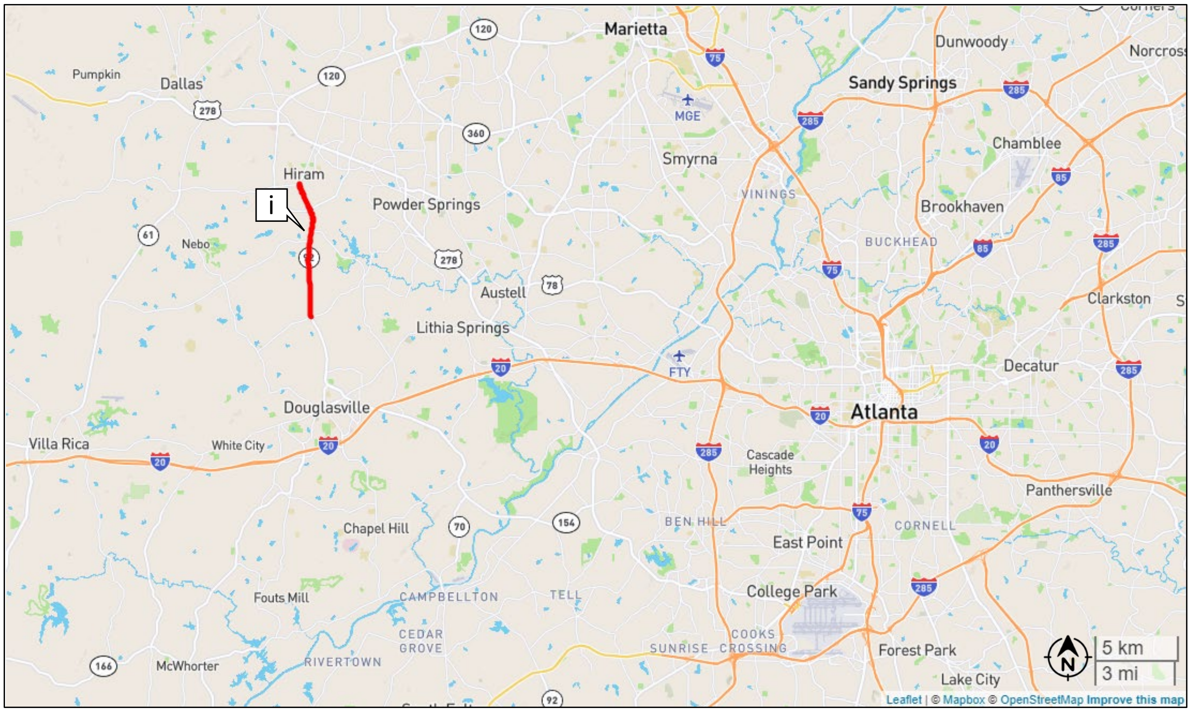

Figure 9. Map. Location of State Route 92 signal retiming section, west of Atlanta, GA.

(Source: FHWA.)

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[2] Cunningham, Chris, Joy Davis, Behzad Aghdashi, Thomas Chase, Sangkey Kim. 2016, https://rosap.ntl.bts.gov/view/dot/57046.

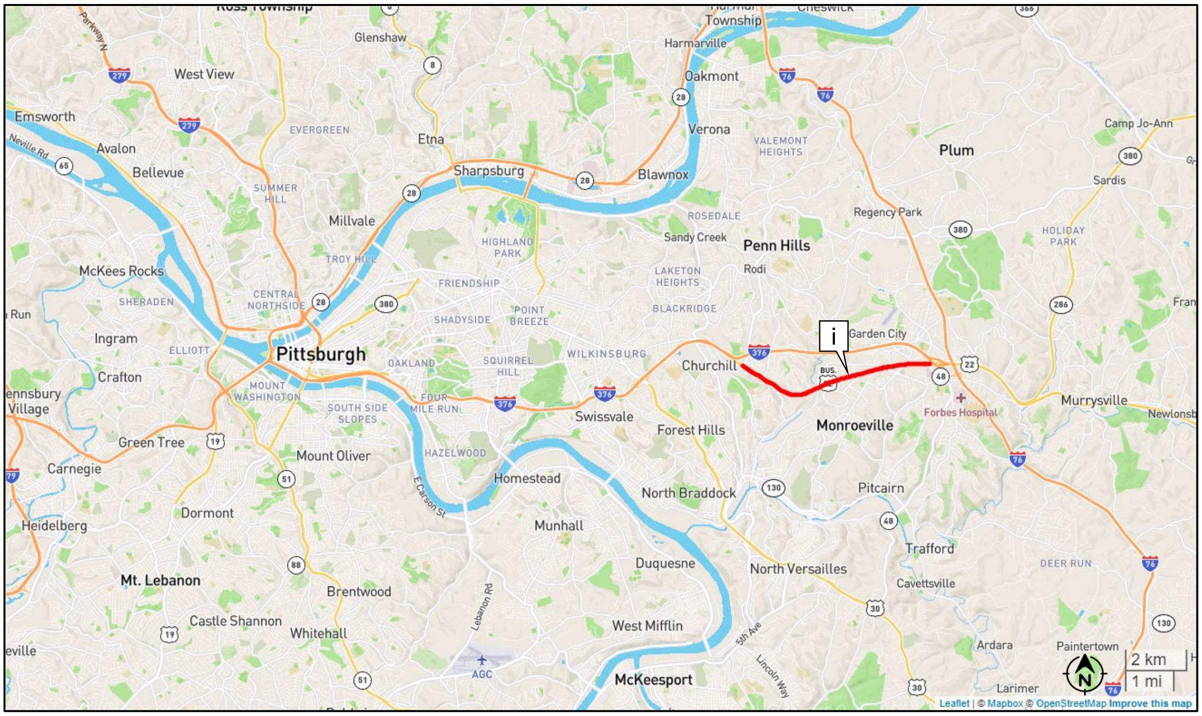

Figure 10. Map. Location of State Route 22 signal control upgrade in Monroeville, PA.

(Source: FHWA.)

Figure 11. Map. Location of split cycle offset optimization technique implementation, Seattle, WA.

(Source: Washington State DOT.)

Figure 12. Map. Location of the I–405 hard shoulder running segment, Lynwood, WA (suburban Seattle).

(Source: FHWA.)

Figure 13. Map. Location of I–205 ramp meters, Vancouver, WA.

(Source: FHWA.)

Table 5. Summary of case study results.

Location	Operations Strategy	Change in Performance	PM3 Measures[1]	Comments
U.S. 23 Flex Route, Ann Arbor, MI	Hard shoulder running, queue warning, advisory speed limits	All performance measures indicate a large improvement in congestion.	Measure: Before/After system reliability (sys rel):[2] 52%/94% truck travel time reliability (TTTR):[3] 2.66/1.55 peak hour excessive delay (PHED):[4] 228/79	Congestion reduction and reliability improvements were large even though traffic increased by 11 percent.
I–540, Raleigh, NC	Ramp metering	Performance showed a slight improvement between the before and after periods, especially for the non-PM3 measures.	Measure: Before/After sys rel: 63%/63% TTTR: 2.28/2.26 PHED: 96/95	Average Annual Daily Traffic was stable, incidents decreased, and inclement weather increased in the after period. The first analysis with National Performance Management Research Data Set data showed a slight degradation in performance. Data were used to show the results presented.
GA–92, Paulding County, GA	Signal retiming	Little change in performance between the before and after periods.	Measure: Before/After sys rel: 99%/99% PHED: 31/40	Before condition was only marginally congested.
U.S. 22, Monroeville, PA (suburban Pittsburgh)	Upgrade to adaptive control	All performance measures indicate a moderate improvement in congestion.	Measure: Before/After sys rel: 65%/92% PHED: 375/324	Traffic and weather conditions essentially the same in the before and after periods.

Table 5. Summary of case study results (continuation).

Location	Operations Strategy	Change in Performance	PM3 Measures[1]	Comments
Mercer Street, downtown Seattle, WA	Upgrade to Split Cycle Offset Optimization Technique (SCOOT) real-time adaptive signal control	All measures except Level of Travel Time Reliability (LOTTR) showed a large improvement in congestion	Measure: Before/After sys rel: 100%/100% PHED: 257/26	Signal density is 12 per mi., causing the 50th and 80th percentile travel times to be close in value.
I–405, Seattle, WA	Hard shoulder running	All measures except TTTR showed a large improvement in congestion	Measure: Before/After sys rel: 49%/54% TTTR: 2.57/2.96 PHED: 4,421/2,129	Examination of the ratios used in LOTTR and TTTR indicate that the numerators and denominators changed at different rates, leading the measures to indicate a slight degradation in performance.
I–205 Vancouver, WA	Ramp metering	All measures except LOTTR showed a large improvement in congestion	Measure: Before/After sys rel: 89%/89% TTTR: 2.06/1.80 PHED: 665/453	Examination of the ratios used in LOTTR indicate that the numerators and denominators changed at different rates, leading the measures to indicate a slight degradation in performance.

[1] In addition to the PM3 measures, other travel time-based performance measures also were used to arrive at the conclusions in this table. These include percentile-based travel time indices (mean and 80th and 95th percentiles) and average speed.

[2] System reliability: percent of facility that is reliable.

[3] Truck travel time reliability.

[4] Peak hour excessive delay, in thousands of person-hours.

Table 6. Additional performance measure changes, peak period/peak direction.

Location	Operations Strategy	Mean Travel Time Index		Planning Time Index		Average Speed (mph)	
		Before	After	Before	After	Before	After
U.S. 23 Flex Route, Ann Arbor, MI	Hard shoulder running, queue warning, advisory speed limits	1.669	1.183	3.083	1.995	43.8	55.0
I–540, Raleigh, NC	Ramp metering	1.555	1.539	2.444	2.514	45.0	45.5
GA–92, Paulding County, GA	Signal retiming	1.309	1.408	2.092	2.215	34.3	31.9
U.S. 22, Monroeville, PA (suburban Pittsburgh)	Upgrade to adaptive control	2.217	2.040	3.681	3.191	20.3	22.1
Mercer Street, downtown Seattle, WA	Upgrade to Split Cycle Offset Optimization Technique (SCOOT) real-time adaptive signal control	7.993	2.733	12.898	3.130	5.0	17.6
I–405, Seattle, WA	Hard shoulder running	1.880	1.400	2.860	2.470	31.8	42.7
I–205 Vancouver, WA	Ramp metering	1.220	1.150	1.730	1.541	49.3	52.0

Note: The before time period is 2016, and the after time period is 2018.

CHAPTER 4. EXAMPLE APPLICATIONS

APPLICATION OF THE EVALUATION METHODOLOGY

The project team selected three of the case studies to demonstrate in this chapter the application of the 12-step methodology discussed in chapter 2. For these examples, the team also customized key steps in the methodology and the process for analyzing operations strategies across the project development continuum. Most of the project development stages in the continuum are defined elsewhere. For example, FHWA has developed numerous guidance documents for incorporating operations into transportation planning and traffic analysis tools.[1,2] Only cursory guidance for the project development topics is included with the primary focus on the evaluation stage, which begins in step 6 of the methodology.

Assemble Data and Compute Metrics

- **Travel times**—Continuously collecting travel-time data is an absolute requirement for conducting before and after analysis of operations strategies because that action captures the variability in conditions that causes unreliable travel. Vehicle probe data, such as the NPMRDS or other probe-based sources, are useful on both interrupted (signals) and uninterrupted (freeways) flow facilities. On freeways, detector data may be used if they exist in both the before and after periods. Mixing data types is not typically done. Travel times are the key piece of data for conducting empirical before and after analyses of operations strategies. To compute reliability measures, travel-time data need to be collected continuously. For analysis, travel times for the entire length of a segment or subsegments must be computed for every time slice in the data. They then form the basis of a travel time distribution from which a variety of performance measures can be derived.

- **Traffic volume**—Continuously collected volume data are the best type for the before and after analysis because uninterrupted collection enables examining peak and offpeak time periods as well as seasonality. The data are collected at either permanent traffic count locations or by detectors deployed for operations strategies. If continuous data cannot be collected, analysts can use AADT derived from factored short counts as a general indicator of traffic demand.

- **Incidents**—Ideally, facilities under study already have incident management deployed. Typically, data on blockage types by duration are available. Work zones are sometimes coded as incidents in the data. If incident data are not available, crash data may be used, but blockage information will not be present.

- **Weather**—The road weather information systems deployed by transportation agencies are the best source of weather data. However, the systems currently are scarcely deployed. An alternative is to use hourly weather observations, which are available from

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[1] https://ops.fhwa.dot.gov/plan4ops/index.htm.

[2] https://ops.fhwa.dot.gov/trafficanalysistools/index.htm.

the National Oceanic and Atmospheric Administration (NOAA).[3] These NOAA sites are scattered around country, mostly at airports, including small regional ones.

- **Operating characteristics**—These characteristics will indicate the most appropriate time periods to analyze. For example, if ramp meters are operational only during peak periods, the analysis should focus on those periods.

Conduct Cluster Analysis

In traffic modeling, cluster analysis is used primarily as a calibration tool, to ensure that models can replicate a wide variety of influencing factors. The method applies the concepts of cluster analysis in the following way. The cluster analysis approach is to compare the travel time-based measures in the before and after periods for incident and inclement weather conditions only. Then analysts examine the output-based measures for consistency in the before and after periods.

Conduct Modeling Tests

If the comparison to control sites is inconclusive or if the demand, weather, and incident characteristics in the before and after conditions are substantially different, then modeling should be pursued as a form of control. The idea is to create before and after scenarios based on the same demand, incident, and weather conditions as in the before case. The comparison enables analysts to answer the question: "What would have happened without the treatment?" For example, if travel times improved in the after case, but incident and weather conditions also improved, then all or part of the travel time reduction could be attributable to the change in conditions not to the operations strategy.

For the method developed during this project, the team considered the HCM procedures for freeway facilities and urban streets (developed in SHRP 2 project L08) because they both produce reliability measures and handle queuing (freeways) and spillback (signalized highways), albeit with less rigor than simulation models. The input data for the HCM model come from the empirical measurements for demand, incidents, weather, and physical attributes of the highway. The results of applying the HCM procedure are expected values for the performance measures under the assumption that the operational treatment has not been implemented. These expected values are compared with the observed values to note differences. In essence, analysts replaced the before condition with a modeled condition.

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[3] https://www.ncdc.noaa.gov/cdo-web/datatools/lcd.

Benefit/Cost Analysis

For this application, BCA can be conducted using the TOPS-BC tool developed by researchers at FHWA.[4] TOPS-BC covers a wide range of operations strategies, including:

- Arterial signal coordination.
- Arterial transit signal priority.
- Ramp metering.
- Traffic incident management.
- Pretrip traveler information.
- En route traveler information.
- Work zone management.
- HOT lanes.
- Speed harmonization.
- Road weather management.
- Hard shoulder running.
- Travel demand management.

The following benefits are covered:

- Value of travel time savings.
- Value of reliability for strategies that affect incident characteristics.
- Fuel consumption savings.
- Safety benefits.

The costs of deploying operations strategies include the initial capital outlay and the ongoing operations and maintenance costs. For an empirical before and after analysis, project cost information for capital outlays is usually available. If so, cost inputs should be modified to match actual capital expenditures. Similarly, TOPS-BC's ongoing operations and maintenance costs should be overridden if local values are available.

TOPS-BC is a sketch-planning modeling tool that forecasts the benefits of implementing operations strategies using simplified relationships. However, users can override the forecasting procedure if key performance measures for the before and after periods are available (as is the case with empirical-based evaluations). However, even with these empirical inputs, fuel consumption savings are modeled using sketch planning procedures:

- Congested speed.
- MTTI.
- Median TTI.
- 80th percentile TTI.
- PTI.
- Crashes.

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[4] https://ops.fhwa.dot.gov/plan4ops/topsbctool/index.htm.

Likewise, TOPS-BC has default unit costs for each type of operations strategy that can be overridden.

EXAMPLE 1: FREEWAY RAMP METERING

Problem Identification

Planning Process

During routine long-range planning activities, a metropolitan planning organization (MPO) will identify deficiencies in the transportation system. For the purpose of this example, assume this step is the starting point for identifying the operations strategy that will address one of these deficiencies.

Models or analytical process used. The primary tool used by MPOs to identify deficiencies in the transportation network for long-range planning is a travel demand model (TDM). In this example, a 6-mile-long freeway segment with four interchanges is forecasted to experience significant congestion for a forecasted future year. This forecast prompts the MPO to develop an improvement alternative that includes a lane addition and the implementation of ramp meters on the segment. The project is added to the metropolitan transportation plan.

Performance measures used. Congestion measures that TDMs develop do not include the full set of measures shown in chapter 2. Notably, TDMs do not directly develop the PM3 measures. Typical measures at this stage include delay, average speed, and the volume-to-capacity ratio.

Data used. The operation of TDMs and their required data in support of planning activities is well documented in the profession. Socioeconomic and demographic data are the primary inputs along with basic network characteristics. Observed volumes compared with forecasted volumes are used to calibrate TDMs.

BCA. BCA for projects listed in planning documents are necessarily simple because little is known about project details. Benefits are generally derived from the change in delay predicted by the TDM for capacity expansion projects, but the benefits of operations strategies at this stage of the project development continuum may not be established. Costs are derived from general unit costs for different types of improvements rather than for the specifics of projects.

