DECISION SUPPORT FRAMEWORK AND PARAMETERS FOR DYNAMIC PART-TIME SHOULDER USE

Considerations for Opening Freeway Shoulders for Travel as a Traffic Management Strategy

U.S. Department of Transportation
Federal Highway Administration

NOTICE

QUALITY ASSURANCE STATEMENT

Cover photos: Kittelson & Associates, Inc.

Technical Report Documentation Page

1. Report No. FHWA-HOP-19-029	**2. Government Accession No.**	**3. Recipient's Catalog No.**

4. Title and Subtitle DECISION SUPPORT FRAMEWORK AND PARAMETERS FOR DYNAMIC PART-TIME SHOULDER USE: Considerations for Opening Freeway Shoulders for Travel as a Traffic Management Strategy	**5. Report Date** November 2019 6. Performing Organization Code
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9. Performing Organization Name and Address Leidos 11251 Roger Bacon Drive Reston, VA 20190 Kittelson & Associates Inc. 300 M Street SE, Suite 810 Washington, DC 20001	**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.** Contract No. DTFH61-16-D-00053
12. Sponsoring Agency Name and Address Federal Highway Administration U.S. Department of Transportation 1200 New Jersey Avenue, SE Washington, DC 20590	**13. Type of Report and Period Covered** Technical Report, September 2017 through May 2019 14. Sponsoring Agency Code HOTM

15. Supplementary Notes

Jim Hunt (jim.hunt@dot.gov) served as the Government Task Manager. The report's authors were supported by Anusha Musunuru, J Lake Trask, Burak Cesme, and Anxi Jia, all of Kittelson & Associates, Inc.

16. Abstract

Dynamic part-time shoulder use (D-PTSU) opens shoulders for travel beyond fixed (or static) time periods (e.g., weekday peak periods). Dynamically operating the transportation system by matching supply-side strategies in accordance with prevailing conditions and travel demands represents an important advancement in agency adoption of Active Transportation and Demand Management (ATDM) concepts. This report provides agencies with relevant information and best practices for operating D-PTSU on freeways. The report explains how the opening of PTSU can be optimized based on speed and volume conditions observed or modeled on the freeway, and methods for determining specific "decision parameters" for opening the shoulder are presented. The report also assists agencies in determining if D-PTSU is an appropriate strategy where no part-time shoulder use is in place, or where static part-time shoulder use is in place.

17. Key Words Part-time Shoulder Use, Hard Shoulder Running, Active Traffic Management, Transportation Systems Management and Operations, Freeway	**18. Distribution Statement** No restrictions.

19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No of Pages** 140	**22. Price** N/A

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

SI* (MODERN METRIC) CONVERSION FACTORS

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 1,000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in.^{2}	poundforce per square inch	6.89	kilopascals	kPa

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

SI* (MODERN METRIC) CONVERSION FACTORS (continued)

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

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

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LIST OF ABBREVIATIONS AND ACRONYMS

AADT	average annual daily traffic
ATDM	active traffic demand management
ATM	active traffic management
CMF	crash modification factors
CMP	congestion management process (Federal guidelines) or Congestion Management Program (locally or regionally adopted)
CMM	Capability Maturity Model
ConOps	concept of operations
d/c	demand-to-capacity (ratio)
DOT	department of transportation
DSF	decision support framework
D-PTSU	dynamic part-time shoulder use
ER	emergency responders
FFS	free flow speed
FSP	freeway service patrol
FHP	Florida Highway Patrol
FHWA	Federal Highway Administration
FI	fatal and injury
GPS	Global Positioning System
GIS	geographic information systems
HCM	Highway Capacity Manual
HOT	high occupancy toll
HOV	high occupancy vehicle
ITS	intelligent transportation systems
LOS	level of service
MDOT	Michigan Department of Transportation
mi/h	miles per hour
MPO	metropolitan planning organization
MTP	metropolitan transportation plan
MUTCD	Manual on Uniform Traffic Control Devices
NHS	National Highway System
NPMRDS	National Performance Management Research Data Set

LIST OF ABBREVIATIONS AND ACRONYMS (continued)

PCE	passenger car equivalent
pc/h	passenger cars per hour
pc/h/ln	passenger cars per hour per lane
PDO	property damage only
PeMS	(California's) Performance Measurement System
PBPD	performance-based practical design
PBPP	performance-based planning and programming
PLM	product limit method
PTI	planning time index
PTSU	part-time shoulder use
SHRP 2	Second Strategic Highway Research Program
SOV	single occupant vehicle
SPF	safety performance function
S-PTSU	static part-time shoulder use
TIP	transportation improvement program
TOPS-BC	Tool for Operations Benefit-Cost
TMA	transportation management area
TMC	transportation management center
TSMO	transportation systems management and operations
TTI	travel time index
V/C	volume to capacity ratio
VHD	vehicle hours delay
VHT	vehicle hours traveled
VMT	vehicle miles traveled
veh/h/ln	vehicles per hour per lane
WSDOT	Washington State Department of Transportation

EXECUTIVE SUMMARY

Part-time shoulder use (PTSU) is a transportation systems management and operations strategy that allows use of the left or right shoulder as a travel lane during some, but not all, hours of the day. PTSU enables agencies to achieve a better balance of available supply (roadway capacity) and demand. It can generally be implemented more rapidly, at lower cost, and within a smaller footprint than a conventional widening project. In 2016, the Federal Highway Administration (FHWA) published *Use of Freeway Shoulders for Travel — Guide for Planning, Evaluating, and Designing Part-Time Shoulder Use as a Traffic Management Strategy.* The 2016 guide comprehensively addresses PTSU from planning and design through implementation and day-to-day operations. It includes information on dynamic PTSU (D-PTSU), static PTSU (S-PTSU), and bus-on-shoulder (BOS).

The 2016 FHWA Publication "Use of Freeway Shoulders for Travel" comprehensively addresses PTSU.

PTSU can be implemented more quickly and cost effectively than a conventional roadway widening. It requires a shoulder that is wide enough to accommodate vehicles and that has pavement strong enough to support repeated vehicle use. D-PTSU is an active transportation and demand management (ATDM) strategy because it makes realtime adjustments to a freeway's capacity based on the traffic demand that is present, thus improving the reliability of travel time on the freeway. D-PTSU is often implemented with other ATDM strategies such as variable speed limits, dynamic lane-use control, and ramp metering. More information on ATDM is available at: https://ops.fhwa.dot.gov/atdm/index.htm.

Many agencies in the United States already employ S-PTSU with fixed operating hours on freeways. D-PTSU opens shoulders for travel beyond fixed (or static) time periods in response to traffic conditions. This report presents a framework and several processes agencies can use to identify the appropriate level of D-PTSU for their freeway facility and to set operating parameters for their D-PTSU as part of the agency's traffic management strategy. The processes of opening and closing D-PTSU are primarily ad hoc, with some agencies using predictive algorithms or control systems with volume and speed thresholds to supplement the operator's discretion in the transportation management center (TMC). Agencies may set core hours of operation to anticipate recurring congestion on the facility. Operators may also vary the opening and closing times based on observed conditions as well as the needs of maintenance, law enforcement, and emergency response personnel.

Three primary decision parameter types—fixed time-of-day, speed-based, and volume-based—are most applicable for responding to breakdowns in free-flow traffic operations under the following conditions:

- If breakdowns are frequent and predictable (e.g., every morning between 7 a.m. and 9 a.m., but rare during other times of the day), **a fixed time-of-day decision parameter may be sufficient**. If there are no breakdowns outside of the peak, there are few benefits to be gained from a dynamic system, and consequently there may be limited value in investing further resources in dynamic decision parameter technology.