Congestion Monitoring

In addition to long-range planning, planners and operators also monitor current conditions and past trends to identify deficiencies of immediate concern. Deficiencies identified from current conditions may or may not match those identified by long-range forecasts. For this example, the assumption is that the same freeway segment identified in the long-range planning process also experiences current congestion problems.

Performance measures used. When using empirical travel-time data, agencies use a wide variety of performance measures, including the PM3 measures and the measures in table 2 to monitor congestion.

Models or analytical process used. Using data analysis software to compile performance measures from travel-time data, a detailed look at the data indicates that queues routinely form at several onramp locations in both the morning and afternoon weekday peak periods, depending on direction.

Data used. Travel-time data from vehicle probes have become nearly ubiquitous in the profession and are the data source of choice for congestion monitoring.

BCA. This analysis generally is not performed at this stage.

Project Level Goals and Objectives

Matching deficiency to an operations treatment. At this stage, the particulars of individual projects are defined. In this example, a freeway segment has been defined as a current problem (from congestion monitoring) that is expected to worsen over time (from long-range planning). In this example, the source of current congestion is demand entering the freeway from several closely spaced interchanges. As a result, ramp metering has been identified as the operations strategy that best addresses the deficiency.

Goals, objectives, strategies, and tactics. For the ramp metering treatment, the project team defined the following terms:

- Goal—Improve travel times on the arterial facility.
- Objective—Reduce peak period congestion by reducing stops by 20 percent.
- Strategy—Establish real-time traffic adaptive control.
- Tactics—Maintain system sensors to constantly measure current demand.

Design and Implementation

At the design stage, detailed traffic modeling is performed to quantify expected benefits. Here the project team highlighted one of the case studies, the implementation of ramp meters on I–540 in Raleigh.

Performance measures used. Delay, speed, and travel time are common performance measures used in traffic analysis. The development of reliability measures is not yet routine; but for several of the SHRP 2 projects, researchers developed methods to produce reliability measures using traffic analysis tools. The PM3 measures are difficult to produce, primarily because they require mixing peak and offpeak conditions, whereas most traffic analysis tool applications focus on peak periods.

Models or analytical process used: Macroscopic, mesoscopic, and microscopic traffic analysis tools are used for traffic modeling at this stage.

For the I–540 implementation, the North Carolina Department of Transportation (NCDOT) conducted a predeployment planning study on the corridor.[5] The study modeled the effect of implementing ramp meters using FREEVAL software (a deterministic model) that employs the HCM's freeway facilities procedure, which includes reliability.[6] Vehicle-hours of delay and average travel time were the main performance measures used. Table 7 shows the results. Note the large influence of the assumed reduction in crashes due to ramp metering.

Table 7. Expected costs and benefits of ramp metering, I–540.

Benefit/Cost Type	Expected Percentage of Reduced Crashes	
	5%	15%
Installation cost	$830,170	$830,170
Programming cost	$405,000	$405,000
Operations and maintenance costs	$255,579	$255,579
Facility replacement cost	$0	$0
Crash reduction benefits	$1,389,956	$4,169,867
User delay benefits	$28,335,293	$79,731,406
Benefits of ramp meters over 10 years	$28,234,500	$73,410,524

(Source: *Planning Level Evaluation of the Effects of Ramp Metering on North Carolina Freeways, NCDOT Report 1016-11.*[7])

Data used. Traffic models require detailed data for inputs and calibration. The same data are used in evaluations: traffic volumes, travel times, and characteristics of incidents and weather. The data can be used in a cluster analysis as an aid to calibration.

Evaluation

For the evaluation stage, the team again borrowed from the I–540 case study in Raleigh, which implemented ramp meters on a 6-mile segment on the northern arc in the westbound direction (figure 14).

Define geographic scope. Figure 15 shows the installation location of four ramp meters. The study area covered the area from the U.S. 70 interchange eastward to 0.5 miles east of the Exit 14 interchange. The extra 0.5 mile on the eastern end was used to capture queuing.

Define analysis periods. The PM3 measures have defined analysis periods. For the remaining performance measures, the two weekday peak periods were 7–9 a.m. and 4–6 p.m.

Define performance measures. The project team used all the measures in chapter 2.

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[5] Chris Cunningham, Joy Davis, Behzad Aghdashi, Thomas Chase, Sangkey Kim. *Planning Level Evaluation of the Effects of Ramp Metering on North Carolina Freeways,* NCDOT Report 2016-11, 2016, https://rosap.ntl.bts.gov/view/dot/57046.

[6] http://freeval.org/.

[7] https://rosap.ntl.bts.gov/view/dot/57046.

Assemble data. Table 8 shows all the data assembled for the evaluation. The NPMRDS data were used to develop performance measures at this stage. The PM3 Final Rule prescribes the computations for the PM3 measures. For the other performance measures from chapter 2, the starting point is the creation of a travel time distribution where each observation is travel time over the entire length of the facility. For every time stamp in the data, travel times for TMCs are summed. This step requires addressing TMCs with missing time-stamped values. The team used this procedure: If at least 75 percent of the facility length was present, factor the travel times based on length. If not, delete the record.

Because several performance measures require a reference speed, the case study calculated the free flow speed as the 85th percentile speed for hours between 6 a.m. and 11 a.m. on weekends. Other definitions can be substituted. The following parameters show the travel time distribution for the weekday peak periods:

- PTI = 95th percentile travel time/free flow travel time.
- 80th percentile TTI = 80th percentile travel time/free flow travel time.
- MTTI = average travel time/free flow travel time.
- Average speed = TMC length-weighted harmonic mean speed.

Table 8. Data for I–540 ramp meter evaluation.

Data Type	Source	Description
Travel time	(1) National Performance Management Research Data Set (2) HERE (North Carolina Department of Transportation (NCDOT) purchased)	Probe-based travel times
Incident	NCDOT	From NCDOT incident management system
Volume	NCDOT/Highway Performance Monitoring System	Continuous counter on I–540; short counts elsewhere
Weather	National Oceanic and Atmospheric Administration	Hourly weather from the Raleigh-Durham airport
Work zones	N/A	N/A

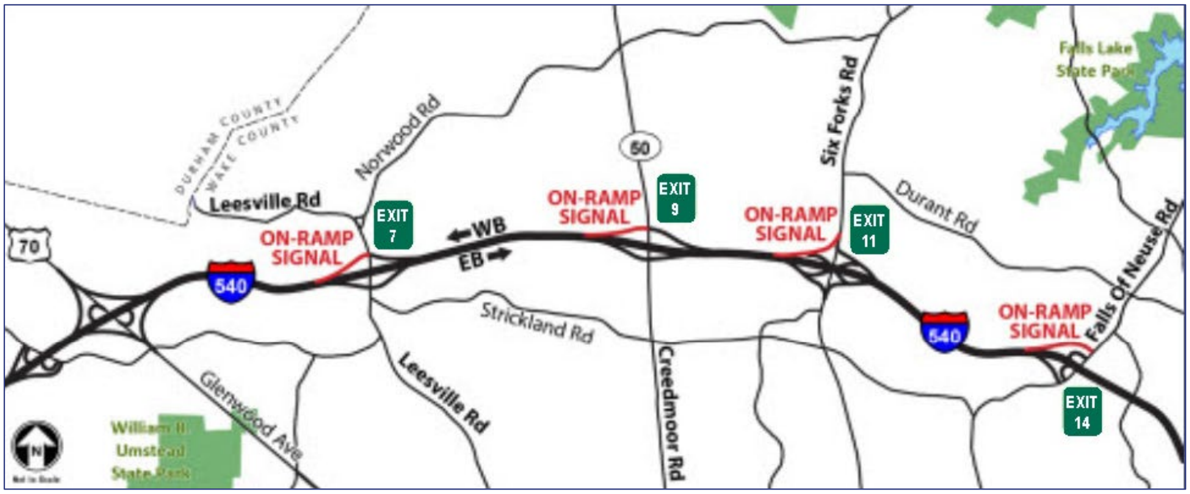

Figure 14. Map. I–540 case study location.

(Source: Adapted from *Planning Level Evaluation of the Effects of Ramp Metering on North Carolina Freeways*.[8])

Naïve before and after comparison. Table 9 compares the PM3 measures for the before and after periods. Table 10 shows the other performance measures. Taken as a group, the naïve analysis indicates very little change in performance due to ramp meters, with most measures showing a small decrease in performance.

Compare conditions in before and after periods. To understand how ramp metering performed during times when incident or weather disruptions were present, the non-PM3 measures were calculated for these conditions (table 11 and table 12). The analysis depends on flagging time stamps in the travel-time data as being influenced by incidents and weather. The results are similar for all conditions combined: little change in performance due to ramp metering.

However, as discussed in the methodology section, the results could be influenced by different conditions for the influencing factors in the before and after periods. Table 13 shows how these conditions vary:

- Traffic volumes are relatively consistent between the periods.
- Peak period incidents decreased substantially (19 versus 7) but overall are low in number.
- Rain influenced peak period hours by an increase of 18 percent, frozen precipitation hours were about the same, and hours with low visibility decreased from 9 to 3.

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[8] https://rosap.ntl.bts.gov/view/dot/57046.

Table 9. PM3 measures, I–540, westbound direction.

Measure	Before (2016)	After (2018)
Percent reliable	64.0%	60.8%
Truck travel time reliability index	2.325	2.273
Peak hour excessive delay (person hours of excessive delay)	47,848	52,424

Table 10. Additional reliability measures, I–540, westbound direction.

Measure	Before (2016)	After (2018)
Mean Travel Time Index		
Mean travel time index: westbound (WB)/AM peak	1.585	1.597
Westbound/PM Peak	1.079	1.057
80th Percentile Travel Time Index		
Westbound/AM Peak	1.980	1.962
Westbound/PM Peak	1.083	1.079
Planning Time Index		
Westbound/AM Peak	2.773	2.849
Westbound/PM Peak	1.153	1.140
Average Speed		
Westbound/AM Peak	45.0 mph	43.1 mph
Westbound/PM Peak	67.5 mph	70.0 mph
Percent Time Congested		
Westbound/AM Peak	34.9%	34.5%
Westbound/PM Peak	1.0%	0.3%

Table 11. Additional reliability measures, I–540, during inclement weather, westbound direction.

Measure	Before (2016)	After (2018)
Mean Travel Time Index		
AM Peak	1.577	1.639
PM Peak	1.073	1.053
80th Percentile Travel Time Index		
AM Peak	1.952	2.034
PM Peak	1.092	1.073
Planning Time Index		
AM Peak	2.486	2.902
PM Peak	1.139	1.199
Average Speed		
AM Peak	44.4 mph	42.7 mph
PM Peak	64.1 mph	66.5 mph

Table 12. Additional reliability measures, I–540, during incidents, westbound direction.

Measure	Before (2016)	After (2018)
Mean Travel Time Index		
AM peak	1.844	1.906
PM peak	1.055	1.035
80th Percentile Travel Time Index		
AM peak	2.257	1.939
PM peak	1.079	1.055
Planning Time Index		
AM peak	3.719	2.136
PM peak	1.162	1.084
Average Speed		
AM peak	38.0 mph	36.7 mph
PM peak	66.4 mph	67.7 mph

Table 13. Travel conditions, I–540.

Measure	Before (2016)	After (2018)
Average annual daily traffic	99,330	99,660
Peak Period Volume (average)	3,818	3,777
Annual Incidents[1]	82	55
Peak Period Incidents	19	7
Annual Hours with precipitation > 0.01 inch	776	881
Annual Hours with frozen precipitation	53	55
Annual Hours with reduced visibility	32	25
Peak Period Hours with precipitation > 0.01 inch	126	149
Peak Period Hours with frozen precipitation	28	25
Peak Period Hours with reduced visibility	9	3

[1] January through October only.

Conduct HCM modeling if conditions warrant. After implementation, NCDOT conducted an evaluation study, again using the HCM's freeway facilities reliability method embodied in the FREEVAL software. The model predicted delay reductions due to implementing ramp meters on this segment (table 14).[9] The benefit/cost (B/C) ratio was found to be 4.80.

BCA (empirical). Because the results showed a slight degradation in performance after ramp meters were installed, the project team decided to conduct a second empirical analysis using the HERE data purchased independently by NCDOT. The concern was that, with the NPMRDS, 2016 data were provided by HERE and 2018 by INRIX, and the differences in data sources and processing methods might make detecting slight differences in performance due to ramp meters impossible. The results of using the HERE data show a slight improvement in performance, except for the PTI (table 15). Also, the values of the performance measures are close in value for the before and after periods, but not exact. This result has implications for future evaluations.

The system reliability PM3 measure showed no difference in the percentage of person-miles that are reliable: 62.8 percent in both the before and after periods. Table 16 shows why the same TMCs that were unreliable in the before period are unreliable in the after period. This result highlights an issue with the binary structure of the system reliability measure: Small changes in performance do not necessarily move the calculated values below the threshold for reliability.

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[9] Cunningham, Chris, Joy Davis, Behzad Aghdashi Behzad, Thomas Chase, Sangkey Kim. *Planning Level Evaluation of the Effects of Ramp Metering on North Carolina Freeways*, NCDOT Report 2016-11, 2016, https://rosap.ntl.bts.gov/view/dot/57046, last accessed December 24, 2023.

Table 14. Model-based vehicle-hours of delay results from post-deployment planning study on I–540 westbound.

Year	Annual Totals for Weekday Peak Periods		
	Vehicle-Hours of Delay Without OnRamp Signals	**Vehicle-Hours of Delay With OnRamp Signals**	**Reduction in Vehicle-Hours of Delay**
2017 (installation)	330,203	330,203	–
2018	341,760	314,980	26,780
2019	353,722	323,655	30,066
2020	366,102	334,983	31,119
2021	378,915	346,708	32,208
2022	392,177	358,842	33,335
2023	405,904	371,402	34,502
2024	420,110	384,401	35,709
2025	434,814	397,855	36,959
2026	450,033	411,780	38,253
2027	465,784	426,192	39,592
Total: 2018–2027	**4,009,320**	**3,670,798**	**338,522**

(Source: *Planning Level Evaluation of the Effects of Ramp Metering on North Carolina Freeways* NCDOT Report 2016-11).[10]

The shift from lower performance to improved performance was small; nevertheless, the improvement indicates that practitioners should be aware of nuances in their data sources. In this case, the project team considered the HERE analysis more dependable because of consistency in the data collection and processing methods and concluded that ramp metering had a minimal positive impact on travel time performance in this corridor.

The values for westbound traffic during the AM peak were input to TOPS-BC. Additionally, capital costs estimated from the planning study also were used:

- Capital costs: $830,000 (including both ramp meter installation and ramp realignment).
- Software integration costs: $405,000.

The corresponding annualized benefits are these values:

- Crash reduction representing a savings of $7,185,074.
- Travel time savings of $1,972,780.
- Fuel consumption savings of $2,550,641.

Considering travel time savings only, the B/C ratio is 1.39. Considering travel time savings and fuel consumption savings, the B/C ratio is 3.19. Considering all three benefit categories, the ratio is 8.27.

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[10] https://rosap.ntl.bts.gov/view/dot/57046.

Table 15. Additional reliability measures, I–540, westbound direction using HERE data.

Measure	Before (2016)	After (2018)
Mean Travel Time Index		
Westbound/AM peak	1.555	1.539
Westbound/PM peak	1.042	1.027
80th Percentile Travel Time Index		
Westbound/AM peak	1.945	1.878
Westbound/PM peak	1.046	1.037
Planning Time Index		
Westbound/AM peak	2.444	2.514
Westbound/PM peak	1.089	1.089
Average Speed		
Westbound/AM peak	45.0 mph	45.5 mph
Westbound/PM peak	67.2 mph	68.1 mph
Percentage Time Congested		
Westbound/AM peak	30.8%	28.4%
Westbound/PM peak	0.8%	0.3%

Table 16. Level of travel time reliability performance of individual traffic message channels using HERE data, I–540.

TMC	Metric	Before Period (2016)				After Period (2018)			
		AM	Midday	PM	Night	AM	Midday	PM	Night
125-04899	P50	109.0	107.0	107.0	107.0	108.0	106.0	106.0	104.0
125-04899	P80	117.0	110.0	111.0	111.0	115.0	109.0	110.0	108.0
125-04899	LOTTR	1.07	1.03	1.04	1.04	1.06	1.03	1.04	1.04
125N05079	P50	30.0	29.0	29.0	29.0	30.0	29.0	29.0	28.0
125N05079	P80	41.0	30.0	30.0	30.0	40.0	30.0	30.0	29.0
125N05079	LOTTR	1.37	1.03	1.03	1.03	1.33	1.03	1.03	1.04
125-05079	P50	111.0	107.0	107.0	105.0	111.0	106.0	106.0	103.0
125-05079	P80	152.0	110.0	111.0	108.0	146.0	109.0	110.0	108.0
125-05079	LOTTR	1.37	1.03	1.04	1.03	1.32	1.03	1.04	1.05
125N05080	P50	32.0	31.0	31.0	31.0	32.0	31.0	31.0	30.0
125N05080	P80	61.0	32.0	32.0	32.0	59.0	32.0	32.0	31.0
125N05080	LOTTR	1.91	1.03	1.03	1.03	1.84	1.03	1.03	1.03
125-05080	P50	65.0	63.0	63.0	62.0	65.0	63.0	62.0	61.0
125-05080	P80	123.0	65.0	65.0	65.0	119.0	64.0	65.0	63.0
125-05080	LOTTR	1.89	1.03	1.03	1.05	1.83	1.02	1.05	1.03
125N05081	P50	25.0	25.0	25.0	24.0	25.0	25.0	24.0	24.0
125N05081	P80	47.0	25.0	25.0	25.0	47.0	25.0	25.0	25.0
125N05081	LOTTR	1.88	1.00	1.00	1.04	1.88	1.00	1.04	1.04
125-05081	P50	111.0	107.0	107.0	106.0	111.0	107.0	106.0	104.0
125-05081	P80	206.0	110.0	110.0	109.0	203.0	109.0	110.0	108.0
125-05081	LOTTR	1.86	1.03	1.03	1.03	1.83	1.02	1.04	1.04
125N05082	P50	17.0	16.0	16.0	16.0	17.0	16.0	16.0	16.0
125N05082	P80	22.0	17.0	17.0	17.0	22.0	17.0	17.0	17.0
125N05082	LOTTR	1.29	1.06	1.06	1.06	1.29	1.06	1.06	1.06
125-05082	P50	126.0	123.0	123.0	121.0	125.0	122.0	121.0	119.0
125-05082	P80	167.0	126.0	126.0	125.0	166.0	126.0	126.0	124.0
125-05082	LOTTR	1.33	1.02	1.02	1.03	1.33	1.03	1.04	1.04

LOTTR = level of time travel reliability, P = Percentile, TMC = traffic message channel.

EXAMPLE 2: TRAFFIC SIGNAL ADAPTIVE CONTROL

Problem Identification

Planning Process

During routine long-range planning activities, an MPO will identify deficiencies in the transportation system. For the purpose of this example, the project team assumed knowing the deficiencies is the starting point for identifying the operations strategy to improve one of the deficiencies.

Models or analytical process used. The primary tool MPOs use to identify deficiencies in the transportation network for long-range planning is a TDM. In this example, the TDM was a four-lane signalized arterial segment that was 3.9 miles long with 14 signalized intersections. With that information identified, the MPO develops an improvement alternative that includes a lane addition and the implementation of traffic adaptive signal control on the facility. The project is added to the long-range transportation plan.

Performance measures used. Congestion measures developed by TDMs do not include the full set of measures shown in chapter 2. TDMs do not directly develop PM3 measures. Typical measures at this stage include delay, average speed, and the volume-to-capacity ratio.

Data used. The operation of TDMs and their required data in support of planning activities is well documented in the profession. Socioeconomic and demographic data are the primary inputs along with basic network characteristics. Observed volumes compared to forecasted volumes are used to calibrate TDMs.

BCA. BCA for projects listed in planning documents are necessarily simple because little is known about project details. Benefits are generally derived from the change in delay predicted by the TDM for capacity expansion projects, but the benefits of operations strategies at this stage of the project development continuum may not be established. Costs are derived from general unit costs for different types of improvements, rather than for the specifics of projects.

Congestion Monitoring

In addition to long-range planning, planners and operators also monitor current conditions and past trends to identify deficiencies of immediate concern. Deficiencies identified from current conditions may or may not match those identified by long-range forecasts. For this example, the project team assumed that the same arterial segment identified in the long-range planning process also is experiencing current congestion problems.

Performance measures used. When using empirical travel-time data, agencies use a wide variety of performance measures, including the PM3 measures and the measures to monitor congestion (table 2).

Models or analytical process used. This case study used data analysis software to compile performance measures from travel-time data. A detailed look at the data indicated that queues routinely form at several onramp locations in both the morning and afternoon weekday peak periods, depending on direction.

Data used. Using travel-time data from vehicle probes has become nearly ubiquitous in the profession and is the data source of choice for congestion monitoring.

BCA. Generally, BCA is not performed at this stage.

Project-Level Goals and Objectives

Matching deficiency to an operations treatment. At this stage, the particulars of individual projects are defined. In this example, an arterial segment has been defined as a current problem (from congestion monitoring) that is expected to worsen over time (from long-range planning). In this example, given that signal progression appears to be the source of the current congestion, the project team identified adaptive signal control as the operations strategy that best addressed the deficiency.

Goals, objectives, strategies, and tactics: For our ramp metering treatment, we define:

- Goal—Improve travel times on the arterial facility.
- Objective—Reduce peak period congestion by improving peak period speeds by 15 percent.
- Strategy—Install adaptive signal control on all intersections in both directions.
- Tactics—Enable the system to modify offsets, cycle lengths, and phasing in response to demand.

Design and Implementation

At the design stage, detailed traffic modeling is performed to quantify expected benefits. Here, the project team highlighted one of the case studies, the implementation of ramp meters on I–540 in Raleigh.

Performance measures used. Delay, speed, and travel time are common performance measures for traffic analysis tools. The development of reliability measures is not yet routine, but for several of the SHRP 2 research projects, researchers developed methods to produce reliability measures using traffic analysis tools. The PM3 measures are difficult to produce, primarily because they require mixing peak and offpeak conditions, whereas most traffic analysis tool applications focus on peak periods.

Models or analytical process used. Macroscopic, mesoscopic, and microscopic traffic analysis tools are used for traffic modeling.

***Data used**:* Traffic models require detailed data for inputs and calibration, as well as for evaluating traffic volumes, travel times, and characteristics of incidents and weather. The data can be used in a cluster analysis as an aid to calibration.

Evaluation

For the evaluation stage, the project team borrowed from the U.S. 22 case study in Monroeville (figure 15). The study's focus was a 3.9-mile, 4-lane corridor with an AADT of approximately 30,000 and 14 signalized intersections. This corridor is primarily a 4-lane divided urban highway operating under a speed limit of 40 mph with an AADT of around 28,000. Land use along the corridor is a mixture of residential, business parks, and commercial developments.

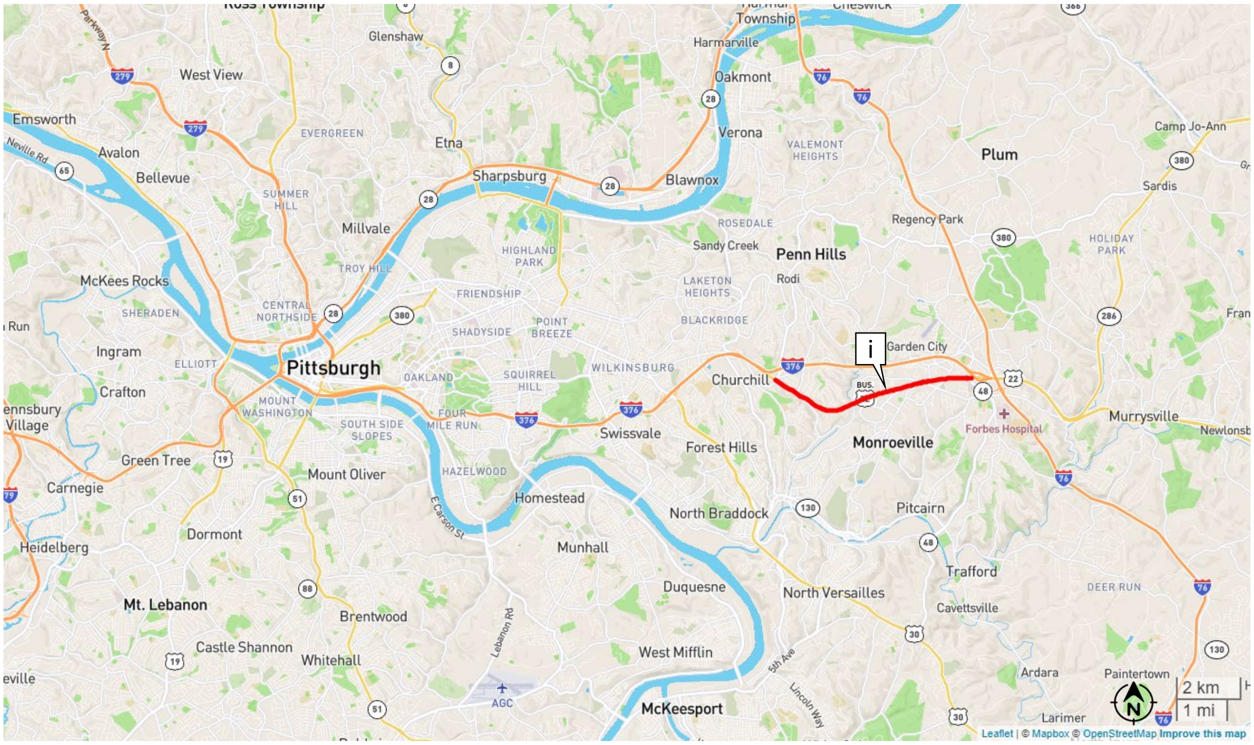

Figure 15. Map. Study area for U.S. 22 deployment.

(Source: FHWA.)

Define geographic scope: Approximately 0.5 miles were added to the 3.9-mile section, which spans intersections, to capture queuing at the furthest upstream intersection.

Define Analysis Periods: The PM3 measures have defined analysis periods. For the remaining performance measures, 7–9 a.m. and 4–6 p.m. on weekdays were defined as the two peak periods.

Define performance measures. The measures used included all those addressed in chapter 2 of this report.

Assemble data: Table 17 shows all the data assembled for the evaluation. The analysts used NPMRDS data to develop performance measures at this stage. PM3 Final Rule prescribes the computations for the PM3 measures. For the other performance measures from chapter 2, the starting point is the creation of a travel time distribution where each observation is travel time over the entire length of the facility. For every time stamp in the data, travel times for TMCs are summed. This step requires addressing TMCs with missing values for a time stamp. The project used this procedure for these scenarios:

- If at least 75 percent of the facility length was present, factor the travel times based on the length.
- If less than 75 percent of the facility length was not present, delete the record.

Because several performance measures require a reference speed, the free flow speed was calculated as the 85th percentile speed for hours between 6 a.m. and 11 a.m. on weekends; other definitions can be substituted.

From the travel time distribution for the weekday peak periods:

- PTI = 95th percentile travel time divided by free flow travel time.
- 80th percentile TTI = 80th percentile travel time/free flow travel time.
- MTTI = average travel time/free flow travel time.
- Average speed = the TMC length-weighted harmonic mean speed.

Table 17. Data for U.S. 22 traffic adaptive signal control evaluation.

Data Type	Source	Description
Travel time	National Performance Management Research Data Set (NPMRDS)	INRIX probe data
Incident and or Crash	N/A	None
Volume	NPMRDS	Pittsburgh-Allegheny County Airport
Weather	National Oceanic and Atmospheric Administration	N/A
Work Zones	N/A	N/A

N/A = not applicable.

Naïve before and after comparison. Table 18 compares the PM3 measures for the before and after periods. Table 19 shows the other performance measures. Taken as a group, the naïve analysis indicates a performance improvement due to implementing adaptive signal control with all measures except for the Westbound PTI showing a small decrease in performance.

Compare conditions in before and after periods. As discussed in the methodology section, the results could be influenced by different conditions for the influencing factors in the before and after periods. Table 20 shows how these conditions vary; note that not all the data available for Example 1 were present at this location:

- Traffic volumes are relatively consistent between the periods.
- Weather conditions are slightly worse in the after period.

Table 18. PM3 Measures for U.S. 22.

Measure	Before (2016) (%)	After (2018) (%)
Percent reliable (both directions)	65.4	92.1
EB	72.8	97.1
WB	58.0	87.2
Peak hour excessive delay (both directions) (person hours of excessive delay)	375,334	323,363
EB	210,846	168,597
WB	164,488	154,766

EB = eastbound, WB = westbound.

Table 19. Additional performance measures, U.S. 22.

Measure	AM Peak		PM Peak	
	Before (2016)	After (2018)	Before (2016)	After (2018)
Mean Travel Time Index				
EB	1.773	1.677	2.217	2.040
WB	1.663	1.630	2.173	2.109
80th Percentile Travel Time Index				
EB	2.053	1.921	2.614	2.357
WB	1.867	1.845	2.504	2.454
Planning Time Index				
EB	2.817	2.556	3.681	3.191
WB	2.648	2.622	3.463	3.518
Average Speed (mph)				
EB	25.371	26.824	20.293	22.058
WB	27.042	27.600	20.704	21.329
Percentage Time Congested				
Both directions	29.1	24.5	65.2	56.6

EB = eastbound, WB = westbound.

Table 20. Travel conditions, U.S. 22.

Measure	Before (2016)	After (2018)
Average annual daily traffic	28,748	28,041
Hours with rainfall > 0.01 inch	1,095	1,244
Hours with frozen precipitation	322	365
Hours with reduced visibility	65	70

Conduct HCM modeling if conditions warrant. Because weather conditions are slightly worse in the after period, and the facility exhibits a positive change in performance, no additional modeling is necessary. It is possible that modeling would demonstrate a slight improvement due to weather, but the expected change would be small.

BCA. The values for the PM peak were input to TOPS-BC. TOPS-BC default costs were used. The calculated B/C ratio for this deployment is 2.17, and 93 percent of the benefits accrue to travel time savings.

EXAMPLE 3: HARD SHOULDER RUNNING, I–405, SEATTLE, WA

Problem Identification

Site description. Interstate 405 (I–405) in the State of Washington is in the Seattle-Tacoma-Bellevue metropolitan statistical area, often referred to as the "Puget Sound Region." I–405 is located east of Lake Washington, connecting to I–5 both north and south of the lake. At roughly the center of the region is Bellevue, a city of approximately 150,000 people with a large urban core that contains significant employed population; a growing residential population; and a large, regional retail shopping center (figure 16).

Figure 16. Map. I–405 current high-occupancy toll lane location and configuration.

(Source: FHWA.)

Planning process. The construction, expansion, and operational changes previously described were made as a result of the Washington State Department of Transportation's (WSDOT) planning process. As one key input to those procedures for the past 25 years, WSDOT conducted routine system performance monitoring, including the regional GP and high-occupancy vehicle (HOV) freeway networks. For the past 15 years, summaries of WSDOT's performance reports were included in the agency's accountability report, known as the *Gray Notebook* (the GNB).[11] From its inception through 2015, the GNB published a variety of facility performance statistics, including mean and 95th percentile travel times for representative trips, traffic volumes, and other performance statistics. More recent editions of the GNB report the Federal PM3 performance statistics, although WSDOT continues to use its entire suite of roadway performance measurements as input to both their long-range planning process and their near-term operations planning.[12]

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[11] https://wsdot.wa.gov/accountability/gray-notebook/home.

[12] See page 8: https://wsdot.wa.gov/publications/fulltext/graynotebook/gray-notebook-Mar21.pdf.

Performance measures used. Performance statistics are routinely generated and reported publicly for both the HOT lanes and their parallel GP lanes. That combination enables WSDOT to describe the travel time benefits the HOT lanes provide to users, regardless of whether those users are paying customers, carpoolers using the facility for free, or transit buses.

WSDOT computes a wide variety of performance measures used to understand roadway performance. A limited number of statistics (the PM3 statistics, a set of corridor-specific travel times by time of day for weekdays, and contour graphics that illustrate the location and extent of congestion) are the basic performance measures used to track roadway performance. When new operational strategies or capacity improvements are implemented or when significant changes in congestion are observed, analysts produce additional performance reports to better understand the changing congestion conditions, determine whether changes in facility operations are required, and, if so, the potential solutions appropriate for addressing those changing conditions.

The project team analyzed congestion to identify how congestion formation and duration in the corridor had changed. These locations were then examined to determine the causes for the new, intense congestion points. Several of these points were associated access points between the toll facility and the GP lanes and indicated places where vehicle merging as vehicles maneuvered to enter or exit the freeway were causing congestion. The project team identified the need for some minor geometric improvements to make the weaving movements of vehicles attempting to enter or leave the HOT facility less disruptive.

However, at the northern end of the facility, the team identified one of the new causes of congestion northbound as ramp traffic merging onto an already full GP facility at the SR 527 interchange.

Models or analytical process used. The performance monitoring system that provided the insight about the merging ramp traffic is a Web-based analytic system (TRACFLOW), originally built for WSDOT in the late 1990s and then updated to be Web accessible.[13] TRACFLOW is able to compute travel times by selected time interval (e.g., 1-, 5-, 15-minute) for user-defined corridors. TRACFLOW can report vehicle volumes and speeds separately for GP and HOT or HOV lanes, and it can compute travel times for both GP and HOV or HOT lanes.

This enables WSDOT to directly compare travel time performance and vehicle volumes for these parallel facilities. That comparison enables WSDOT to both report on GP and HOV/HOT lanes separately as well as compute and report time savings gained when vehicles are able to use the HOT lanes, either as carpools or as paying customers. WSDOT also uses these data for calibrating regional travel forecasting models maintained by the Puget Sound Regional Council, the area MPO.