- **Volume-based decision parameters** are most reliable for realtime prediction of oncoming breakdowns. Volume increases as breakdown approaches, and this incremental change often enables an analyst to predict the breakdown soon enough to initiate a sweep and open the shoulder prior to the onset of a breakdown. Volume-based decision parameters are most straightforward to apply on freeways with frequent and reasonably predictable traffic patterns (e.g., breakdown every morning peak), where the rate of volume increase, the driver population, the heavy vehicle percentage, and other parameters of the traffic stream are similar day to day.
- **Speed-based decision parameters are less reliable indicators of oncoming breakdowns.** In general, speed does not substantially decrease until just prior to the onset of breakdown, and there may be insufficient time to conduct a sweep prior to the onset of breakdown if a speed-based decision parameter is used. However, volume-based decision parameters should be supplemented by speed-based decision parameters. If a volume-based decision parameter fails to detect the onset of breakdown but speeds begin to decrease, then it may still be appropriate to begin a sweep and open the shoulder. The added capacity through D-PTSU often relieves the congestion quickly and enables the freeway to "recover" from short-term breakdown.

This report presents five data-driven methods for selecting and optimizing the opening time of a PTSU facility. While they are primarily presented in the context of making day-to-day decisions for a D-PTSU facility, they could also be used during concept of operations (ConOps) development to establish either hours of operation for S-PTSU or core hours of operation for D-PTSU. The five methods are:

I. **Demand-to-Capacity Patterns** – Using sensors or traffic counts on the facility, an operating agency assesses historical demand profiles to determine levels of congestion relative to the available facility base capacity as well as the expected capacity with shoulder use.

II. **Empirical Performance Data** – Using whole-year travel time reliability data, an operating agency explores the frequency and pattern of breakdown events to identify times when the facility experiences congestion.

III. **Macroscopic Decision Parameter Optimization** – Using the Highway Capacity Manual (HCM) freeway facilities method, an operating agency examines different types of decision parameters (speed vs. volume-based) and decision parameter values for a facility.

IV. **Microscopic Decision Parameter Refinement** – Using calibrated microsimulation tools, an operating agency simulates the facility in question with the initial proposed decision parameter algorithm.

V. **Monitoring and Adjustment** – The operating agency uses realtime operating experience to adjust the decision parameter values and open or close the shoulder at different thresholds.

Other research documented in this report includes a synthesis of D-PTSU literature and a summary of known D-PTSU facilities worldwide. D-PTSU implementations to date have been located on freeway facilities, thus this report focuses on freeway applications of D-PTSU.

CHAPTER 1. INTRODUCTION

Part-time shoulder use (PTSU) is a transportation systems management and operations (TSMO) strategy that reduces congestion-related delay by allowing use of the left or right shoulders as travel lanes during some but not all hours of the day. PTSU is also referred to as hard shoulder running, hard shoulder use, temporary shoulder use, or a variety of other names. This strategy is primarily used in locations where congestion recurs due to lack of peak period capacity through a corridor (by time of day, and/or day of week, special events) and where other alternatives to improve operations are infeasible, cost-prohibitive, or cannot be realized within short periods of time.

As the reliability of automobiles and tires has increased and incident management strategies have improved, the need for shoulders to serve exclusively as refuge areas 24 hours per day has decreased. Many agencies in the United States already employ PTSU on freeways. In some cases, PTSU provides an interim solution until conventional widening occurs. For information on PTSU in general, refer to the *Federal Highway Administration (FHWA) report Use of Freeway Shoulders for Travel — Guide for Planning, Evaluating, and Designing Part-Time Shoulder Use as a Traffic Management Strategy*, hereafter called the FHWA report on the Use of Freeway Shoulders for Travel. PTSU is most cost-effective in constrained right-of-way conditions, provided minimum geometric values (such as shoulders wide enough for vehicle travel) and pavement strength are met. PTSU is classified into three types:

- Bus-on-shoulder (BOS) – open only to authorized buses and usually at the driver's discretion.
- Static part-time shoulder use (S-PTSU) – open to vehicles only during predetermined hours.
- Dynamic part-time shoulder use (D-PTSU) – open to vehicles in response to realtime traffic conditions.

Table 1 notes key advantages and challenges of S-PTSU versus no shoulder use and D-PTSU versus S-PTSU.

Table 1. Advantages and Challenges of D-PTSU.

Scenario	Advantages	Challenges
Static part-time shoulder use (S-PTSU) versus No Shoulder Use	At and upstream of recurring congested bottlenecks: reduces congestion and potential for congestion-related crashes.	Reduced space in certain hours of day for: • Disabled vehicles • Emergency response • Incident clearance • Enforcement • Crash investigation • Maintenance Must have or provide adequate geometric widths, lateral and vertical clearances, sight distances, drainage, and pavement structural section for traffic to operate on shoulder lane. No ability to respond to day-to-day variation in traffic conditions.

Table 1. Advantages and Challenges of D-PTSU. (continued)

Scenario	Advantages	Challenges
Dynamic part-time shoulder use (D-PTSU versus S-PTSU	Same advantages of S-PTSU, plus the ability to address non-recurring congestion by opening the shoulder as needed (outside of fixed time periods).	Same challenges as for S-PTSU, except there is an ability to respond to day-to-day variation in traffic conditions. Requires frequent dynamic message signs, real-time video surveillance, transportation management center staffing for opening/closing shoulder any time shoulder may be opened, excellent 24/7 communication and coordination between operations, maintenance, emergency response, and enforcement personnel

Currently in the United States, D-PTSU, the focus of this report, is less common than the other types of PTSU. D-PTSU flexibly opens shoulders for travel beyond fixed (or static) time periods, typically using either a speed-based decision parameter, a volume-based decision parameter, or some combination of the two. In some cases, there may also be "core" hours when the shoulder is always open due to recurring congestion. D-PTSU, in the appropriate circumstances, can increase facility capacity, reduce delays, and improve travel time reliability. D-PTSU can be a particularly cost-effective component of a comprehensive agency TSMO strategy for addressing congestion and reliability issues within the transportation system. D-PTSU represents an important advancement and maturity in agency TSMO practices and is consistent with active and integrated operations promoted through two key U.S. Department of Transportation programs: Active Transportation and Demand Management (ATDM) and Integrated Corridor Management. More information on these programs is available at https://ops.fhwa.dot.gov/atdm/index.htm.

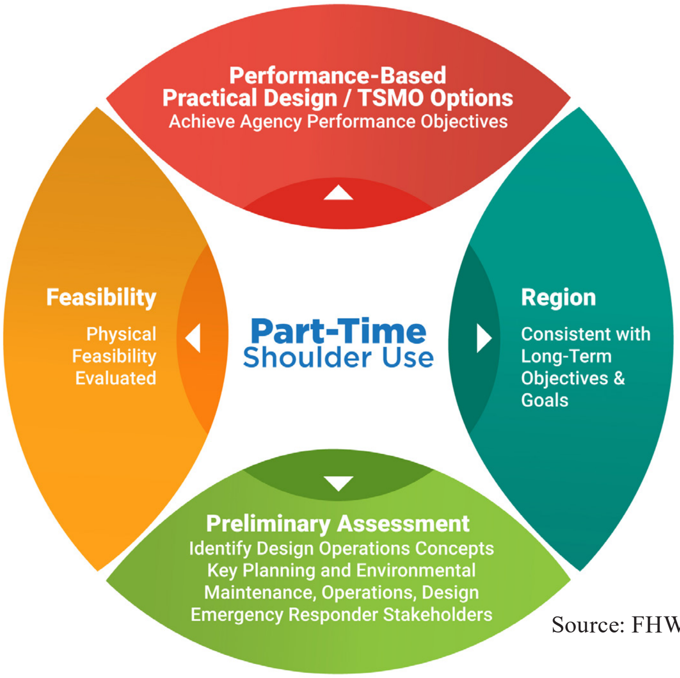
This report presents a decision framework and a process that agencies can use to identify the appropriate decision parameters for opening the shoulder on their D-PTSU facilities as part of the agency's traffic management strategy. Decision parameters are presented within the context of a decision support framework that considers non-operational factors as well as operational decision parameters to help an agency determine if it is appropriate to open or close the shoulder at any given time. The report further provides insights on decision parameters in the form of speed and volume thresholds that would activate opening the shoulder on a D-PTSU system. While D-PTSU could be applied to an arterial, there are no known applications to date within the United States, and this report focuses on freeway applications of D-PTSU.