Data used. For urban freeway performance evaluation, WSDOT typically uses data from the detectors the agency placed in the roadway to provide data for its traffic management system. Detector data provide traffic volume, speed, and density statistics at locations roughly every half mile within the urban freeway system. Detector data are stored at 20-second intervals and aggregated to a number of larger time intervals. Most planning analyses use data aggregated for

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[13] TRACFLOW outside users can access the application at https://tracflow.wsdot.wa.gov/.

either the 5-minute or 15-minute interval. (Five-minute intervals give more fidelity to the results than 15-minute data but require additional time and effort to summarize.)

Congestion Monitoring

Performance measures used: WSDOT routinely computes a wide variety of performance measures that are used to understand roadway performance. The following list shows statistics commonly used for examining roadway performance:

- PM3 statistics (percent of reliable travel, LOTTR, TTTR, and PHED).
- Travel times for defined routes by time of day (mean, median, 80th, 95th percentiles) for both GP and HOV and HOT lanes.
- Travel time indices: buffer index, maximum throughput travel time index, planning time index, and travel time index (TTI, PTI, BI, MT^3I).[14]
- Frequency of congestion (formation of congestion by time of day and location), typically presented as contour graphics showing the probability of congestion forming on each corridor by time of day and direction.
- Person- and vehicle-miles of travel.
- Mode split on facilities.
- Person- and vehicle-hours of delay.
- Travel delay costs.
- Transit ridership by facility and park-and-ride capacity utilization near freeways.
- Freeway capacity utilization (hours during which congestion limits freeway utilization and the degree to which that capacity is reduced due to congestion).

These measures are supplemented with incident, construction, and crash weather statistics used to identify hazardous locations that need safety improvements, as well as to examine the impact of incidents of all kinds on the formation and size of congestion.

Models or analytical process used: While regional forecasting models are used as part of the planning process, a great deal of the decisionmaking is based on the data reported from monitoring of current conditions and trends over time, using the measures described in the Performance measures used section in this chapter.

The Federal PM3 measures are useful statistics for describing the overall congestion conditions in a region, but more detailed congestion statistics such as those listed in the Performance measures used sections in this chapter provide a more detailed understanding of the causes and

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[14] BI = buffer index; MT^3I = maximum throughput travel time index.

scope of congestion in the region. This, in turn, leads to the identification of congestion mitigation strategies, which can be examined for their potential benefits using analytical tools appropriate for those improvements.

Unfortunately, the congestion monitoring process identified that the initial design of the I-405 express toll lanes generated a number of operational problem areas, and those problem areas both lowered facility performance and generated significant negative public feedback.

Data used: The travel time statistics were key to addressing the overall impact of the congestion to travelers within the corridor because travel time is easily understood by the public. The location-specific vehicle volumes and speeds were extremely useful in quantifying the size and scope of the congestion as part of the analysis of the value of potential improvements.

The data used for congestion monitoring are the same as those used for planning described. As noted, WSDOT also uses its incident management database, which tracks the location, cause, response, and duration of all incidents identified on the State roadway system.[15]

Project Level Goals and Objectives

Matching deficiency to an operations treatment. Using the congestion analysis, WSDOT was quickly able to identify that the ramp volumes entering from SR 527 into an already dense traffic stream on I–405’s GP lanes were the primary cause of congestion in the northern section of the northbound corridor in the PM peak period. Because the ramp already was dynamically metered, metering was not an appropriate solution to the problem. Additional operational improvements were needed to limit the congestion caused by traffic entering from that ramp.

The selected operational solution was to add an additional lane at the ramp, enabling ramp traffic to remain in the new lane until drivers decide to be in one of the adjacent lanes. The research team expected the improvement to greatly reduce the congestion caused by merging ramp traffic and, consequently, improve travel times for the corridor segment leading up to, and including, the ramp traffic.

Goals, objectives, strategies, tactics. The goal of the hard shoulder running solution was to reduce overall congestion in the corridor during the afternoon peak period, when ramp volumes were creating congestion that propagated upstream of the ramp, slowing traffic and increasing travel times for the corridor drivers. This goal was driven by the WSDOT’s interest in reducing corridor congestion experienced after implementation of the HOT lanes. Significant merge congestion at the SR 527 interchange resulted due to increased northbound PM peak period volumes in the northern third of the corridor as a result of the increased capacity of the southern two-thirds of the corridor.

The primary objective of the hard shoulder running was to decrease the frequency, duration, and severity of congestion forming on the roadway near the SR 527 ramps. Such a decrease was expected to also improve upstream congestion and travel times in the corridor. Finally, those same improvements were expected to improve the Federal PM3 reporting measures.

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[15] https://tracflow.wsdot.wa.gov/.

Design and Implementation

Performance measures used. The following performance measures were used to evaluate the outcome of the hard shoulder running project:

- Mean, median, 80th, and 95th percentile travel times by time of day for the corridor segment from SR 522 to I–5 in Lynnwood, a segment which includes the SR 527 interchange.
- The cumulative frequency diagram of the northbound PM travel times for the SR 522 to I–5 corridor segment.
- LOTTR values for all northbound, ½-mile roadway segments on I–405 between SR 522 and I–5, as well as the LOTTR value summarized for the entire corridor segment. LOTTR values were computed separately for GP and HOT lanes.
- TTTR values for the GP portion of the corridor segment (because trucks are not allowed into the HOT lane, TTTR values were not computed for the HOT lane).
- PHED values for the corridor segment for both GP and HOT lanes.
- Mean and median volumes by 5-minute interval for each ½-mile roadway segment.
- Means and median speeds by 5-minute interval for each ½-mile roadway segment.

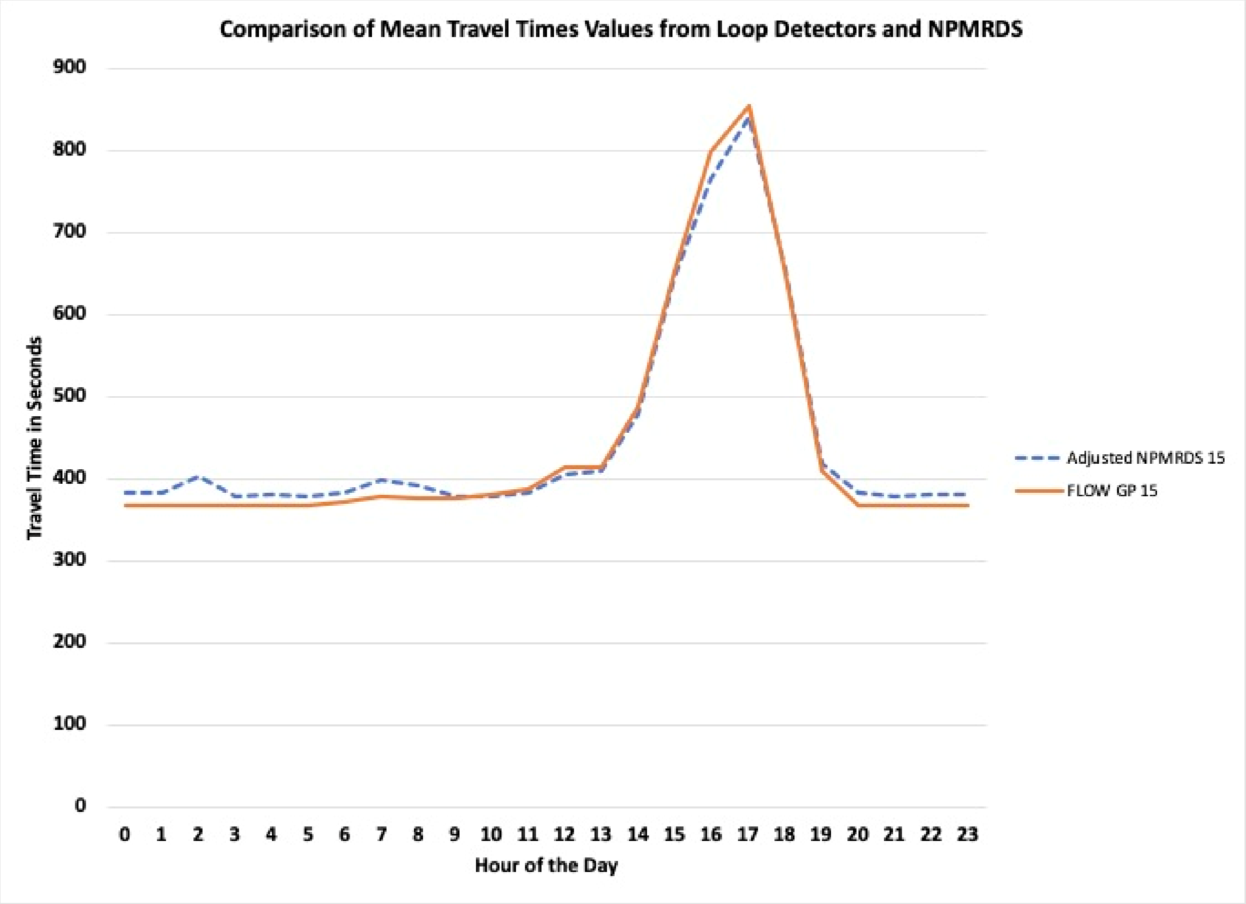
While the PM3 measures are reported at the 15-minute interval, the analysts used the 5-minute interval level to provide additional details on the performance of the corridor.

Models or analytical process used: The evaluation analysis used the WSDOT analytical software built to access and process the department's loop data archive. This analysis system computes roadway performance statistics for not just current conditions but also for any historical time period from 2010 to the present. (Data older than 2010 are available but not stored online.)

Data used: The analysis of potential improvements to I–405 and the analysis work performed to select and finalize the hard shoulder running system consisted of a variety of different technical models. All those models used the loop detector data that WDOT routinely collected.

While the NPMRDS data could have been used for the travel time and delay computations, this project used loop detector data because the TRACFLOW system formats the volume and speed data in similar ways, making it far easier to combine these datasets when performing several of the evaluation's analysis steps.

NPMRDS travel-time data were compared against the loop data to ensure that the two data sources would produce similar outcomes. To make this comparison, adjusting the NPMRDS travel times was necessary because the NPMRDS segmentation (based on the TMC segmentation system) is slightly different from the ½-mile segmentation used by WSDOT's loop database. The need to use the TMC segmentation resulted in a slightly longer NPMRDS travel analysis corridor (virtual trips) than used by the virtual trips defined by WSDOT's loop database used. Thus, to make the comparison between the two measurement systems, the assumption was that travel times were proportional to the length of the trip. Additionally, the analysts adjusted estimated NPMRDS travel times based on the ratio of the differences in trip length. Figure 17 shows an example of the relationship between these two measurement systems.



FLOW GP 15 = Loop Detectors.

Figure 17. Graph. Comparison of National Performance Management Research Data Set and loop detector travel times, 2016.

(Source: FHWA.)

As shown in figure 18, NPMRDS produces similar but slightly different travel time estimates than WSDOT's loop data. As a result of producing slightly different travel times and vehicle speeds, NPMRDS also produces slightly different estimates of PHED, simply because of the differences in segmentation used. In general, the NPMRDS segments are longer than the ½-mile segments that WSDOT's loop dataset used. Long segments can combine small slow-moving segments with small fast-moving segments to produce average values. If the small, slow segment experiences excessive delay, but the fast segment does not, the NPMRDS system could produce either more or less excessive delay, if its single long segment operates slowly enough to be defined as experiencing excessive delay. Thus, PHED calculations based on NPMRDS will be slightly different from those from the loop system, but it is not possible to know beforehand whether the calculations will be larger or smaller than the loop-based estimates, and in most cases, the differences between the two systems should be small.

For this evaluation, the WSDOT loop data have one additional major advantage over NPMRDS, which is that the WSDOT loop detectors can differentiate between travel in the HOT and GP lanes. That ability is not possible with NPMRDS. NPMRDS' vehicle-probe-based travel time estimates rely on the Global Positioning System (GPS) for vehicle location. GPS's position accuracy is not sufficiently precise to differentiate the lane in which a vehicle is traveling.

Consequently, for this evaluation, the project team chose to use WSDOT loop data. To supplement the loop detector performance and use data, the evaluation team also obtained data from WSDOT on all incidents occurring northbound on I–405 from 2014 through 2019. The following list shows the events included in the definition of *incidents*:

- Collisions.
- Disabled vehicles.
- Incidents.
- Maintenance.
- Other obstructions.
- Roadwork.
- Slow moving maintenance.

For each of these events, the team identified the location, the dates, and the starting and ending times of the event. (Note that for each event, the event "ends" when the last responder or construction and maintenance worker leaves the scene of that incident, collision, or activity, not when all congestion generated by that activity has dissipated.)

This project obtained hourly weather data from SeaTac airport. Weather data consisted of temperature, humidity, wind speed, rainfall during the last hour, and visibility. These were the best available data for the evaluation. The project team accepted that the actual weather experienced on the study corridor will be somewhat different from that observed at the airport, which is located 25 to 35 miles south of the study corridor.

Evaluation

Define geographic scope. The first task for the evaluation was to define the geographic extent of the study area. Because hard shoulder running implementation was for only northbound traffic, only northbound data were examined. If a control site was needed, the southbound direction could have been studied. A control site was not used to limit the cost of the evaluation.

The second aspect of the evaluation's geographic scope that had to be determined was the length of the corridor that needed to be included in the evaluation. I–405 is more than 30 miles long. The HOT lane runs for only the last 17 miles of the corridor, and the hard shoulder running is located only between mileposts 26.8 and 28.7.

The decision was to use a study corridor from approximately the onramps from SR 522 (milepost 23.9) to the northern end of I–405 at the I–5 interchange. South of SR 522, the roadway is wider

(3 GP and 2 HOT), and the lane drops at that interchange generate significant congestion south of SR 522. Although some additional operational improvements were made at the SR 522 interchange, the project team felt that starting just north of SR 522 enabled examination of congestion, which propagated back from the SR 527 interchange merge point.

Define analysis periods. The next task was to define the evaluation time periods. The original HOT lane configuration opened in September 2015. The hard shoulder running improvement was opened to traffic in April 2017. Consequently, the team decided that the "before" period (with "before" defined as the period before the implementation of the hard shoulder running, to measure the impacts of the hard shoulder running system) should consist of all of 2016. This year is the period when the HOT lane was in operation, and the construction of the electronic signs should have little effect on PM peak traffic. Use of the entire year for 2016 also limits seasonal effects and avoids the "break-in" period at the start of the initial HOT operations, as drivers adapted to using the HOT lane.

For the "after" period, the project team decided to use both years 2018 and 2019. The hard shoulder running system became operational before both those years.

When performing the analysis, the team used only weekday data because during the hard shoulder running operational period, the HOT lanes only operate during weekdays, and the hard shoulder running operation is only rarely used on weekends. Again, the team made this decision in part to reduce the effort required to evaluate the operational improvements realized from the use of the hard shoulder.

Define performance measures. The performance measures used for the evaluation are those described early in this chapter and include those stated in chapter 2. In general, the PM3 measures are used to provide summary statistics, which describe the overall outcomes experienced in the corridor's performance. However, more traditional and disaggregated performance measures provide a more detailed description of changing roadway performance. These more detailed outcomes are important for providing narratives that describe changing conditions to the public and elected officials.

Assemble data. To perform the evaluation, the team used the following steps to assemble the data:

- Roadway performance data were only obtained for northbound I–405.
- Travel times were obtained for all weekdays for the 4 years used in the analysis—2014, 2016, 2018, and 2019—with a new travel time computed every 5 minutes for each weekday of each year.
- Volumes and speeds were extracted for each ½-mile roadway segment.
- Incident and construction data (referred to hereafter as "incidents") were obtained for northbound I–405 (southbound incidents and, thus, the effects of rubbernecking were not included in the evaluation).
- Incidents were assigned to the analysis road segment that contained the location of the incident. For construction events, the construction event was assigned to all analysis road segments that contained any part of the construction event. Weather conditions were assigned to segments as well.

Naïve before and after comparison: The mean, median, and 80th and 95th percentile travel times for each reporting period were computed, which enabled computing the LOTTR values for each roadway segment and for the study corridor as a whole for each time period. For each segment, if any of the four time periods showed an LOTTR value greater than 1.5, that segment was flagged as being unreliable (table 21).

Table 21. I–405 level of travel time reliability values by roadway segment.

		Before Period (2016)					**After Period (2018)**				
Milepost	**Metric**	**AM**	**Midday**	**PM**	**Night**	**—**	**AM**	**Midday**	**PM**	**Night**	**—**
23.5	50th	30.0	30.0	30.0	30.0	—	30.0	30.0	30.0	30.0	—
	80th	30.0	30.0	107.8	30.0	—	30.0	30.0	70.0	30.0	—
	LOTTR	**1.00**	**1.00**	**3.59**	**1.00**	**Un**	**1.00**	**1.00**	**2.33**	**1.00**	**Un**
24	50th	30.0	30.0	30.3	30.0	—	30.0	30.0	30.0	30.0	—
	80th	30.0	30.0	73.8	30.0	—	30.0	30.0	32.9	30.0	—
	LOTTR	**1.00**	**1.00**	**2.44**	**1.00**	**Un**	**1.00**	**1.00**	**1.10**	**1.00**	**Rel**
24.5	50th	30.0	30.0	48.5	30.0	—	30.0	30.0	32.6	30.0	—
	80th	30.0	32.0	104	30.0	—	30.0	33.0	45.3	30.0	—
	LOTTR	**1.00**	**1.07**	**2.16**	**1.00**	**Un**	**1.00**	**1.10**	**1.39**	**1.00**	**Rel**
25	50th	30.0	30.0	57.9	30.0	—	30.0	30.0	30.0	30.0	—
	80th	30.0	30.0	119.2	30.0	—	30.0	30.0	48.0	30.0	—
	LOTTR	**1.00**	**1.00**	**2.06**	**1.00**	**Un**	**1.00**	**1.00**	**1.60**	**1.00**	**Un**
25.5	50th	30.0	30.0	68.2	30.0	—	30.0	30.0	30.0	30.0	—
	80th	30.0	30.0	109	30.0	—	30.0	30.0	51.9	30.0	—
	LOTTR	**1.00**	**1.00**	**1.61**	**1.00**	**Un**	**1.00**	**1.00**	**1.73**	**1.00**	**Un**

—No data, LOTTR = level of travel time reliability, Rel = reliable, Un = unreliable.

Compare conditions in before and after periods. The naïve analyses do not account for whether the measured changes are the result of different system operations or are the result of different exogenous factors. That is, are the improvements measured on I–405 occurring because the hard shoulder running allows the roadway to operate better under similar demand, weather, and incident conditions or because the after period had better weather, fewer incidents, and lower traffic volumes. As a result, the team calculated the same basic performance statistics by type of operating conditions. For this analysis, given the 1-year "before" time period, these conditions were left fairly general. Thus, the summary performance statistics were generated for wet versus dry conditions and for incident versus nonincident conditions. Including and excluding various types of incidents was possible. Therefore. examining roadway performance when crashes occurred was possible, versus when any type of incident occurred.

Summaries of the roadway's performance under these different operating environments were then computed to develop table 22 and table 23.

Table 22. I–405 corridor level of travel time reliability values for incident and nonincident conditions.

Time Period	80th Percentile Incident Travel Times (minutes)	50th Percentile Incident Travel Times (minutes)	Level of Travel Time Reliability (LOTTR) Incident Conditions	80th Percentile Nonincident Travel Times (minutes)	50th Percentile Nonincident Travel Times (minutes)	LOTTR Nonincident Conditions
2014	17.4	12.6	1.39	12.8	8.8	1.46
2016	17.3	12.5	1.38	15.5	12.1	1.27
2018	20.0	12.4	1.61	10.7	7.2	1.48

Table 23. I–405 corridor general purpose lane level of travel time reliability values for rain versus no rain conditions.

Time Period	80th Percentile Rain Travel Times (minutes)	50th Percentile Rain Travel Times (minutes)	Level of Travel Time Reliability (LOTTR) Rain (conditions)	80th Percentile No Rain Travel Times (minutes)	50th Percentile No Rain Travel Times (minutes)	LOTTR No Rain (conditions)
2014	13.7	9.0	1.52	12.8	8.9	1.45
2016	15.9	11.5	1.38	15.4	12.3	1.25
2018	10.1	7.0	1.61	10.9	7.3	1.48

For I–405, these types of tables showed that the changes observed in the naïve analysis correctly indicated that the hard shoulder running implementation rendered significant benefits and that the changes observed were not the result of changes in exogenous factors such as the number or type of incidents occurring on the corridor or changes in weather patterns.

BCA. TOPS-BC was used to estimate a B/C ratio of 5.53 for the hard shoulder running improvement.

The final analysis performed for the I–405 evaluation was to explore the "unexpected" outcomes detailed in reviews of the outcomes identified. For example, while congestion decreased in the section of the corridor that contained the hard shoulder running system as well as in the upstream segment, an increase in congestion occurred downstream of the hard shoulder running segment.

The ability to examine detailed segment-specific performance outcomes showed that the northernmost segments experienced a slight increase in peak period demand, largely due to the removal of the bottleneck at the SR 527 ramps. That modest increase in the arrival of vehicles caused a minor increase in delay in those segments, leading to the I–5 ramps.

Thus, the detailed performance measures available to WSDOT not only identified locations and causes for congestion formation leading to the selection and implementation of hard shoulder running, but the performance measures also were able to fully describe the resulting changes in corridor performance. The change was a significant, overall improvement; however, the change also created a modest bottleneck at the I–5 interchange due to better roadway performance upstream of I–5).

The other analytical outcome was the ability to describe why the LOTTR value for the corridor increased despite very large travel time improvements occurring in the corridor. The detailed travel time statistics showed that the routine (50th percentile) travel times improved even more than the 80th percentile travel times (4.9 minutes versus 4.3 minutes). This travel time improvement increased the LOTTR value, which is computed as the ratio of the 80th to 50th percentile travel time. So, while drivers on the road experienced significant travel time improvements, the reliability of the roadway—as measured by LOTTR—worsened, even though a "bad trip" (the 80th percentile travel time) was considerably faster in the "after" time period than in the before time period.

Therefore, the details of the roadway performance statistics provide a good narrative to be given about the outcome of the hard shoulder running, where any one performance statistic may give a skewed indication of performance—even when that statistical view of the outcome is correct. That is, in the case of I–405, the road is less reliable in terms of the PM3 measures, in that a bad trip is proportionately worse than a routine trip after implementing the hard shoulder running. By definition, the road is slightly less reliable. But in this case, that loss of reliability is an acceptable outcome given the overall improvements observed in roadway performance.

APPENDIX A. PERFORMANCE EFFECTS OF OPERATIONS STRATEGIES FROM PAST STUDIES

OVERVIEW

This section discusses the evaluation of specific operations strategies. A "specific operations strategy" is an individual deployment activity related to the overall strategy category: a "substrategy," in effect. For example, ramp metering and dynamic junction control are substrategies that fall under the F rubric.

BENEFITS, COSTS, AND CONTEXTS OF OPERATIONS STRATEGIES

The following information is based on an assessment of past evaluations maintained in the ITS Benefits Database.[36]

These data also are the source for the benefits and costs in TOPS-BC; an indication is made (e.g., Ref B-72) if a benefit or cost is the default value for TOPS-BC.

Active Transportation and Demand Management

Dynamic Lane Management

Objective

The goals are to preserve the capacity of roadway segments by identifying potential bottlenecks resulting from imbalances in lane use or planned lane closures to support work zone operations or unplanned events such as incidents, and to redistribute demand to maximize the use of the remaining capacity.

Strategy

Dynamic lane management involves deploying gantries and overhead lane control displays at ½- to ¼-mile-intervals, communications, and control systems. The system manages capacity by opening and closing lanes at a facility in response to real-time conditions. Traffic incidents may warrant closing certain lanes, whereas congested conditions may result in opening additional lanes (such as reversible or shoulder lanes) to traffic. When closures occur, dynamic lane management also provides a means of warning drivers ahead of the closure so that they may anticipate the merge ahead of the closure. Lane status is generally communicated to drivers by overhead or side-mounted signage.

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[36] https://www.itskrs.its.dot.gov/benefits.

Relevant Deployment Context

- Well suited for work zone traffic control.
- Typical sign spacings are $^{1}/_{3}$ to ½ mile apart.
- Lane closures ahead are first announced to drivers 1 mile in advance.

Range of Mobility Impacts From Past Evaluations

- Throughput increase of 3 to 7 percent. (Ref B-71)
- Capacity increase of 3 to 22 percent. (Ref B-71)
- Primary incidents decrease of 3 to 30 percent. (Ref B-71)
- Secondary incidents decrease of 40 to 50 percent. (Ref B-71)

Conditions Supporting Success

- Sufficient storage space to test signs before installation.
- Ability to close roadways to traffic during certain times of the day to facilitate overhead sign installation.
- Overdesigned sign gantries that can easily accommodate additional ITS devices.
- Effort to inform the public about the system and ways to interpret its signs before activating the system.
- Perpetual funding sources and mechanisms for operations and maintenance.

Generalized Deployment Costs

- Minnesota: $2.15 million per mile, on I–35W.
- Minnesota: $3.75 million per mile, on I–94.
- Washington State: $3.2 million per mile on I–5, $2.1 million per mile on SR 520, and $2.8 million per mile on I–90.

Evaluation in the Project Development Continuum

Evaluated at all levels of project development with existing methods and data; however, detailed lane-by-lane demand is required for detailed modeling.

Variable Speed Limits

Objective

Limit the shock waves caused by large speed differentials when queues are being formed.

Strategy

Variable speed limit (VSL) systems provide flexible speed limits for motorists to avoid sudden changes in speed due to congestion or roadway conditions. VSLs enable a road operator to post speed restrictions—regulatory or advisory, depending on local policy—based on real-time information that may not be available to the motorists or information such as congested conditions ahead—a major incident, a work zone, or a hazardous environmental condition (e.g., fog, icy road). This strategy gradually slows traffic down ahead of a congested area to reduce the occurrence of traffic collisions and attempts to set speed limits in the congested regions so that traffic continues to flow smoothly, rather than deteriorating to less efficient stop-and-go conditions. Most VSL programs use roadside or overhead signage to notify motorists. In the connected-vehicle environment, this information may be transmitted directly to the driver's onboard equipment. Speed harmonization is a type of VSL system used during congested periods to reduce the stop-and-go nature of congested traffic.

Relevant Deployment Conditions

- Locations with high congestion, large speed differentials, recurrent back of queues, and high crash rates are desirable to offset the high costs associated with the system.

- Locations with recurrent inclement weather—icy roads, snow, fog, or other visibility-impairing elements—which would benefit from motorists with reduced speeds, are desirable.

- Reliable line power should be available to the site of the sign or able to be installed at a cost-effective rate to ensure available operation.

- Right-of-way to install VSL signs or overhead sign gantries should be available.

- Reliable communications to the traffic operations center should be available.

- Closed-circuit television (CCTV) monitoring of the site should be present to track system performance and verify messaging.

- VSL signs should be placed at frequent intervals to help maintain motorists' awareness of the changed condition.

- The agency should adopt a policy for VSL activation.

Range of Mobility Effects From Past Evaluations

- Reduction in travel time of 20 percent. (Reference (Ref) B-59)
- Reduction in travel time of 17.6 percent. (Ref B-60)
- Reduction in travel tune of 2 to 7.6 percent(Ref B-31)
- Reduction in travel time of 28 to 32 percent. (Ref B-45)
- Reduction in travel time of 0 to 27.4 percent. (Ref B-65)
- Reduction in delay of 7.6 percent. (Ref B-46)
- Reduction in delay of 15 percent. (Ref B-61)
- Reduction in crashes of 7 percent (default for TOPS-BC). (Ref B-68)

- Reduction in crashes of 8 to 30 percent. (Ref B-62)
- Reduction in personal injury crashes of 55.7 percent. (Ref B-63)
- Reduction in crashes of 8 to 25 percent. (Ref B-64)
- Reduction in crashes of 4.5 to 8 percent. (Ref B-65)
- Reduction in crashes of 9 to 35 percent. (Ref B-66)
- Reduction in crashes of 18 percent. (Ref B-67)
- Reduction in fuel use of 5 to 16 percent. (Ref B-59)
- Reduction in fuel consumption of 12 to 17 percent. (Ref B-45)
- Reduction in fuel use of 6.3 percent. (Ref B-48)

Conditions Supporting Success

- The shoulder size must provide sufficient space to permit enforcement officers (if used) to pull over violators.

- Outreach to the judicial system regarding the legal aspects of VSL can strengthen enforcement efforts.

- Public outreach could help to familiarize people with the goals and benefits of the system.

- Due to potential driver confusion regarding signage, VSL should be deployed with caution when a dynamic lane management system is in place.

- An accompanying queue warning system can contribute to the success of a VSL deployment by justifying the speed limits to drivers.

Generalized Deployment Costs

- Virginia Department of Transportation: $3.2 million VSL system (hardware, software, training, and operational support included) for 2 years on a 7.5-mile section (2008 dollar). (Ref C-29)

- Utah DOT (UDOT): $173 to $329 (per day) equipment rental cost for portable VSL system (2018 dollar). (Ref C-30)

- Washington State: $3.2 million per mile on a three-lane section. (Ref C-22)

- Washington State: $4 million per mile on a five-lane section. (Ref C-22)

- Germany: $1.2 million to $1.7 million per mile. (Ref C-22)

- United Kingdom: $18 million per mile. (Ref C-22)

- Michigan: $67,000 per mile for a portable system. (Ref C-22)

- Virginia: $425,000 per mile. (Ref C-22)

- Oregon: $560,000 per mile. (Ref C-22)
- Seattle: $3.6 million per mile on I–5. (Ref C-22)
- Minnesota: $2.15 million per mile on I–35W. (Ref C-22)
- Wyoming: $28,000 per mile. (Ref C-22)

Evaluation in the Project Development Continuum

The continuum may be capable of being evaluated at all levels of project development, but only microscopic simulation can capture the complex interaction of vehicles and driver behavior that characterize VSL.

Queue Warning System

Objective

Avoid rapid deceleration and potential crashes of vehicles entering the back of a forming queue.

Strategy

The queue warning systems' basic principle is to inform travelers of the presence of downstream stop-and-go traffic (based on real-time traffic detection), using warning signs and flashing lights. By anticipating an upcoming situation of emergency braking and slowing down, drivers can avoid erratic behavior and reduce queuing-related collisions. DMSs show a symbol or word when stop-and-go traffic is near. VSLs and lane control signals that provide incident management capabilities can be combined with queue warning. The system can be automated or controlled by a traffic management center operator.

Relevant Deployment Conditions

- Frequently congested freeways or roads.
- Facilities with frequent queues in predictable locations.
- Facilities with sight distance restricted by vertical grades, horizontal curves, or poor illumination.
- Power must be available to site or able to be installed at cost effective rate.
- Right-of-way to install both or either queue warning system signs and overhead sign gantries must be available.
- Communications to transit-oriented communities (TOC) must be available.
- CCTV monitoring of the site should be present to monitor system performance.

- Signs should be placed to contain end of queuing fully at site.

- Sensors to support queue warning system operation must be installed at close spacings. Sensors should be located before and after ramp entrances.

Range of Researched Benefits

- 44-percent reduction in crashes. (Ref B-34).
- 22-percent reduction in crashes, 54-percent reduction in near misses. (Ref B-35).
- 18-percent to 45-percent reduction in crashes. (Ref B-36).
- 14-percent reduction in crashes (work zones). (Ref B-37).

Conditions Supporting Success

- Locations with high rates of secondary crashes, recurring congestion and queuing, and limited sight distances.

- Public outreach to familiarize the public with the goals and benefits of the system.

- Lane control signals upstream of lane blockages.

- Frequent analysis (e.g., once per minute) of speed and occupancy data for improved system responsiveness.

- Different types of warnings activated, depending on the severity of the congestion ahead.

- Work zones also benefit from queue warning with portable dynamic message sign units placed upstream of expected queue points.

Generalized Deployment Costs

- Finland: $30 million. (Ref C-22)
- Scotland: $630,000. (Ref C-22)
- Virginia: $25,000 at two weigh stations. (Ref C-22)
- West Virginia: $85,000 for fog warnings. (Ref C-22)
- Minnesota: $15 million, or $3.75 million per mile, on I-94. (Ref C-22)
- Florida: $26 million for a mobile warning system. (Ref C-22)
- California: $2.5 million for reduced visibility warnings. (Ref C-22)

Evaluation in the Project Development Continuum

The main impact is on crashes so only methods that account for the effect of reduced incidents on mobility can be used for evaluation. Current methodologies, including microscopic simulation, do not have the capability of directly evaluating queue warning.

Ramp Metering (Adaptive)

Objective

Control the number of merging vehicles at freeway on-ramp junctions in order to avoid flow breakdown due to overcapacity conditions.

Strategy

Ramp metering is a strategy that regulates the flow of on-ramp traffic entering the freeway with a goal of maintaining the freeway flow at or below capacity. This strategy also reduces congestion by helping break up platoons of vehicles that are entering the freeway from an onramp, typically at ramps that are served by an upstream traffic signal. Ramp metering systems generally operate only during periods of congestion, typically during peak periods, and manage traffic through a dynamic release rate (e.g., a rate determined by the traffic state on the freeway).

Relevant Deployment Conditions

- High volume onramps that serve freeways with frequent congestion, either recurrent or nonrecurrent.
- High volume onramps that serve freeways with a known downstream bottleneck.
- Onramps with sufficient length to permit queue storage behind the ramp meter (based on ramp traffic demand and the metering rate).
- Onramps with sufficient acceleration length to permit vehicles to accelerate from a stopped position at the ramp meter to freeway speeds at the merge point.
- Detection facilities (e.g., downstream and upstream mainline detectors, ramp detectors) to provide the necessary inputs to the algorithm used.
- Onramps that have access to ITS network communications architecture.