CHOOSING PART-TIME SHOULDER USE

The decision to pursue PTSU should be made as part of a comprehensive assessment founded on performance-based practical design (PBPD) and TSMO options for achieving the agency's performance objectives for the facility design and operations. First, the physical feasibility of PTSU should be evaluated to determine if it is a feasible option, and a region should decide if the PTSU strategy is consistent with its long-term transportation goals and objectives. Then, a preliminary assessment should be made to identify one or more design and operations concepts for evaluation. This assessment, conducted under the overall umbrella of a PBPD process, should assess the operational and safety effects of part-time shoulder use to ensure it is indeed a cost-effective means for achieving the agency's performance objectives for the facility. Throughout this evaluation, key planning and environmental, maintenance, operations, design, and emergency responder stakeholders should be involved to ensure a successful outcome. Figure 1 shows these PTSU planning considerations.

It remains the policy of FHWA that constructing and maintaining roadway shoulders along all major and minor arterials and freeways provides inherent value. Shoulder width is one of the 10 controlling criteria that FHWA requires in a formal written design exception if minimum design criteria are not met on "high-speed" roadways on the National Highway System. Refer to 23 CFR 625.3(f) and the memorandum "Revisions to the Controlling Criteria for Design and Documentation for Design Exceptions", dated May 5, 2016, available at https://www.fhwa.dot.gov/design/standards/160505.cfm. Aside from their structural benefits for pavement and drainage, shoulders provide refuge for vehicles in emergency situations, access for first responders, and an additional recovery area for drivers trying to avoid conflicts in the adjoining travel lanes. The safety benefits of shoulders are documented in the AASHTO Highway Safety Manual and other studies. Because of these factors, the decision to use shoulders for travel should be carefully considered and limited in both its application and period of usage.

Figure 1. Diagram. Considerations in choosing part-time shoulder use.



Source: FHWA

Although part-time shoulder use can be a very cost-effective solution, it may not be an appropriate strategy where minimum geometric clearances, visibility, and pavement requirements cannot be met, or where it may have an adverse impact on safety. Appendix A provides questions agencies can consider during the planning, design, implementation, and operations of PTSU facilities, and gives an insight into the broad range of topics associated with PTSU.

RELATIONSHIP WITH OTHER ACTIVE TRAFFIC MANAGEMENT TREATMENTS

D-PTSU is often implemented in combination with other active traffic management (ATM) treatments. Selected ATM treatments and ways they enhance PTSU operations are noted below:

- *Ramp metering* – for right-side PTSU (on a freeway with right-side ramps), metering can mitigate the conflicts between shoulder traffic and ramp traffic by preventing platoons on entrance ramps. Additionally, activating ramp meters may reduce the duration of PTSU by providing an incremental increase in freeway capacity.
- *Dynamic junction control* – PTSU may create conflict points or necessitate lane-changing if implemented “through” interchanges with multilane entrance or exit ramps. To prevent this, dynamic junction control could be used to change lane assignment when the shoulder is open and reduce the number of ramp lanes and add or drop a freeway lane (general purpose or shoulder) onto a ramp.
- *Dynamic lane assignment* – If sign structures and communication are constructed to indicate lane control for the shoulder (typically with a green arrow and red X), they could also be installed over all lanes to close lanes when an incident, construction, or maintenance activities dictate it. Closure of a general purpose lane could be accompanied by opening the shoulder to minimize the loss in capacity.
- *Dynamic speed limit* – When the shoulder is open to traffic, it may be advantageous to lower the speed limit due to reduced lateral offset between traffic and roadside objects and potentially reduced stopping sight distance for traffic that is closer to a barrier wall. Additionally, a lower speed limit may reduce the duration of PTSU by providing an incremental increase in freeway capacity.
- *Queue warning* – While PTSU reduces the likelihood of queues, it typically provides additional data collection, making queues easier to identify, in turn making it possible to warn drivers of downstream delays more reliably.

PTSU is an investment for an agency. Generally, the investment in roadway construction is less than a conventional widening project, but the investment in the transportation management center (TMC) and overall facility management may be greater. Implementing the second, third, or fourth ATM treatment is generally not as challenging as implementing the first, and there are benefits and efficiencies in implementing strategies together.

NETWORK CONSIDERATIONS

Freeways supply much of the capacity in a region's road network, and changes in their capacity may have broad implications for the region's travel patterns. PTSU increases freeway capacity in some hours of the day and leaves it unchanged in other hours. This change may not have an effect on freeway volume, may shift volume from the shoulders of the peak period to peak hours themselves, or it may increase volume on the freeway to due to diversion from other facilities and/or induced demand.

The degree to which any of these changes happen will vary from freeway to freeway, and be influenced through such factors as:

- The availability/viability of alternate roadway routes.
- The availability/viability of multimodal travel options.
- Driver familiarity with the region and comfort taking alternate routes and modes.
- Area type (urban versus rural).
- Type of trips served.
- Length of PTSU segment
- Location of nearby bottlenecks.

In short, many factors influence how the choices of drivers will vary when PTSU is implemented. Like any larger freeway project, a PTSU project should not be analyzed in isolation but as part of a regional network. Macroscopic tools such as travel demand models are useful for estimating the network-level effects of PTSU prior to implementation.

PURPOSE, SCOPE, AND TARGET AUDIENCE

The purpose of this report is to provide agencies with relevant information and experience for implementing and operating D-PTSU on freeways. This report includes an overview of D-PTSU domestic and international practices and focuses on identifying the decision parameters for determining when to open and close D-PTSU. Specifically, this report assists agencies in answering the following questions:

- Would D-PTSU be an appropriate strategy in a location where no part-time shoulder use (even static) is currently in place?
- Should D-PTSU be considered in a location where static part-time shoulder use is in place?
- How can the operations of an existing D-PTSU installation be optimized through careful selection of speed- and volume-based "decision parameters" that are then used on a realtime basis to decide to open the shoulder?
- What are the considerations for closing the shoulder?
- When, if at all, should conversion of PTSU into a permanent full-time lane be considered?

This report does not address:

- D-PTSU on arterial streets, because of the lack of U.S. experience with arterial D-PTSU.
- The "part-time" use of a shoulder in work zones during construction (e.g., as part of a lane shift or lane closure).
- Static (fixed hours of day) part-time shoulder use (S-PTSU). S-PTSU is covered in the FHWA report Use of Freeway Shoulders for Travel, Guide for Planning, Evaluating, and Designing Part-Time Shoulder Use as a Traffic Management Strategy (FHWA-HOP-15-023).
- Pedestrian and bicycle considerations.

The target audience for this report consists of state DOTs, toll agencies, MPO planners and designers, and TMC managers and operators.

ORGANIZATION OF REPORT

The report is organized as follows:

Chapter 1. Introduction describes the purpose, scope, content, organization, defines dynamic part-time shoulder use, and identifies the intended audience for the report.

Chapter 2. Overview of Dynamic Part-Time Shoulder Use describes how D-PTSU works, intelligent transportation system infrastructure needs, the advantages of D-PTSU over S-PTSU, the relative challenges of D-PTSU compared to S-PTSU, and examples of D-PTSU installations around the world.