Range of Mobility Impacts From Past Evaluations

- 14-percent increase in throughput. (Ref B-47)
- 10-percent increase in capacity (default for TOPS-BC). (Ref B-68)
- 5-percent to 8-percent increase in speeds. (Ref B-47)
- 48-percent decrease in travel times. (Ref B-47)
- 0-percent to 18-percent decrease in delay. (Ref B-47)
- 25-percent reduction in delay. (Ref B-39)
- 1-percent to 4-percent reduction in travel times. (Ref B-40)
- 12-percent reduction in crashes (default for TOPS-BC). (Ref B-68)
- 26-percent to 39-percent decrease in primary incidents. (Ref B-47)
- 22-percent reduction in crashes. (Ref B-39)
- 64-percent reduction in crashes. (Ref B-40)

Conditions Supporting Success

- Public outreach to familiarize the public with the goals and benefits of the system.
- Sufficient ITS infrastructure to allow real-time monitoring and operation.
- Predictive traffic systems that can forecast future freeway demands.
- Sufficient ramp sensor infrastructure to avoid queue spillback when conditions are detected.
- Frequent analysis (e.g., once per 30 seconds) of freeway and on-ramp travel conditions to assess a proper metering rate.
- Coordination of meter timing with cities that have connecting arterials.
- Enforcement plans with the Highway Patrol.

Generalized Deployment Costs

- Kansas DOT: $30,000 per adaptive ramp metering system that includes a roadside warning beacon and a stop bar used to trigger the ramp meter signal (2009 dollar). (Ref C-23)
- TOPS-BC: $50,770 per ramp location, including signal, controller, detection, and communications. (Ref C-46)
- Arizona DOT: $4,300 per ramp meter signal and support assembly (2009 dollar). (Ref C-24)
- Arizona DOT: $7,978.63 per control cabinet (Type 341A)—ramp meter (2009 dollar). (Ref C-25)

Evaluation in the Project Development Continuum

For forecasting methodologies, changing the capacity inputs typically used rather than adjusting the delay output as the impact is modeled directly. Other methods that account for the effect of reduced incidents on mobility also can be used for evaluation (not covered in this report).

Dynamic Lane Control

Objective

Increase merging capacity at key freeway interchanges.

Strategy

Dynamic lane control updates the lane configuration at a ramp merge or diverge throughout the day to best accommodate the current traffic demands. When entrance volumes are high and mainline volumes are not, a dynamic junction control system may close the shoulder lane of the freeway upstream of the merge point to accommodate a higher volume of traffic from the entrance ramp. Alternatively, when exiting volumes are particularly high at a junction, the system may reallocate one of the through lanes as an exit lane to accommodate the excessive demand.

Relevant Deployment Conditions

- Locations with recurrent congestion and persistent queues due to high volumes of merging traffic.

- High crash rates, with particular prevalence of rear-end collisions upstream of the ramp merge and side-swipe collisions in the merge area.

- High ramp flows that warrant additional lanes for the entrance at times.

- Locations where two major entrances and ramps merge together.

In-pavement lighting and electronic signage may be used to direct traffic and provide dynamic lane assignments. In-pavement lighting will need to be designed in cooperation with maintenance crews in areas of winter snowfall to ensure plowing does not damage the equipment.

Range of Mobility Impacts From Past Evaluations

- 4-percent decrease in mainline delays. (Ref B-86)
- 13-percent decrease in ramp delays. (Ref B-86)
- 4-percent decrease in mainline travel times, 13-percent on ramps. (Ref B-47)
- 7-percent decrease in mainline travel times. (Ref B-86)
- 8-percent decrease in mainline travel times. (Ref B-86)

Conditions Supporting Success

- If deployed alongside hard shoulder running, ramp tapers may need to be reduced at exits to improve dynamic junction control operation.

- Lane control signals above all lanes can facilitate traffic control at the junction.

- CCTV cameras can be a valuable resource for monitoring conditions at the junction during dynamic allocation of lanes.

- Wide shoulders in the vicinity of the junction provides additional flexibility for other supporting strategies (e.g., hard shoulder running) at the junction in the future.

- Predictive traffic systems that can forecast future freeway and entrance ramp demands.

- Coordination of ramp control with cities that have connecting arterials.

- Public outreach on the goals and benefits of the system.

- Surveillance equipment and communication links from the transportation management center to the field controllers make it possible for engineers to override the dynamically specified lane assignments if needed.

Generalized Deployment Costs

No data available.

Evaluation in the Project Development Continuum

Based on past evaluations, adjusting the delay output to forecasting methods is the preferred approach.

Dynamic Pricing

Objective

To manage limited supply during periods of high demand.

Strategy

Dynamic pricing involves using tolls to manage limited supply during periods of high demand. Prices are set to maintain a prescribed level of performance on the facility, such as a minimum acceptable speed. Provisions are sometimes established that allow HOV and transit vehicles to receive discounted toll rates. This strategy has historically been called “congestion pricing.”

Relevant Deployment Conditions

- Detection equipment must be present to provide the necessary inputs to the algorithm used.

- Cameras are an essential complement to tags and GPS units to gain a record of the identity of vehicles and can be used to deter toll violators.

- Tolled lanes often involve a repurposing of an existing HOV lane for solo vehicle use with an associated fee. In other cases, the entire roadway may be subject to a variable toll that depends on the current level of demand.

- On managed priced facilities, tolls can be adjusted in response to prevailing demand, and also may vary as a function of distance traveled.

Range of Mobility Impacts From Past Evaluations

- 9-percent to 33-percent increase in peak period throughput.
- 9-percent to 33-percent increase in peak period throughput. (Ref B-75)
- 3-percent to 19-percent increase in speeds. (Ref B-76)
- At least 25-percent decrease in travel times. (Ref B-73)
- 5-percent increase in transit ridership. (Ref B-74)

- 9-percent increase in transit on-time performance. (Ref B-74)
- 17-percent decrease in collisions. (Ref B-76)
- 5.3-percent reduction in crashes. (Ref B-77)

Conditions Supporting Success

- Electronic toll systems enable smooth toll collection and traffic flow on priced facilities.
- Enforcement plans with the highway patrol.

Generalized Deployment Costs

- Minnesota DOT: $6 million to $23 million per mile for dynamic pricing on freeway shoulder lanes (2010 dollar). (Ref C-41)

- Orange County, CA: $134 million for 10-mile-long express lanes toll facility (approximately $13.4 million per mile) (mid-1990s dollar). (Ref C-42)

- Georgia: $20.8 million to $23.7 million for 26 miles of HOV to HOT conversion (approximately $0.9 million per mile) (2005 dollar). (Ref C-42)

- Washington: $17 million to convert HOV lanes to HOT lanes (approximately $1.9 million per mile) (2004 to 2008). (Ref C-42)

- Minnesota DOT: $13 million to convert HOV lanes to HOT lanes (approximately $2.5 million per mile) (2005). (Ref C-42)

Evaluation in the Project Development Continuum

Past evaluation efforts have focused on changes in outcomes, but being able to predict demand shifts as input to forecasting methods is preferable.

Predictive Traveler Information/Dynamic Message Sign

Objective

To alert travelers to congestion so that they can divert their planned route or delay their trip.

Strategy

Traveler information systems generate travel time estimates based on the predicted (as opposed to the recently observed) performance of the system, which uses models, expected incident clearance times, schedules of regional special events, and other methods and information to generate the predictions. The resultant travel time estimates, therefore, are expected to be more reliable and accurate than those based on past data, particularly if conditions are changing quickly over time. In this case, DMS provide travel time guidance to various destinations. DMS utilizes a static sign with a variable matrix to publish the travel time to a destination in minutes. By providing travel times to motorists, they can make informed decisions on whether the route's trip time is acceptable for their needs or if they should use an alternate route.

Relevant Deployment Conditions

- Corridors that experience frequent nonrecurrent congestion or high travel time variability.
- Corridors that experience inclement weather conditions or high weather-related crashes.
- Corridors that serve as key routes for special events that impact traffic operations.
- Predictive information can be useful on corridors where drivers have viable travel alternatives since the predictions may influence their choices.
- Signage placement is effective if the sign location precedes decision points for travelers.
- Information may be disseminated through DMSs or through other information systems (e.g., 511).

Range of Potential Benefits

- 9.8 minutes of delay reduced, on average, with 3.7 percent-divergence. (Ref B-1)
- 4-minute time savings for those diverting (default for TOPS-BC). (Ref B-68)
- 5-percent to 13-percent increase in on-time performance. (Ref B-69)

Conditions Supporting Success

- Corridors instrumented with sufficient ITSs to generate accurate travel time.
- Connection between the system and the transportation management center (TMC), as opposed to an isolated field system.
- Presence of alternate routes.
- Coordination with local agencies that manage the alternate routes (such as cities or counties) to help foster regional collaboration for traffic management.
- Trip planning benefit—predicted travel time information distributed through existing systems accessible from other locations (e.g., 511, the Internet).

Generalized Deployment Costs

- California DOT (Caltrans): $200,000 large DMS display support structure includes purchase and installation (2018 dollar). (Ref C-8)
- Caltrans: $100,000 per unit for large DMS includes purchase and installation of sign on existing mounting structure (2018 dollar). (Ref C-9)
- United States DOT (USDOT): $108,500 per unit for large DMS includes purchase and installation (2016 dollar). (Ref C-10)

- NCDOT: $330,000 per DMS installation (2004 dollar). (Ref C-11)

- Greenville, SC: $185,300 cost per DMS with structure, equipment only (2010 dollar). (Ref C-12)

- New Hampshire DOT: $223,000 cost per DMS. Includes installation, power runs (ditching), back up for 4 hours, microwave communication equipment (canopy), equipment cabinets, all necessary equipment, device testing, connection to network management system, and subsystem integration testing (2010 dollar). (Ref C13)

Evaluation in the Project Development Continuum

Strategies involving traveler response to traveler information have been difficult to evaluate, mainly because of the difficulty in isolating the treatment effect using empirical field data. Many studies have relied on stated-preference surveys to estimate the effect.

Dynamic Wayfinding

Objective

To direct highway travelers to available parking spots to reduce unnecessary travel.

Strategy

Dynamic wayfinding is the practice of providing real-time, parking-related information based on space availability and location to optimize the use of parking facilities and minimize time spent searching for available parking. In an ATDM approach, parking availability is monitored continuously and routed to the user.

Relevant Deployment Context

- Land use business districts where both or either demand for parking exceeds supply and have high instances of double parking.

- Demand for parking is high throughout much of an area’s onstreet parking facilities.

- Locations with high parking demand and a high proportion of unfamiliar drivers (e.g., airports, special events, CBDs, etc.).

Range of Mobility Impacts From Past Evaluations

- 9-percent reduction in travel times. (Ref B-108)
- 5-percent to 10-percent reduction in cruising time. (Ref B-109)
- 10-percent decrease in intersection vehicle delays for special events. (Ref B-110)
- 43-percent decrease in parking-spot search time. (Ref B-111)
- 25-percent reduction in traffic volumes related to parking space searches. (Ref B-112)

Conditions Supporting Success

- Support technology such as communications, space counter and detection, etc.
- Support incentives for parking cash-out, discounted and free transit, carpool and vanpool, etc.
- Public outreach, education, and marketing.
- Establish pricing policies that respond to changing conditions and demands.
- Support valet parking programs.

Generalized Deployment Costs

Advanced parking management systems cost between $250 and $800 per space (2007 dollar).

Evaluation in the Project Development Continuum

This strategy is highly specialized. It applies only to unique circumstances such as parking searches and special events. It is, therefore, difficult to evaluate using forecasting methods that deal with average or typical conditions. It also is difficult to isolate the strategy's effect from confounding factors in empirical-based evaluations.

Arterial Management: Traffic Signal System Operation

Objectives

Traffic signal systems—which support safety, operations and organizational objectives that are selected on the basis of user mix and traffic demand contexts——include the following core objectives:

- Assign safe rights-of-way.
- Provide for the safety, comfort, and convenience of pedestrians and bicycles.
- Distribute the green time equitably to service the needs of all intersection users.
- Maintain smooth traffic flow at intersections and on arterial networks.
- Maximize the throughput of users at intersections and along arterial streets.
- Manage the location and formation of queues during high demand periods.

Strategy

Traffic signal systems involve investing in systems and technology to provide intersection control, detection, communication, and system and advance control. These systems are integrated to support the monitoring, maintenance, evaluation, and management of signal timing. This integration typically involves manual, fully, or semiautomated methods to evaluate and update signal timing parameters such as cycle, splits, and offsets based on traffic demand locally at one intersection or along a corridor of intersections. The mobility improvements tend to scale with the level of variance that exists between the old and new timing plans. Older timing plans were set to accommodate traffic volumes that could be very different from the current traffic volumes.

Relevant Deployment Context

- Traffic signals that have timing plans that are more than a few years old.
- Traffic signals in areas that have experienced indirect changes to traffic operations (e.g., land use changes, roadway construction, etc.).

Range of Mobility Impacts From Past Evaluations

- 8-percent increase in capacity (default for TOPS-BC). (Ref B-68)
- 7-percent to 25-percent travel-time improvement. (Ref B-50)
- 7.4-percent reduction in travel time. (Ref B-51)
- 23-percent reduction in delay. (Ref B-52)
- 5-percent to 20-percent reduction in travel times. (Ref B-53)
- 2-percent reduction in crash rate. (default for TOPS-BC). (Ref B-68)
- 31-percent reduction in accidents. (Ref B-50)
- 5-percent reduction in fuel use. (default for TOPS-BC). (Ref B-68)
- 2-percent to 9-percent fuel reduction. (Ref B-50)
- 10-percent to 15-percent fuel savings. (Ref B-53)
- 7.8-percent reduction in fuel costs. (Ref B-51)

Conditions Supporting Success

- Retiming efforts are done with representative traffic volumes or forecasts that align closely with reality.

- Retiming efforts consider adjacent traffic signals and evaluate whether the corridor benefits from adjusting their timing.

- Retiming efforts utilize or upgrade existing infrastructure, such as detection or flashing-yellow arrows (where allowed).

Generalized Deployment Costs

- National: Costs to update signal timing range from $2,500 to $3,100 per signal per update (2005 dollar). (Ref C-34)

- California: The average cost to retime signals under the Metropolitan Transportation Commission (California) program is $2,400 per intersection (2006 dollar). (Ref C-35)

- National Transportation Operations Coalition: $3,000 per signal. Signal retiming interval occurs every 3 to 5 years (2007 dollar). (Ref C-36)

Evaluation in the Project Development Continuum

Evaluation of the project should be possible at each stage of the project development continuum with existing methods and data. For the operations and management phase, the high-resolution data from advanced signal control systems make it possible to adjust signal timing and progression factors based on demand patterns.

Adaptive Signal Control

Objective

Support equitable distribution and smooth traffic flow across a range of highly variable traffic conditions.

Strategy

Arterial signal control involves the deployment of traffic data collection and analysis modules to evaluate traffic performance and update signal timing at individual signalized intersections, corridors, or networks of arterials so that timing parameters are based on current traffic conditions. The splits, offsets, and cycle lengths are incrementally adjusted over time to best suit the evolving needs of the individual approaches and intersections throughout the day. These systems can respond reactively to atypical traffic conditions (e.g., high demands caused by special events), or proactively to anticipated recurrent congestion based on historical data.

Relevant Deployment Context

Signalized arterials that experience highly variable or unpredictable traffic demand.

Range of Mobility Impacts From Past Evaluations

- 10-percent increase in capacity (default for TOPS-BC). (Ref B-68)
- 13-percent decrease in travel time. (Ref B-79)
- 10-percent decrease in travel time. (Ref B-81)
- 2-percent to 36-percent decrease in travel times. (Ref B-82)
- 39-percent decrease in travel time. (Ref B-83)
- Up to 29-percent decrease in travel time. (Ref B-84)
- Up to 38-percent reduction in delay. (Ref B-84)
- 21-percent decrease in delay. (Ref B-79)
- 5-percent to 42-percent decrease in delay. (Ref B-78)
- 19-percent to 44-percent decrease in delay. (Ref B-80)
- 10-percent to 41-percent decrease in number of stops. (Ref B-78)
- 31-percent decrease in stops. (Ref B-79)
- Up to 55-percent reduction in stops. (Ref B-84)
- 2-percent reduction in crash rate (default for TOPS-BC). (Ref B-68)
- 28.84-percent reduction in crash rate. (Ref B-85)
- 5-percent reduction in fuel use (default for TOPS-BC). (Ref B-68)

Conditions Supporting Success

- Engineers in a central office can manually adjust intersection timing plans (using CCTV and communication links to the field hardware) to alleviate trouble spots that the adaptive system is not handling optimally.
- Splits, offsets, and cycle lengths are the commonly adjusted parameters for an adaptive system. Constraining one or more of these parameters may limit the adaptability of the system.

Generalized Deployment Costs

- National: Average installation cost per intersection of an adaptive traffic control system is $65,000 (2010 dollar). (Ref C-43)
- Pennsylvania: Capital cost to implement adaptive signal control at 45 intersections was estimated at $3 million ($67,000 per intersection) (2014 dollar). (Ref C-44)
- National: Average cost to implement adaptive signal control technology is $28,725 per intersection (2013 dollar). (Ref C-45)

Evaluation in the Project Development Continuum

Evaluation of the project should be possible at each stage of the project development continuum with existing methods and data. For the operations and management phase, the high-resolution data from advanced signal control systems make changing signal timing and progression factors based on demand patterns possible.

Transit Signal Priority

Objective

To reduce transit bus delays and running time.

Strategy

Transit signal priority gives priority to the vehicle by extending the green phase until the vehicle passes through the intersection or by reducing the duration of the red phase if it already is active. As the overall objective is to minimize person-hours of delay, these systems may give more or less priority to a transit vehicle based on the vehicle's current schedule adherence and occupancy.

Relevant Deployment Context

- Transit routes where buses experience delay due to traffic signals.
- Areas interested in improving transit travel times and reliability, increasing the attractiveness of transit as an alternative to single-occupant vehicle travel.

Range of Potential Benefits

- 1.5-percent to 15-percent decrease in travel time. (Ref-78)
- 8-percent to 12-percent decrease in travel times. (Ref B-100)
- 6-percent to 27-percent decrease in bus travel times. (Ref B-103)
- 15-percent to 20-percent decrease in bus travel times. (Ref B-101)
- 35-percent decrease in bus travel time variability. (Ref B-103)
- 19-percent reduction in travel time variability. (Ref B-99)
- 29-percent and 59-percent improvement in bus travel time variability during AM and PM peak periods, respectively. (Ref B-102)
- 15-percent to 80-percent decrease in delay at intersections. (Ref B-100)
- 2-percent to 3-percent decrease in fuel consumption. (Ref B-78)

Conditions Supporting Success

- Project champion, early stakeholder involvement (planning, engineering, and operations) and communications.

- The efficacy of a transit signal priority program is a function of traffic congestion, current ontime performance, and route demand.

Generalized Deployment Costs

- Nationwide: $2,500 to $40,000 per intersection and $50 to $2,500 per vehicle, depending on the type of equipment used (2010). (Ref C-53)

- Minnesota: $2.1 million. (Ref C-53)

Evaluation in the Project Development Continuum

The effects accrue almost exclusively to bus performance, so special modeling considerations are needed for the forecasting-based stages of the continuum. For empirical-based evaluations, detailed bus performance data such as automatic vehicle identification are essential.

Congestion Pricing

Zone-Based Pricing

Objective

To reduce travel within highly congested areas by increasing the cost of travel.

Strategy

The actions put in place by zone-based pricing include cordon and area pricing and involve paying either variable or fixed charges to drive within or into a congested area within a city. Because this type of project involves placing new tolls on multiple existing free roads, it can be politically challenging to implement. Pricing can vary according to vehicle type (e.g., private or commercial vehicles, cars or trucks) and by time of day (e.g., depending on traffic conditions). Typically, tolling equipment is placed on all roads leading into and out of a cordon zone.

Relevant Deployment Conditions

- Zones or areas with excessive congestion.
- Detection equipment must be present to provide the necessary inputs to the algorithm used.
- Cameras are an essential complement to tags and GPS units to create a record of the identity of vehicles and can be used to deter toll violators.
- Tolls can be adjusted in response to prevailing demand.

Range of Potential Benefits

- 13-percent to 22-percent reduction in traffic. (Ref B-87)
- 14.4-percent reduction in traffic. (Ref B-90)
- 22-percent increase in vehicle speed. (Ref B-87)
- 10-percent to 15-percent increase in travel speed. (Ref B-88)
- 30-percent reduction in delay. (Ref B-87)
- 9-percent increase in transit ridership. (Ref B-87)
- 2-percent increase in transit ridership. (Ref B-88)
- 20-percent increase in transit ridership. (Ref B-89)
- 5-percent to 10-percent reduction in accidents involving injuries. (Ref B-87)
- 15-percent reduction in air pollution and particulates. (Ref B-90)

Conditions Supporting Success

- Improved public transit can be financed through the cordon and area tolls.
- Considerations for discounts for residents, low income, disabilities, etc.
- Enforcement plans with the local agencies.

Generalized Deployment Costs

- London, England; Milan, Italy; Oslo, Norway; and Stockholm, Sweden: Operating costs for cordon pricing in European cities ranged from \$9.2 million to \$238.5 million (2003–2008). (Ref C-48)

- Singapore: \$125 million in-vehicle technology an installation cost plus \$10 million annually in operating costs. (2007). (Ref C-50)

- Chicago, IL: Estimated \$300 million upfront capital cost plus \$100 million annually in operating costs (2012). (Ref C-49)

Evaluation in the Project Development Continuum

The mechanism for improving performance is the reduction of and shifts in demand, so forecasting-based procedures could benefit from addressing demand changes.

Parking Pricing

Objective

To reduce travel within highly congested areas by increasing the cost of parking.

Strategy

Parking pricing encompasses parking policies that rely on market forces to influence the decision to drive and park:

- Variable pricing of curbside parking
- Commuter parking taxes
- Cash-out programs that require employers to provide their employees the option to take the value of free or subsidized employee parking in cash in lieu of using the parking space provided by the employer.

Relevant Deployment Conditions

- Business districts where demand for parking exceeds supply or there are high instances of double parking.
- Demand for parking is high throughout much of an area's onstreet parking facilities.
- In areas that want to encourage use of alternate transportation modes to reduce traffic congestion and energy consumption.

Range of Mobility Effects From Past Evaluations

- 25 to 34 percent fewer vehicles would be driven to work when employees are charged for parking (rather than free). (Ref B-97)
- 17-percent decrease in single-occupancy drivers after the cash-out program. (Ref B-97)
- 64-percent increase in carpooling, transit ridership increase of 50 percent, and 33 percent walk or bike mode share increase from cash-out program. (Ref B-97)
- 17-percent reduction in auto mode share; public transport up 27 percent. (Ref B-98)
- 10-percent increase in parking fees reduces vehicle trips by 1 to 3 percent. (Ref B-98)
- 18 percent more vehicles were able to find legal metered spaces. (Ref B-96)

- 7-percent decrease in traffic volumes. (Ref B-96)

Conditions Supporting Success

- Implement wayfinding to direct motorists to available off-street parking.
- Support incentives for parking cash-out, discounted and free transit, carpool and vanpool, etc.
- Conduct extensive public outreach, education, and marketing.
- Establish pricing policies that respond to changing conditions and demands.
- Support valet parking programs.
- Collaborate with the local law and parking enforcement on enforcement plans.

Generalized Deployment Costs

London: Annual operating costs for a parking pricing system in central London averaged $77 million. (Ref C-52)

Evaluation in the Project Development Continuum

This strategy is highly specialized, so only forecasting-based methods that deal with the policies above can be used. For empirical-based evaluations focused on outcome measures, confounding factors make it difficult to isolate the strategy's effect.

Integrated Corridor Management

Objective

To apply a holistic approach to managing congestion in corridors by combining multiple operations strategies to balance highway demand and supply.

Strategy

The proactive use of managed lane strategies, alternate routing of traffic, and proactively managing and controlling traffic within freeway corridors offer are a few useful approaches to ICM. These strategies have the potential to achieve significantly greater levels of utilization of the existing roadway capacity, improved travel times, enhanced safety, and reliability of travel.

Relevant Deployment Conditions

- Corridors with significant congestion and unreliable travel times.
- Corridors with appropriate infrastructure in place to support ICM, such as parallel freeways and arterials, and additional transit options for alternative travel.
- Ability to connect in a multimodal fashion both through technology and open communication. This means that the different transit organizations and transportation agencies such as bus transit, rail transit, HOV lane management, etc., must be able to communicate with one another.
- A localized TMC is critical for housing all communication and traffic data in one centralized location.

Range of Mobility Impacts From Past Evaluations

- 14-percent to 38-percent potential increase in person throughput. (Ref B-93)
- 42-percent reduction in the average number of stops. (Ref B-94)
- 9-percent increase in average speeds. (Ref B-94)
- 48-percent to 58-percent potential reduction in average travel times. (Ref B-93)
- 9-percent reduction in travel times on arterials. (Ref B-95)
- 3.3-percent reduction in delay. (Ref B-92)
- 26-percent reduction in average delay. (Ref B-94)
- 10.6-percent improvement in travel time reliability. (Ref B-91)
- 3-percent improvement in travel time reliability. (Ref B-91)
- 4-percent improvement in travel time reliability. (Ref B-91)
- 33-percent to 34-percent potential reduction in fuel consumption. (Ref B-93)

Conditions Supporting Success

- ITS experts need to be involved in the integration process to ensure it is designed, developed, deployed, and operated effectively.
- Interagency and institutional support, coordination, and strong leadership are critical to keep aspects of the project organized and on track.
- Public outreach could be beneficial to familiarize the public with the goals and benefits of the system and to help them make more informed travel choices. A dedicated public-facing website of the corridor information is recommended.

Generalized Deployment Costs

- Dallas, TX: $13.6 million with annualized costs of $1.62 million per year for 10 years. (Ref C-51)

- San Diego, CA: $12 million with annualized costs of $1.42 million per year for 10 years. (Ref C-51)
- Minneapolis, MN: $3.96 million. (Ref C-51)
- San Francisco, CA: $7.5 million average annual capital and operations and maintenance (O&M) costs. (Ref C-51)

Evaluation in the Project Development Continuum

Forecasting-based evaluation methods that account for both supply and demand changes as the most effective. Given that ICM incorporates multiple strategies, the evaluation framework for each one must be followed.

Freeway Management

Hard Shoulder Running

Objective

To take advantage of the additional roadway space occupied by the shoulder as a means of increasing the facility's capacity.

Strategy

Hard shoulder running is known as temporary shoulder use. Hard shoulder running is often invoked to address capacity constraints that arise as a result of incidents or other unusual circumstances during nonpeak periods. Furthermore, hard shoulder running is used during congested periods to alleviate the duration and severity of recurrent congestion. In some cases, access to the shoulder may be limited to only a subset of vehicles, such as transit buses or carpools.

Relevant Deployment Conditions

- Sufficient right-of-way must be available to accommodate shoulder travel throughout section.
- Roadside should be reviewed to determine if additional guardrail or barrier needs to be installed if travel is permitted on shoulder.
- Shoulders should be as wide as a travel lane to facilitate movements when lane is open to travel.
- Shoulder pavement depth should be sufficient to handle projected traffic on lane.
- Shoulder should have no adverse superelevation.

- Methods to accommodate shoulder travel through interchanges safely should be developed and provided.
- Power must be available to site or able to be installed at a cost-effective rate.
- Right-of-way to install overhead sign gantries must be available so lane control signs can be installed, if deploying an actively managed facility.
- Communications to TOC must be available.
- CCTV monitoring of site should be present to monitor system performance and incidents.
- Lane control sign gantries should be placed so that at least one is visible at all times.
- Sensors should be installed on the shoulder at close spacings (e.g., every 100 m) to detect disabled vehicles.
- Upgrades to allow shoulder to handle vehicular traffic should not compromise drainage of road.

Range of Researched Benefits

- 10-percent to 25-percent travel time-reduction. (Ref B-30)
- 22-percent reduction in variability of travel time. (Ref B-30)
- 58-percent reduction in personal injury accidents. (Ref B-30)
- 5-percent to 55-percent reduction in crashes. (Ref B-47)
- 4-percent reduction in fuel use. (Ref B-30)

Conditions Supporting Success

- Where hard shoulder running begins or terminates at a ramp junction, junction control is often required to maintain lane continuity and safe operations.
- For improved safety, a VSL system should be used to slow freeway traffic down when hard shoulder running is active.
- Public outreach to familiarize the public with the goals and benefits of the system.
- Regularly spaced emergency pull offs (e.g., every 500 to 1,000 m) are desirable for use when shoulder lane is open to travel.
- Continuous roadway lighting may provide safety benefits when hard shoulder running is operational.
- Retractable barriers may be used to open and close shoulders to general vehicular traffic.

Generalized Deployment Costs

- Minneapolis, MN: $1,500 per mile to $100,000 per mile depending on pavement and overhead signage. (Ref C-47)

- Birmingham, AL: $2.2444 million per mile. (Ref C-22)
- Frankfurt, Germany: $2.125 million per mile on the A5 roadway. (Ref C-22)
- Minnesota: $5.2 million per mile. (Ref C-22)
- Washington State: $50,000 per mile. (Ref C-22)
- Virginia: $1.2 million per mile. (Ref C-22)

Evaluation in the Project Development Continuum

Forecasting-based evaluation methods are well suited to analyzing this strategy as it increases roadway capacity directly.

Reversible Lanes

Objective

To improve traffic flow by allowing a particular lane to operate in the direction of higher travel.

Strategy

Typically, this strategy is employed in an urban area with some degree of separation (either barrier or pavement markings) from the GP lanes, along with signing to convey the direction of travel that is permissible. By allowing the lane to flow with the direction of higher travel, this strategy offers more capacity to that travel direction. Reversible lanes are often cost effective (in terms of pavement and right-of-way) because the strategy leaves the dynamic lane to be used ondemand, thereby reducing infrastructure requirements. Reversible lanes can be used on both freeways and arterial roadways.

Relevant Deployment Conditions

- Corridors with high directional traffic volumes in one direction that change direction, depending on time of day.

- Corridors with limited right-of-way for widening.

- Corridors with the capability of being instrumented with lane control signals and sufficient pavement markings (or separation).

Range of Researched Benefits

- 30-percent reduction in delay. (Ref B-42)
- 14 minutes per trip saved over 13.8 miles. (Ref B-43)

Conditions Supporting Success

- Public outreach to familiarize the public with the goals and benefits of the system.
- Sufficient ITS infrastructure to allow for real-time monitoring and operation.
- Dedicated maintenance to provide upkeep to these assets.

Generalized Deployment Costs

- Caltrans: $1.9 million for 8-mile section for ITS components (2007 dollar). (Ref C-26)
- Colorado DOT: Estimated $22.2 million one-time capital cost with $710,000 annual costs for 13-mile reversible lane system pilot program with movable barriers on I–70 in Denver (2011 dollar). (Ref C-27)
- Phoenix, AZ: $18.3 million to add overhead beacons and lane-control signs to existing reversible lane system (2009 dollar). (Ref C-28)
- City of Arlington, TX: $3 million cost for a reversible lane system on one minor and two major arterial roads. The system utilizes signage and dynamic overhead lane control signs. (Ref C-28)

Evaluation in the Project Development Continuum

Forecasting-based evaluation methods are well suited to analyze this strategy as it increases roadway capacity directly. Capacity reduction in the opposite direction must be addressed.

APPENDIX B. PAST EVALUATION METHODS

Estimating the impacts of transportation projects—and of operations strategies specifically—can be achieved through either by applying models or by conducting before and after analyses with empirically collected travel-time data, which can be collected through a variety of technologies (e.g., roadway sensors, prove vehicles). The expected impacts of proposed projects must be ascertained through the use of some type of forecasting model, while before and after analyses are best conducted using empirical data (actual measurements of the impacts).

However, models have often been used in the past to evaluate completed projects due to a lack of empirical data on performance in the before and after periods, especially for effects related to congestion and mobility. For example, a review of freeway and arterial management strategy evaluations in the ITS Benefits database revealed that benefits are derived from both modeling and measurement approaches. An example is the work of Peng et al., who discuss modeling as a way to measure ITS benefits given the difficulty in assembling empirical data at the time.[1,2] The impact factors (benefits) in the ITS Benefits database have been widely reviewed and applied in other applications such as the *Operations Benefit/Cost Analysis Desk Reference* and the Highway Economic Requirements System model.[3,4]

In the case of highway safety analysis, a hybrid approach, known as the EB method, combines empirical and modeled data to control for random variation in empirical data due to low sample sizes and exogenous factors.[5] The EB method has been incorporated into the *Highway Safety Manual*.[6] Because it seeks to control for factors that influence the primary effect of the treatment (crashes), the EB approach represents a step beyond naïve before and after studies, which do not. This approach has promise for adaptation to the current project.

Lomax et al. do not provide technical guidance on how to conduct ITS evaluations but rather argue for including additional user-based performance measures in a multicriteria analysis approach, rather than a benefit and cost approach.[7] Newman-Askins et al. reviewed ITS evaluation methodologies and found that the nature and extent of the effects of ITS projects is fundamentally different from those of conventional road projects because they are complicated by the presence of the unique variables affecting the outcomes of projects, including driver behavioral response. The researchers also observed: "There is little historical data available to quantify, most ITS impacts and some ITS impacts, such as increased comfort or travel time

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[1] https://www.itskrs.its.dot.gov/benefits.

[2] Peng, Zhong-Ren, Beimborn, EdwEdward, and Neluheni, Malindi, *A Framework for the Evaluation of the Benefits of Intelligent Transportation Systems,* University of Wisconsin, November 30, 2000, https://pdfs.semanticscholar.org/70f9/f131523eff339c38aae02950ab146e5f9121.pdf.

[3] https://ops.fhwa.dot.gov/publications/fhwahop12028/sec2.htm.

[4] https://www.fhwa.dot.gov/policy/2015cpr/appendixa.cfm.

[5] Hauer, Ezra, *Observational Before-After Studies in Road Safety*, ISBN 0080430538, 1997.

[6] For a summary, see: *An Introduction to the Highway Safety Manual*, American Association of State Highway and Transportation Officials (AASHTO), http://www.highwaysafetymanual.org/Documents/HSMP-1.pdf.

[7] Lomax, Tim, Vidali, Sharada, and Eisele, William, *Evaluating Intelligent Transportation System Impacts: A Framework for Broader Analyses,* March 2000, https://static.tti.tamu.edu/tti.tamu.edu/documents/ITSRCE-00_02.pdf.

reliability, are qualitative or difficult to measure or value," which, in hindsight, is probably accurate historically given that their references are all pre-2000.[8] However, with the advent of widely available empirical travel time and speed measurements—first from roadway detectors and more recently from probe vehicles—empirical (observational) analysis of completed projects is now highly feasible.