Chapter 3. Decision Support Framework, describes the considerations for developing a concept of operations (ConOps) for dynamic part-time shoulder use. It describes the overall concept of decision parameters for opening and closing the shoulder, describes the various levels of dynamic operations for a part-time shoulder use lane, and provides a decision support framework for choosing the decision parameters and level of dynamic operations for the part-time shoulder lane. The role of non-traffic considerations such as maintenance, weather, shoulder blockages, and emergency response are discussed as well.

Chapter 4. Decision Parameters for Opening Shoulder describes reactive and predictive methods for determining when a dynamic shoulder should be opened to traffic, with a focus on traffic-related decision parameters.

Chapter 5. Considerations for Closing the Shoulder describes traffic and non-traffic considerations and decision parameters (maintenance, weather, incidents, emergency response, and safety) for closing the shoulder.

Appendix A lists questions agencies can consider during the planning, design, implementation, and operations of PTSU facilities.

Appendix B provides fact sheets for national and international examples of dynamic part-time shoulder installations.

Appendix C describes software and manual methods for developing decision parameters for opening and closing D-PTSU lanes. This appendix summarizes the Product Limit, FREEVAL, and VISSIM methods.

Appendix D provides tables with generalized thresholds for opening a shoulder on a typical freeway with default traffic characteristics.

Appendix E provides a list of additional resources on PTSU, including D-PTSU.

CHAPTER 2. WHAT IS DYNAMIC PART-TIME SHOULDER USE?

This chapter provides an overview of dynamic part-time shoulder use (D-PTSU). This active traffic management (ATM) strategy provides additional roadway capacity when realtime conditions warrant it and preserves the benefits of a full-width shoulder at other hours of the day. This chapter describes how D-PTSU works, intelligent transportation system (ITS) infrastructure needs, the advantages of D-PTSU over static part-time shoulder use (S-PTSU), the relative of challenges of D-PTSU compared to S-PTSU, and highlights example D-PTSU installations around the world.

DYNAMIC PART-TIME SHOULDER USE AND OPERATIONS

The usage of shoulders as travel lanes for variable, rather than fixed, hours of the day started in Germany in 1996, and was next implemented in the Netherlands in 1999. The overall success of international implementations prompted their introduction in the United States. In 2009, D-PTSU was first implemented in the United States in Minneapolis, Minnesota on I-35W.

D-PTSU means that the shoulder is opened or closed as needed—typically in response to observed or anticipated congestion. It differs from S-PTSU where there are predetermined (fixed) hours of operations. S-PTSU was implemented in the United States beginning in the 1970s and remains more common than D-PTSU. Noteworthy facilities include the original I-66 facility in Virginia (subsequently converted to D-PTSU and removed in 2018 as part of a major widening project); the US 2 trestle in Everett, Washington; GA 400 in suburban Atlanta; and several freeways in the Boston area. With D-PTSU, there may be core hours of operations when congestion is likely, and the shoulder is always opened during that time, even with a dynamic system (Jenior, Dowling, Nevers, & Neudorff, 2016). Recent installations of PTSU in the United States have tended to be dynamic. In 2015, Georgia DOT implemented D-PTSU on I-85 and Colorado DOT implemented D-PTSU on a rural section of I-70 with peak periods on weekends. In 2017, Michigan DOT implemented D-PTSU on US 23 and Washington State DOT implemented D-PTSU on I-405. In 2018, the Illinois Tollway implemented D-PTSU on 16 miles of I-90. Like European agencies, agencies in the United States are increasingly starting with D-PTSU rather than S-PTSU, enabling the added flexibility of D-PTSU and associated off-peak benefits to be realized.

Reasons for implementing D-PTSU include:

- Routine recurring congestion that is less predictable in time of occurrence and length of occurrence than typical morning and evening peak hours due to commuter traffic.
- Seasonal congestion during weekends and holidays primarily due to recreational travel.
- Anticipated congestion due to special events or incidents.
- High frequencies of non-recurring congestion for other reasons.
- Ability to more effectively close the shoulder by LCS if an incident or emergency warrants it and revert to a safety shoulder.

Typically, D-PTSU is applied where the demand exceeds capacity at certain times during certain days of the week, such as bottlenecks or similar problem areas in the network where there is both recurring and non-recurring congestion (e.g., special events, extreme weather conditions, and seasonal traffic). D-PTSU enables PTSU benefits at hours outside of a fixed schedule.

Considerations related to drivers when planning implementation of D-PTSU (EasyWay, 2015) include:

- Driver expectancy – drivers accustomed to the shoulder being closed versus open during certain hours of the day, days of the week, or during special events, and seasons.
- Underutilization – drivers having adaptation concerns and not using the facility even though it is open.
- Overutilization – drivers using the shoulder when it is closed because they are adapted to using it at other times of the day when it is open.

Figures 2 through 5 show dynamic part-time shoulder use facilities in the United States and internationally.

Source: © Kittelson & Associates, Inc.

Figure 2. Photo. Yellow dashed lines divide the left shoulder (used for part-time travel) from the general purpose lanes in Colorado.

Source: © Kittelson & Associates, Inc.

Figure 3. Photo. A lane-use control sign (on the far right side) indicates whether the shoulder is open or closed to traffic.

Source: © Justin Geistefeldt

Figure 4. Photo. A left shoulder is available for travel on a dynamic part-time shoulder use facility in the Netherlands.

Source: Danish Road Directorate (Vejdirektoratet)

Figure 5. Photo. A right shoulder is available for travel on a dynamic part-time shoulder use facility in Denmark.

DECISION TO OPEN/CLOSE DYNAMIC PART-TIME SHOULDER

The decision to open a shoulder to traffic depends on several factors that can broadly be grouped into two categories: logistical or policy considerations and traffic operations considerations. Specific logistical or policy considerations for opening and closing a shoulder dynamically include:

- Core hours of operations. Many agencies always open the shoulder during the a.m. peak, the p.m. peak, or both on weekdays. Opening at these times is more a function of policy and driver expectancy than realtime speed and volume conditions on the roadway.
- Maximizing safety and driver compliance by not opening or closing the shoulder unnecessarily.

- Legislative restrictions on hours of operations or days of use (if any).
- Coordination and agreements with emergency responders.
- Coordination with an agency's own maintenance activities.
- The capabilities of the traffic management center (TMC). TMCs may not have sufficient staff at all hours of the day to open the shoulder. Additionally, a TMC that has full coverage of the shoulder via closed-circuit television (CCTV) may be able to open the shoulder more frequently and rapidly than an agency with limited CCTV coverage or a policy requiring a physical "sweep," or inspection, of the shoulder by a maintenance or law enforcement vehicle.

While safety is the primary reason to close the shoulder, the traffic engineering profession does not currently have sufficiently precise tools for predicting the safety effects of D-PTSU. Consequently, it is logically assumed there is a safety benefit to closing the shoulder to traffic during low volume periods when it has no meaningful impact on congestion, but the magnitude of this impact cannot be quantified at this time as there is little field data and predictive models haven't been completed. Specific factors that can help an agency determine when to open or close a shoulder dynamically include:

- Traffic volumes above or below a certain threshold.
- Vehicle operating speeds below/above a certain threshold.
- A combination of the two.

These conditions may be observed in realtime or anticipated based on historical performance. Typical thresholds and techniques for determining facility-specific values are presented in chapter 4.

TMCs have generally relied on the experience of their operators to decide when to open and close D-PTSU lanes. This report is not intended to supplant that experience. Instead, this report provides information that inexperienced agency operators can use as a starting point for operating their D-PTSU, and which experienced operators can evaluate to see if they might improve the productivity of their D-PTSU.

The experience of the facility operators plays a key role in the decision to open and close the shoulder.

Interviews were conducted with officials from State departments of transportation (State DOT) in the United States and agencies internationally as part of this project's research. Interviews provided the following observations:

- First and foremost, the experience of the facility operators plays a key role in the decision to open and close the shoulder. This is particularly true on older facilities where operators have many years of experience.
- For State agencies that use a decision-support algorithm to recommend D-PTSU open and close decisions, historical traffic volume information is considered before the thresholds are set within the software. These thresholds are based on either traffic volume or both traffic volume and vehicle speeds.

- The thresholds for traffic volume range from 1,400-1,500 vehicles per hour per lane (veh/h/ln) and the thresholds for vehicle speeds range from 45-55 miles per hour (mi/h). Agencies primarily use one of the following: a volume threshold, a flow threshold, or a combination of the two. The specifics of this were not obtained from agencies because they were contained within proprietary algorithms.
- Some agencies do not use any sort of realtime information to open and close D-PTSU. They maintain hours of operations that are nearly fixed, with planned deviations such as opening the shoulder earlier on Friday afternoon compared to other weekdays and opening for known special events. This is particularly true on shorter or newer facilities.
- For agencies that open the shoulder at any time in response to traffic conditions, such as the Hessen state in Germany, opening usually occurs within 5 minutes of speed and volume thresholds being exceeded.
- D-PTSU facilities on I-405 in Washington, US 23 in Michigan, and I-66 in Virginia use a combination of decision support algorithms, historical traffic volume information, and operator discretion to open and close the shoulder for traffic. D-PTSU was removed on I-66 as part of a permanent widening project during the time this report was being prepared.
- The criteria for opening and closing the shoulder on I-70 in Colorado is traffic volume, and the shoulder is only open during peak recreational periods such as weekends during ski season, Christmas week, and some summer weekends. Colorado legally limits the opening of D-PTSU to 100 days per year. Hence, historical traffic volume information and trends are greatly used in open-and-close decisionmaking for this facility, and once it is opened it is kept open all day unless an incident or inclement weather occurs. The shoulder is closed during heavy snowfall as a safety measure.
- Similar to the D-PTSU facilities in the United States, the criteria to open D-PTSU facilities in Europe is based on higher traffic volumes and lower vehicle operating speeds. Control systems recommend opening the shoulder before the expected breakdown. Shoulders are closed when volume decreases, crashes occur, or when disabled vehicles occupy the shoulder.
- European agencies do not usually have set hours of operations. There is little or no static part-time shoulder use in Europe, and agencies are more comfortable without core hours of operations.
- Positive or negative safety impacts have not been demonstrated clearly in the United States because many facilities opened recently and do not have enough data to carry out the analysis. The safety benefits from studies conducted on European D-PTSU facilities are reported later in this chapter. Highway agencies generally provide emergency turnouts along the roadway section with D-PTSU. These areas act as refuges for disabled vehicles and reduce the frequency of incident-related shoulder closures.

KNOWN DEPLOYMENTS

Table 2 lists known D-PTSU deployments in the United States as of May 2018.

The first known installation of D-PTSU was in the German state of Westphalia in 1996.

D-PTSU was first implemented in the German state of North-Rhine Westphalia in 1996. It remains most common in Europe, with known applications in East Asia as well. The United Kingdom was once a key PTSU country but has migrated to a strategy called "All Lanes Running" that is more like converting the shoulder to a permanent lane. Table 3 lists known D-PTSU deployment internationally as of May 2018. Appendix B provides fact sheets for selected worldwide D-PTSU facilities and agencies.

Table 2. Dynamic part-time shoulder use facilities in the United States.

Location	Corridor	Length (mi)	Year	Shoulder Used	Max. Speed Allowed	Lane Width (ft)	Notes
Idaho Springs, Colorado	I-70 EB	13.0	2015	Left	Variable speed limit	11	Dynamically-priced lane, primarily used in ski season weekends and holidays and some summer weekends. Between US 40/Empire and Idaho Springs. Must be used less than 100 days a year per legislation.
Gwinnett County, Georgia	I-85 NB	1.3	2015	Right	Freeway posted speed	11-12	Initially opened with fixed hours of operations, now operated dynamically. Primarily used on weekday afternoons. Auxiliary lane between two interchanges.
Ann Arbor, Michigan	US 23	8.5	2017	Left	Variable speed limit (~60 mi/h)	11-12	Between M-14 and M-36 in both directions. Primary used in morning and afternoon peaks
Minneapolis, Minnesota*	I-35W NB	3.0	2009	Left	Freeway posted speed	11-12	Priced Lane located at end of managed lane on I-35W northbound between 42nd Street and downtown Minneapolis was routinely opened on weekends and throughout daytime on weekdays. Now removed as part of a major widening project.

* I-35W was removed in 2018 as part of major widening projects.

Table 2. Dynamic part-time shoulder use facilities in the United States. (continued)

Location	Corridor	Length (mi)	Year	Shoulder Used	Max. Speed Allowed	Lane Width (ft)	Notes
Fairfax County, Virginia*	I-66	6.5	2015	Right	Variable speed limit	12	Was static from 1992-2015, and dynamic from 2015-2018. From 2015-2018 it was routinely opened in the off-peak direction and on weekends. Extended in both directions from US 50 to I-495 and roadway had HOV lane on the left side. Now removed as part of major widening project
Lynnwood, Washington	I-405 NB	1.8	2017	Right	Variable speed limit	13	Between SR 527 interchange and I-5 interchange. Open during core hours in afternoon peak. Core hours begin earlier on Friday year-round and on Thursday in the summer.
Chicago, Illinois	I-90	16	2017	Both	Freeway posted speed	12	Shoulders are not routinely opened (except to buses) but can be opened any time for incident management purposes. Between I-294 and Barrington Road in both directions on Jane Addams Tollway

* I-66 was removed in 2018 as part of major widening projects.

Table 3. International dynamic part-time shoulder use facilities.

Location	Corridor	Length (mi)	Year	Notes
Germany:Baden-Wuerttemberg	A 8	2.6	2013	Stuttgart interchange – Stuttgart-Moehringen (both directions)
Germany: Bavaria	A 8	6.1	2005	Hofoldinger Forst – Holzkirchen
	A 8	9.8	2007	Holzkirchen – Munich-South interchange
	A 9	18.9	2012-2017	Holledau interchange – Neufahrn interchange (both direct.)
	A 73	6.8	2008	Forchheim-South – Erlangen-North
	A 99	11.1	2001-2005	Munich-North interchange – Haar (both directions)

Table 3. International dynamic part-time shoulder use facilities. (continued).