Cambridge Systematics and Kittelson Associates addressed the before and after evaluation of operations projects in SHRP 2 Project L17.[9] They developed a procedure for tracking changes in travel time-based performance measures due to operations strategy improvements, identifying and accounting for the influence of underlying congestion factors in the before and after periods (incidents, weather, demand, and work zones). They discuss the use of modeling and control sites as a means of adjusting observed changes in travel-time measures when the underlying conditions in the before and after periods are different enough to influence the observations.

Researchers at FHWA conducted a study to explore evaluation procedures for operations projects.[10] It discusses several types of experimental designs for conducting evaluations:

- **Ex Post Facto Design** is also called a causal-comparative design. One of the primary limitations of this design is its inability to determine causality because it cannot control for confounding factors, rival hypothesis or explanations, or other threats to the evaluation.
- **Pre-Experimental Design** is the simplest type of evaluation design because it does not include an adequate control or comparison group. The data are collected twice: once in the before-implementation state and once in the after-implementation phase. This type of design is the least rigorous in establishing a causal link between project activities and outcomes.
- **Quasi-Experimental Design** uses control groups as a means of filtering out confounding factors, but these groups are not randomly assigned.
- **Full Experimental Design** randomly assigns all eligible project evaluation subjects (e.g., travelers, highway segments, technology deployments) to the treatment or control group. This method assumes that the subjects in both the control and the treatment group have similar attributes and characteristics due to randomization.

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[8] Newman-Askins, Raechelle, and Ferreira, Luis, and Bunker, Jonathan M2003 "Intelligent Transport Systems Evaluation: From Theory to Practice." In Jaeger, Vicki, Eds. *Proceedings 21st Australian Road Research Board and 11th Road Engineering Association of Asia and Australia Conference*, Cairns, Queensland, Australia.

[9] Cambridge Systematics and Kittelson Associates, Gap Filling Project 4: A Guidebook for Standard Reporting and Evaluation Procedures for Transportation Systems Management and Operations (TSM&O) Strategies, 2014, https://transops.s3.amazonaws.com/uploaded_files/SHRP2_L17_Gap-Filling_Project_4_GuidebookForStandardReportingAndEvaluationProceduresFor_TSM%26O_Strategies.pdf.

[10] Kamalanathsharma, Raj, Yelchuru, Balaji, Hadi, Mohammed, and Adams, Victoria, A Framework for Evaluating Transportation Improvements Using Empirical Data, FHWA-HOP-18-035, January 29, 2018.

As a practical matter, most evaluations of transportation improvements, with the exception of safety evaluations that apply the EB method, follow a pre-experimental design. While a full experimental design is the “gold standard” for evaluations, it cannot be achieved in the field by practitioners. Therefore, the current project intends to focus on quasi-experimental design methods.

In the past few years, researchers have made an effort to develop a detailed operational analysis of traffic signal systems. These evaluations are based on high-resolution controller event data, consisting of a log of discrete events such as changes in detector and signal phase states. Day et al. explored this approach of using high-resolution controller event data.[11] They developed a portfolio of performance measures for system maintenance and asset management; signal operations; nonvehicle modes, including pedestrians; and travel time-based performance measures for assessing arterial performance. Most of these measures relate to evaluating how well signal timing and phasing support attainment of operational objectives such as equitable distribution of green light time and smooth flow. Evaluation of the measures provide an indication of how signal timing settings are performing and can indicate specific areas where improvement is needed.

The analyses are meant to improve system maintenance and asset management as well as signal operations, including signal capacity and system progression. Travel-time data can also be used to estimate changes in performance experienced by travelers due to signal operation improvements.

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[11] Day, C. M., D. M. Bullock, H. Li, S. M. Remias, A. M. Hainen, R. S. Freije, A. L. Stevens, J. R. Sturdevant, and T. M. Brennan, *Performance Measures for Traffic Signal Systems: An Outcome-Oriented Approach*, Purdue University, West Lafayette, Indiana, 2014. doi: 10.5703/1288284315333.

APPENDIX C. PERFORMANCE MEASURE CALCULATION

This appendix presents methods for calculating performance measures beyond the PM3 measures.

TRAFFIC DATA

For operational strategy evaluation needs, the relevant traffic data are traffic volume, speed, and travel times, and the most common freeway data source is the archive of the traffic operations data collected by many State departments of transportation (DOTs) ITSs. Most ITS deployments utilize point sensors to collect data for each travel lane. These sensors are usually spaced 1/3 to 1/2 mile apart. Point sensors collect traffic volume, speed, occupancy, and vehicle classification in some ITSs. Other ITSs rely on probe vehicles to provide speed, travel time, or both along the traveling routes. Some ITSs also archive the real-time travel-time data posted on roadside message boards. The observation interval of operations data can range from 20 seconds to 15 minutes. Archive data are most often saved as plain text files, where each row represents one observation interval at a detection location identified by unique location references such as detector identification (ID) and lane ID.

In addition to traffic operations data, most State DOTs also maintain various counting programs. Some of these counts are continuously made at permanent sites—such as automatic traffic recorder (ATR), automatic vehicle classifier, and weigh-in-motion sites, whereas other counts are made for short periods of time with no fixed locations. The data formats used by counting programs are similar to those used for traffic operations data; however, the minimum observation interval is usually 1 hour, which might be too long for operational strategy evaluations.

For evaluation sites not included in a State DOT's data coverage, operational strategy evaluations should conduct their own data collection. Details on how to conduct data surveys should follow published FHWA guidelines.

Another data collection option is to purchase commercial traffic data from private vendors. Private vendors provide speed and travel-time data on selected roadway sections by using GPS, Bluetooth®, or wireless location techniques. Some vendors also could provide separate speed data on trucks. Private speed data formats are like archived ITS data, where each row represents one observation interval at one location. However, their location-referencing method is different. They most commonly use TMC links, which are not widely known outside the private traveler information industry; thus, extra effort may be needed to use the commercial traffic data in operational strategy evaluations. Table 24 provides an overview of the data sources.

Table 24. Potential data sources.

Traffic Data Type	Source	Data Format	Observation Level	Collection Type	Data Coverage
Volume	State department of transportation (DOT)	Sensor data archives	Lane level, by vehicle types in some systems	Intelligent transportation system (ITS) sensors	Usually spaced 1/3 to 1/2 mile apart along major freeways and some major arterials.
	State DOT	Traffic count reports from permanent or short-term traffic collection devices	Station level by vehicle types	Automatic traffic recorder devices	Sparsely located throughout the State highway system.
Speed and travel time	State DOT	Sensor data archives	Lane level	ITS sensors	Usually spaced 1/3 to 1/2 mile apart along major freeways and some major arterials.
	State DOT	Probe data archives	DOT-defined segment level	Toll tag reader, license plate reader	Along roadway segments between exit and roadside reader devices.
	State DOT	Travel time archive	DOT-defined segment level	ITS sensors	Live travel time posted on roadside message boards throughout major commute routes as well as on the traffic message channel's (TMC) website.
	Private vendor	Speed data archive	TMC segment level, by vehicle types with some vendors	Global Positioning System (GPS) probe, wireless technology, cell phone location tracking	Along predefined roadway segments on major freeways and arterials.

Disruption Data

Incidents and Work Zones

For operations strategies evaluations, the most relevant incident and work zone data are the records that show when and where any travel lane has been blocked and when it was cleared. Most ITS systems also archive incident and work zone activities as incident logs. When traffic operations personnel identify an incident, they assign a unique incident ID to it and record each new activity as a new line in the log until the incident is cleared. Logs usually record such information as incident and work zone start and end times, duration, type, severity, impact, and location.

In addition to incident data collected by traffic operations personnel, another common data source is accident reports from State public safety agencies.

Private traveler information vendors could also provide incident data; however, their incident data are geospatially referenced to the same TMC links as their traffic data link. Therefore, they have the same shortcomings as private traffic data.

The typical inclement weather events that impact traffic operations are rain, snow, dense fog, and high wind. For operational strategy evaluations, the required data are when and where the inclement weather started and ended, the amount of rainfall and snowfall, visibility, pavement condition, sky condition, wind speed, and wind direction.

State DOT Road Weather Information System (RWIS) Environmental Sensor Stations (ESS) provide inclement weather data. Most ESSs report at 20-minute intervals, although some report at 10-minute intervals. ESS data have a limited geographic scope, and many available weather stations have limited capabilities—for example, some ESS stations do not measure precipitation intensity, making it difficult to assess the effect of rain or snow on traffic flow.

Another potential weather data source is the National Weather Service Automated Surface Observing System (ASOS). Many of these ASOS stations, which are located at airports, have 1-minute data archives. Although ASOS data are updated more frequently than State DOT ESSs, they are limited to airport locations, making them inadequate to capture local variations in precipitation levels.

A third option is to purchase commercial weather data from private vendors. These private weather stations are much more densely spaced than either ESS or ASOS stations, making it easier to find a weather station that is close to traffic detection locations. Many of these weather stations collect data continuously. The weather data that are collected include precipitation rate, daily rain, temperature, dewpoint, pressure, wind direction, wind speed, humidity, and clouds.

Table 25 summarizes sources of disruption data.

Table 25. Sources of disruption data.

Data Type	Source	Data Format	Detection Coverage
Incident/work zone	State department of transportation (DOT)	Incident logs	Freeways covered by freeway service patrol and roadside assistance.
	State Highway Patrol	Accident reports	Statewide.
	Private vendor	Incident logs	Throughout major urban areas.
Inclement Weather	State DOT Environmental Sensor Stations (ESS) station	Weather archives	Sparsely located throughout the State highway system.
	Automated Surface Observing System (ASOS) station	Weather archives	Located near airports.
	Private vendor	Weather archives	More densely located than ESS or ASOS stations.

The project team suggests using weather data at an aggregated level. For example, it rained lightly in the AM peak, it rained heavily during the AM peak, it snowed in the AM peak, it was clear in the AM peak. The team made this suggestion for two primary reasons: 1) the data available often are not precise enough to describe the conditions on the road segment being studied during a specific 15-minute time period. (That is, it may have been raining at the airport at 8:15 a.m., but not on your freeway segment, which is 15 miles south of the airport). 2) For some weather conditions, the aftereffects of weather are just as important as the active weather condition. For example, the fact that it is not snowing now (9 a.m.) is not important if 6 inches of snow fell between 6 a.m. and 8 a.m. that morning. Therefore simpler, more accurate aggregate weather outcomes are more useful—and easier to obtain—when using that data to create clusters of operating conditions.

Roadway Geometric Data

The following list shows the most relevant roadway geometric data for evaluating operations strategies:

- *Ramp locations* to create freeway sections between interchanges.
- *Intersection locations* to create arterial sections between major intersections.
- *Number of lanes* to aggregate lane-level traffic data.
- *Roadway length between detection locations* to calculate travel times between two detection locations.

Traffic operations data collected from ITSs usually come with a detector configuration file that provides detector information such as lane number, direction, distance to upstream and downstream detectors, and location. Some ITS systems reference detection locations by milepost or latitude and longitude. Other ITS systems reference their detector locations by crossroad names. While it is easy to convert mileposts to distance, calculating distance based on crossroad names involves extra effort since the detection locations first must be identified manually in a geographic information system (GIS) map.

Likewise, first match the latitude and longitude coordinates to road locations. Then, calculate the actual road distance between the locations (an extra step, compared with mileposts).

Private data use TMC segments for their detection locations. The data come with TMC link configurations such as link ID and link length. One or more adjacent TMC links combined produces a roadway section.

Operations Data

For evaluating operations strategies, the relevant operating data include the following operations policies, which are implemented on the study roadways. Operations policies include:

- Managed lanes: HOV and HOT, truck only, toll lanes, etc.
- Special shoulder and ramp function: queue bypass lane during peak hours.
- Speed zones: speed limits, zone type (school zone, work zone), different speed limit for trucks, VSL.
- Intersection configuration: signal control, turning lanes, pedestrian crossing.

Developing Travel Time-Based Performance Measures

For detector data (“spot” speeds and volumes), travel times are synthesized for the lowest level of aggregation present in the data. The assumption is that the spot speeds are uniform across a length of highway equal to half the distance to the nearest upstream and downstream detectors. Detector spacing significantly affects the accuracy of this assumption—the closer the spacing, the more reasonable the assumption. Figure 18 shows the steps in this aggregation process.

At the end of the process, the project team computed travel times over the length of the study section for each time increment, e.g., 5-minute intervals. Similarly, the team calculated travel time distribution for probe data using the same process except there were data aggregated laterally. These travel times form the basis of the travel time distribution from which performance measures are computed. This report used the MTTI, the 80th percentile TTI, and the PTI (i.e., the 95th percentile TTI.). The calculation of these three measures requires that a benchmark be established; this benchmark is typically the free flow or “ideal” travel time. For free flow conditions (used in this report), analysts can use either detector or probe data by observing travel times during low traffic volume periods, such as weekend mornings. The next step is to compute the mean, 80th percentile, and 95th percentile travel times from the travel time distribution. Then, compute the performance measures by dividing these travel times by the free flow or ideal travel times.

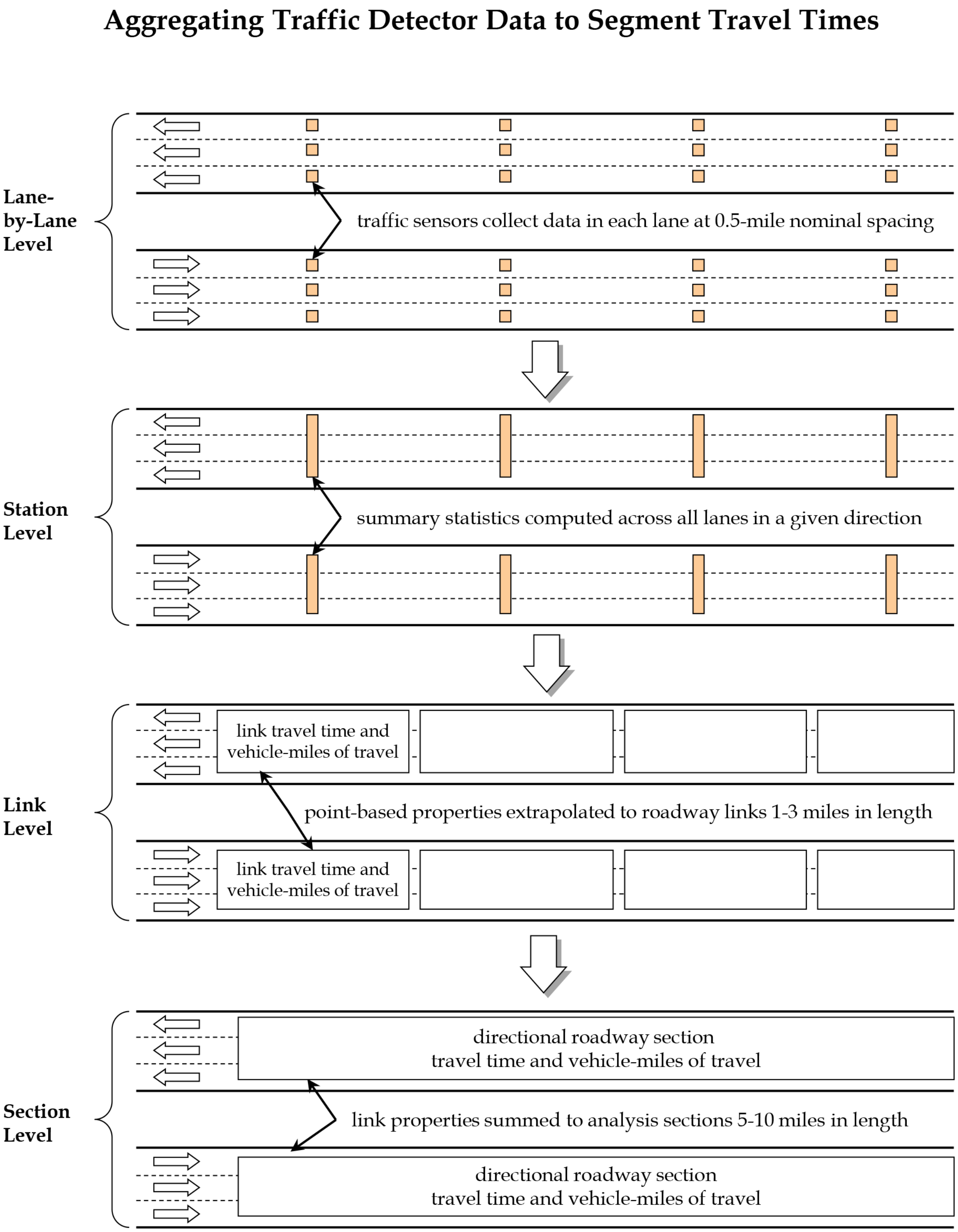

Figure 18. Diagram. Procedure for aggregating detector data to the facility level.

(Source: Turner, S., R. Margiotta, T. Lomax. *Monitoring Urban Freeways in 2003: Current Conditions and Trends from Archived Operations Data.* Report No. FHWA-HOP-05-018, Accessed at https://static.tti.tamu.edu/tti.tamu.edu/documents/FHWA-HOP-05-018.pdf, December 2004.)

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November 2024

FHWA-HOP-24-001