Location	Corridor	Length (mi)	Year	Notes
Germany: Hessen	A 3	6.7	2001	Hanau – Offenbach (both directions)
	A 3	2.8	2004/2007	Kelsterbach - Moenchhof interchange (both directions)
	A 3	4.9	2015	Limburg-North - Diez
	A 5	11.5	2003	Friedberg – Frankfurt North-West interchange (both direct.)
	A 5	2.1	2008	Frankfurt interchange – Frankfurt-Niederrad
	A 5	3.9	2010	Darmstadt-Eberstadt - Darmstadt interchange (both direct.)
Germany: Lower Saxony	A 7	20.1	2005	Soltau-Ost – Walsrode interchange (both directions)
Germany: North Rhine-Westphalia	A 4	1.0	1996	Refrath – Cologne-Mehrheim
	A 45	1.9	2014	Schwerte/Ergste – Westhofen interchange
	A 57	1.9	2011	Cologne-Longerich – Cologne-Bickendorf
Germany: Rhineland-Palatinate	A 63	5.6	2011	Saulheim – Mainz-South interchange (both directions)
The Netherlands	A1	2.9	2011	Bussum - kp.Eemnes
	A1	2.8	2011	kp.Eemnes - Bussum
	A1	4.4	2008	kp. Hoevelaken - Barneveld
	A2	9.5	2011	kp.Vonderen - Urmond
	A2	10.2	2011	Urmond - kp.Vonderen
	A4	0.9	2005	Leidschendam - kp.Prins Clausplein
	A12	0.5	2005	knp.Prins Clausplein - Voorburg
	A4	1.5	2011	kp.Nieuwe Meer - kp.Badhoevedorp
	A10	1.7	2011	kp.Amstel - kp.Nieuwe Meer
	A4	1.6	2011	kp.Badhoevedorp - kp.Nieuwe Meer
	A10	2.2	2011	kp.Nieuwe Meer - kp.Amstel
	A8	0.8	2007	kp.Zaandam - kp.Zaandam
	A7	4.8	2007	kp. Zaandam - Purmerend-Zuid
	A7	5.5	2015	Purmerend - kp. Zaandam
	A8	0.9	2015	kp. Zaandam - Oostzaan
	A9	3.9	2011	kp. Rottepolderplein - Velsen
	A9	4.8	2011	Velsen - kp.Raasdorp
	A9	5.5	2011	Uitgeest - Alkmaar
	A9	6.2	2011	Alkmaar - Uitgeest
	A13	3.1	2007	Berkel en Rodenrijs - Delft - Zuid
	A15	0.5	1999	Papendrecht - Sliedrecht-West

Table 3. International dynamic part-time shoulder use facilities. (continued).

Location	Corridor	Length (mi)	Year	Notes
	A27	3.1	2011	kp.Everdingen - Houten
	A50	11.7	2006	kp.Waterberg - kp.Beekbergen
	A50	11.7	2006	kp.Beekbergen - kp.Waterberg
	A1	8.6	2006	kp.Beekbergen - Deventer -Oost
	A1	7.6	2006	Deventer - Oost - knp.Beekbergen
	A12	14.6	2012	Bunnik - Veenendaal West
		5.1	2009	Veenendaal West - Ede
	A12	4.3	2009	Ede - Veenendaal West
		15.1	2012	Veenendaal West - Bunnink
	A12	6.6	2010	Zoetermeer - kp.Gouwe
	A12	1.5	2010	Afrit Gouda - kp.Gouwe
		6.9	2010	kp.Gouwe - Zoetermeer
		2.5	2011	Zoetermeer - Zoetermeer-Centrum
	A20	1.8	2006	R'dam Pr. Alexander - kp.Terbregseplein
	A27	3.1	1999	Houten - kp. Everdingen
	A27	3.4	2006	kp.Gorinchem - Noordeloos
	A28	3.9	2004	Zwolle-Zuid - Ommen
	A28	3.8	2004	Ommen - Zwolle-Zuid
	A28	2.6	2013	Leusden Zuid - kp.Hoevelaken
	A28	3.6	2013	kp.Hoevelaken - Leusden Zuid
	A15	1.9	2015	Trentweg - Welplaatweg
	A15	1.9	2015	Welplaatweg - Trentweg
Denmark	M13	1.2	2016	Hillerød Freeway b/n Junction 8 and Junction 6
South Korea	R 1	64.7	Unknown	Gyeongbyu Expressway
	R 100	1.3	Unknown	Seoul Belt/Ring Expressway
	R 50	32.9	Unknown	Yeongdong Expressway
	R 15, 50, 110	11.0	Unknown	Seohaean Expressway
	R 10, 102	0.8	Unknown	Namhae Expressway
	R 45	1.1	Unknown	Jungbu Naeryuk Expressway
	R 55	6.2	Unknown	Jungang Expressway
United Kingdom	M42, J3, A7	11	2006	40 km deployed, 400 km of HSR identified by Highways Agency
France	A4 – A86	1.4	2005	
	A3 – A86	Unknown	Unknown	
	A48	Unknown	Unknown	
	A1	Unknown	Unknown	

Note: German implementations in Baden-Wuerttemberg, Bavaria, and Hessen have a variable speed limit. The other German implementations have a maximum speed limit of 100 km/h (62.13 mi/h).
D-PTSU = dynamic part-time shoulder use.

DYNAMIC PART-TIME SHOULDER USE RESEARCH

This section includes a summary of the operational and safety analysis findings of the dynamic part-time shoulder deployment in the United States and internationally.

Operations

A study conducted in Germany reported a 20-25 percent increase in the capacity of a freeway after the implementation of D-PTSU (Geistefeldt J., 2012). The freeway has three general purpose lanes per direction, which the shoulder providing a fourth lane when it is open.

The German Highway Capacity Manual includes the design capacities for freeways with D-PTSU presence internal and external to the urban areas (FGSV, 2015). The design capacities in vehicles per hour (veh/hr) for basic freeway segments with a gradient of less than or equal to 2 percent with the presence of D-PTSU are:

- Two lanes plus PTSU in a rural area: 4,200 veh/hr to 4,700 veh/hr.
- Two lanes plus PTSU in an urban area: 4,400 veh/hr to 5,200 veh/hr.
- Three lanes plus PTSU in a rural area: 5,600 veh/hr to 6,300 veh/hr.
- Three lanes plus PTSU in an urban area: 6,000 veh/hr to 7,000 veh/hr.

In each case above, the lower capacity value reflects a heavy vehicle percentage of approximately 30 percent, and the higher capacity value reflects a heavy vehicle percentage of approximately 5 percent. The number of lanes reflects the number of lanes in one direction not including a part-time lane on the shoulder.

A study conducted in Denmark reported that the average travel time was reduced by 1-3 minutes on a 9.32-mile section from Allerod to Motorring 3, and 5 minutes on a 7.45-mile section towards junction 6. The traffic volume on the freeway increased after D-PTSU opened, and much of the traffic shifted from local roads onto the freeway (Danish Road Directorate, 2016).

Colorado DOT found there was a 14 percent increase in the throughput, a 38 percent improvement in travel time in general purpose lanes, and an 18 percent increase in the average vehicle speeds across all lanes of eastbound I-70 during high traffic volume periods on the weekends after D-PTSU was implemented (CDOT, 2017).

Safety

The study results in this section are categorized into three types based on findings: positive impacts on safety, negative impacts on safety, and challenges regarding the safety performance evaluation of D-PTSU facilities. The majority of safety studies conducted in Germany and the Netherlands indicated that D-PTSU has a positive effect on safety, but studies in the United States have had more mixed results.

A before-after safety study on freeway A3 in the Hessen state of Germany reported there has been a nearly constant crash rate on the D-PTSU segment, whereas fewer upstream crashes, specifically congestion-related (i.e., rear-end) crashes, occurred after D-PTSU implementation (Geistefeldt J. , 2012). The crashes were disaggregated into personal injury and property damage only crashes for this analysis. By reducing queuing and increasing speed through a bottleneck area, researchers noted that D-PTSU can reduce upstream congestion-related crashes. This positive safety finding led Hessen to implement D-PTSU on other freeways. (Jones, Knopp, Fitzpatrick, & et. al., 2011).

A study in the Netherlands in 2007 found that D-PTSU reduced crash frequency by 25-28 percent due to the reduction in the upstream congestion. During "low-" and "high-" volume situations, the study from the Netherlands found a D-PTSU lane on the right is more crash-prone than a general-purpose lane. Like the United States, drivers in the Netherlands drive on the right side of the road. However, D-PTSU has safety benefits when there is a "medium" traffic volume (the study does not specify what constitutes high, medium, and low volumes), which has been observed in other countries as well (Rijkswaterstaat, 2007). A later study in the Netherlands noted that traffic on a right shoulder tends to travel more slowly than traffic in general-purpose lanes, but traffic on a left shoulder tends to travel faster than traffic in general-purpose lanes. Despite the higher speeds, the left shoulder tends to have fewer crashes because there are no conflicts with ramp traffic.

The majority of safety studies conducted in Germany and the Netherlands indicated that D-PTSU has a positive effect on safety, and U.S. studies have had mixed results.

A study conducted on a segment of I-66 in Virginia reached similar conclusions: crash frequency dropped by 8 percent after S-PTSU to D-PTSU conversion. This study involved a before-after safety analysis using crash data for 1 year before and after September 2015, when conversion of the facility from S-PTSU to D-PTSU occurred. The segment has a left-side high-occupancy vehicle (HOV) lane and right-side D-PTSU. The crash modification factors (CMFs) for all severities of crashes are:

- 0.75 for all crash types.
- 0.71 for multiple-vehicle crashes.
- 0.69 for rear-end crashes.

The CMFs for fatal and injury crashes are:

- 0.69 for all crash types.
- 0.59 for multiple vehicle crashes.
- 0.61 for rear-end crashes (Suliman, 2017).

Some safety studies concluded that there are negative effects in the safety performance between the hours when the part-time shoulder use was open and closed to traffic. An older study on the shoulder use segment on I-66 in Virginia when it was an S-PTSU facility stated that, for the crashes specific to the right shoulder, motorists' behaviors at the merge and diverge areas during adverse light conditions are significant, and there was an increase of about 38 percent in all crashes (Lee, Dittberner, & Sripathi, 2007).

Following the implementation of D-PTSU on I-35W, Minnesota DOT observed that rear-end crash frequency increased in certain roadway sections in the D-PTSU region. Additional analysis showed that the observed increase in the crash frequency was attributed to the change in traffic volume and traffic patterns. The analysis also indicated no direct effect on the likelihood of rear-end crashes due to the operations of the D-PTSU lane (Davis, 2017).

The challenges in evaluating safety performance of those segments with D-PTSU installations include a lack of crash data for evaluation and changes in volume after the D-PTSU opened. Most of the D-PTSU segments in the United States are relatively short and have been implemented in the last few years. Hence, there is limited crash data for identifying the trends in the safety performance of the roadway with D-PTSU. For example, Washington State DOT (WSDOT) reported that in the first 5 months of D-PTSU operations on northbound I-405 between SR 527 and I-5, 11 incidents were reported on the roadway section, including 4 crashes, 6 disabled vehicles, and 1 unclassified incident (Hanson & Westby, 2017). However, this is not enough data to identify the trends in the safety performance of the D-PTSU segment.

Currently, the National Cooperative Highway Research Program is conducting research under Project 17-89, Safety Performance of Part-time Shoulder Use on Freeways. A report on the findings is expected to be available in 2020.

ADVANTAGES AND CHALLENGES OF D-PTSU OVER S-PTSU

S-PTSU has several traffic operational benefits over a conventional shoulder that is closed to traffic at all times (24/7). These benefits apply to peak congestion hours, typically on weekdays. D-PTSU expands the operational benefits of S-PTSU beyond recurrent weekday peak congestion hours to the rest of the day and throughout the week, including weekends.

D-PTSU expands the operational benefits of S-PTSU beyond recurrent weekday peak congestion hours to the rest of the day and throughout the week.

S-PTSU requires adequate horizontal, vertical, and lateral geometry for traffic operations on the shoulder. The pavement structural section and drainage should be adequate to accommodate the expected traffic loads to the operating agency's satisfaction. S-PTSU reduces the shoulder space available for breakdowns, emergency response, incident clearance, enforcement, crash investigations, and emergency maintenance during the hours of the day when the S-PTSU is open. In addition, when snow is present S-PTSU increases the freeway cross-section that should be plowed and decreases the space available for temporary snow removal storage.

D-PTSU has the same needs and challenges as S-PTSU, extending those same challenges to additional hours and days of the week. In addition, D-PTSU requires a level of traffic management infrastructure and organization much greater than that required by S-PTSU. Agencies should have advanced facility monitoring, maintenance, and operations capabilities on the facility. In addition, facility operations, maintenance, emergency response, and enforcement operations should be well coordinated at all times when the possibility of opening the shoulder exists.

COSTS OF DYNAMIC PART-TIME SHOULDER USE

Table 4 provides a list of the potential cost component considerations for D-PTSU and S-PTSU. This list is based on a review of prior Federal Highway Administration (FHWA) documents and outreach to agencies operating D-PTSU facilities.

Part-time shoulder use is one of the strategies addressed by the Tool for Operations Benefit-Cost (TOPS-BC), a spreadsheet-based tool developed by FHWA for benefit-cost analysis. Part-time shoulder use is identified in TOPS-BC as “Advanced Transportation Demand Management Hard Shoulder Running.” The user will likely need to modify default unit costs and add inputs to address the specifics of any particular location and application. See the FHWA report on the Use of Freeway Shoulders for Travel for more information on cost-benefit analysis.

Table 4. Cost component considerations for dynamic part-time shoulder use and static part-time shoulder use.

Cost Component	D-PTSU	S-PTSU
Capital Cost Component		
System engineering process activities	Typically needed	Typically needed
Shoulder reconstruction, widening	Sometimes needed	Sometimes needed
Emergency turnout construction	Sometimes needed	Sometimes needed
Ramp widening/improvements	Sometimes needed	Sometimes needed
Gantry structure spanning roadway or cantilever structure	Typically needed	Sometimes needed
Pavement marking modifications	Typically needed	Typically needed
Initial training of operations/maintenance personnel, law enforcement, and others as needed.	Typically needed	Typically needed
Public outreach/communication campaigns	Typically needed	Typically needed
ITS Capital Cost Components		
Speed sensors, vehicle detectors, travel time indicators	Typically needed	Not needed
Camera/surveillance system	Typically needed	Sometimes needed
Dynamic/Changeable Message signs	Typically needed	Sometimes needed
Overhead lane use control signals	Potentially needed to supplement dynamic/ changeable message signs	Not needed
Variable speed limit sign system	Sometimes needed	Sometimes needed
Controllers	Typically needed	Not needed
Communications and power software	Typically needed	Not needed
Central hardware and TMC enhancements	Typically needed	Not needed

Table 4. Cost component considerations for dynamic part-time shoulder use and static part-time shoulder use. (continued)

Cost Component	D-PTSU	S-PTSU
Ongoing Operations/Maintenance Components		
Additional TMC staff or hours of staffing	Typically needed	Sometimes needed
Emergency patrols	Typically needed	Typically needed
Upgraded/enhanced level of enforcement	Typically needed	Typically needed
Training for operations/maintenance personnel and law enforcement	Typically needed	Typically needed
Pre-Opening Sweeps	Typically done in the field or remotely with CCTV	Typically done in the field or remotely with CCTV
Maintenance and snow removal similar to general purpose lane	Typically needed	Typically needed
Ongoing maintenance costs and replacement costs of signs, structures, pavement marking, etc.	Typically needed	Typically needed, but quantity of equipment may be less
Upgraded TMC operations – Integrated operator, first responder, maintenance, and enforcement communications	Typically needed	Sometimes needed.
Upgraded operating procedures	Typically needed	Sometimes needed
Upgraded ITS maintenance program/ongoing maintenance and replacement costs of all ITS-related equipment and infrastructure	Typically needed	Sometimes needed

CCTV = closed circuit television. ITS = intelligent transportation systems. TMC = transportation management center.

Source: Adapted from FHWA. 2015. *Use of Freeway Shoulders for Travel – Guide for Planning, Evaluating, and Designing Part-Time Shoulder Use as a Traffic Management Strategy*, FHWA-HOP-15-023, Washington, DC. Tables 8 and 9, available at: https://ops.fhwa.dot.gov/publications/fhwahop15023/index.htm, last accessed February 20, 2019.

Michigan DOT (MDOT) and WSDOT provided general cost estimates from their experiences with D-PTSU. MDOT provided the research team with the bid tab summary report for the US 23 project. The research team also reviewed the 2018 Weighted Average Item Price Report on MDOT's website. MDOT found that for a 17 mile-project on US 23 that used ½-mile gantry spacing, the overall ITS system cost approximately $17 million. This translates to roughly $500,000 per gantry location (Palmer, 2018). WSDOT reported an estimated cost of $200,000-$300,000 per location using a signal pole/mast arm system instead of gantries. WSDOT's advanced transportation management software was written and modified for dynamic shoulder lane use in-house and was not included with the estimated costs (Dang, 2018). According to WSDOT's 2010 Congestion Report Gray Notebook Special Edition, a "smarter highways" gantry with variable message and speed signs like those often used with D-PTSU included can range from $650,000 to $900,000 (FHWA, 2018).

The research team also reviewed Virginia DOT's pay item list of statewide averages for May 1, 2016, through June 1, 2018, and the FHWA Intelligent Transportation Systems Joint Program Office Cost database.

Table 5 lists some estimated cost ranges associated with some of the main items necessary for D-PTSU projects. Each project and location will have unique characteristics and design requirements, but these ranges can provide an initial or planning-level viewpoint for agencies as they consider this strategy.

Table 5. Estimated cost ranges for key components.

Component	Estimates	Sources/References
Gantry structure spanning roadway or cantilever structure	$200,000-$400,000 each	MDOT
Speed sensors, vehicle detectors, travel time indicators	$5,000-$20,000 each	MDOT; FHWA-HOP-13-029; ITS-JPO Costs Database for Roadside Detection
Camera/surveillance system	$10,000-$20,000 each	MDOT; VDOT; ITS-JPO Costs Database for Roadside Detection
Dynamic/changeable message signs	$160,000-$220,000 each	MDOT; VDOT
Overhead lane use control system	$30,000-$60,000 each (1-panel system) $100,000-$170,000 each (3-panel system)	MDOT
Variable speed limit sign system	$50,000-$250,000	Rural Intelligent Transportation Systems (ITS) Toolkit, Variable Speed Limit
Controllers	$15,000-$25,000	ITS-JPO Cost Database – DMS sign controller (Colorado DOT); MDOT

CDOT = Colorado Department of Transportation. DMS = dynamic message signs. ITS-JPO = Intelligent Transportation Systems Joint Program Office. MDOT = Michigan Department of Transportation. VDOT = Virginia Department of Transportation.

Note that these cost estimates are based on averages reported in the FHWA JPO Costs Data Base and construction on specific projects completed in Michigan and Virginia over the period 2010 to 2016. They reflect the specific conditions of those designs, localities and periods of time.

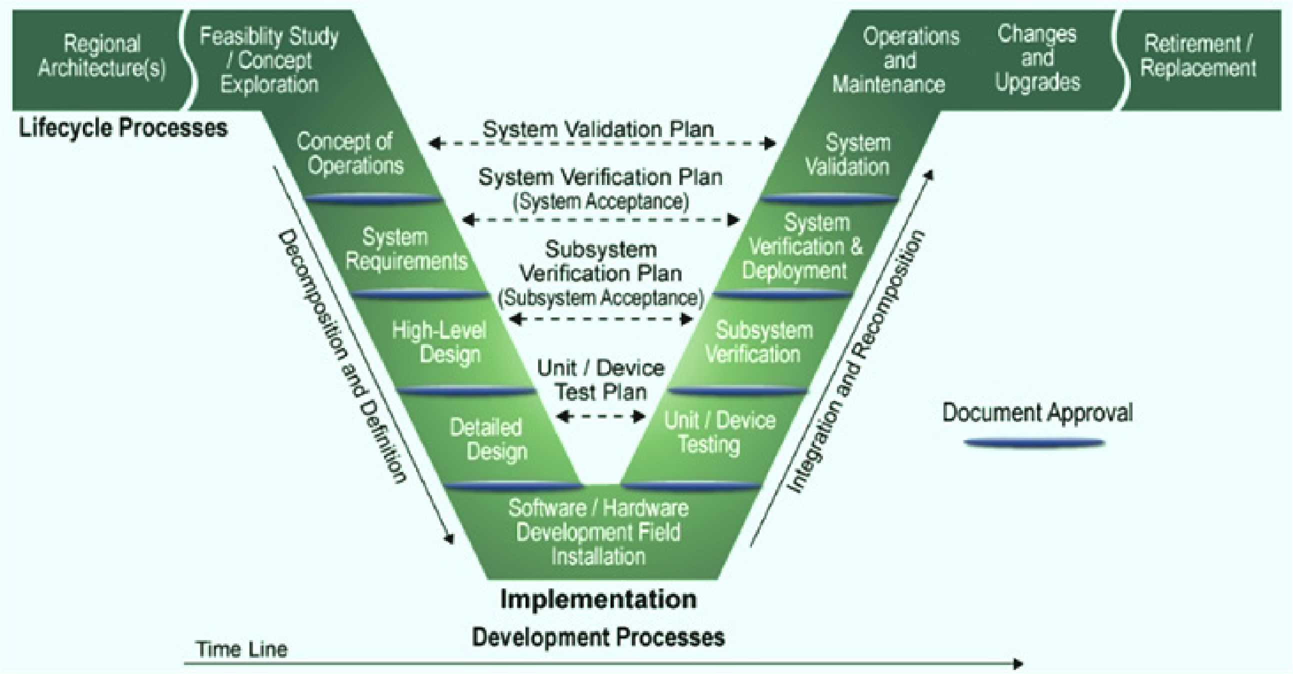
CHAPTER 3. DECISION SUPPORT FRAMEWORK FOR DYNAMIC SHOULDER USE OPERATIONS

This chapter describes the considerations for developing a concept of operations (ConOps) for dynamic part-time shoulder use (D-PTSU). It describes the overall concept of decision parameters for opening and closing a freeway shoulder to traffic, describes the various levels of dynamic operations for PTSU, and provides a decision support framework for choosing the decision parameters based in part on the level of D-PTSU. Methods for selecting initial decision parameter values are provided in the next two chapters.

SYSTEMS ENGINEERING

D-PTSU projects are ITS projects and require systems engineering if federal funds are used.

Systems engineering, in general, is an organized, interdisciplinary approach to developing and implementing a system. For Intelligent Transportation System (ITS) projects using Federal-aid highway funds, a systems engineering analysis is required per 23 CFR 940.11. D-PTSU projects, by their very nature, are ITS projects. A variety of methods exist for systems engineering, including iterative methods (e.g., Agile), and the waterfall method. The waterfall method, illustrated with a Vee diagram, is shown in figure 6 and lists activities commonly done as part of systems engineering. Developing a concept of operations is a key systems engineering activity and is where the details of D-PTSU operation are determined and documented.



Source: FHWA (https://ops.fhwa.dot.gov/plan4ops/sys_engineering.htm)

Figure 6. Diagram. Systems Engineering V diagram for intelligent transportation systems projects.

This diagram captures pre-installation activities such as planning, requirement specification, and design, as well as post-installation activities such as testing, validation, operations, and maintenance. D-PTSU systems often make us of existing ITS infrastructure, add additional infrastructure for D-PTSU, and sometimes add additional infrastructure for other ATM treatments such as variable speed limits. Systems engineering provides a process for agencies to ensure the necessary components are installed and function both independently and with each other so the D-PTSU system operates efficiently and as intended. A key step in the systems engineering process is the development of a concept of operations (ConOps) document that specifies how D-PTSU will operate and "look" to drivers. The following section provides additional information on ConOps documentation.

DEVELOPING THE CONCEPT OF OPERATIONS

A typical ConOps document prepared by an agency implementing D-PTSU describes the rationale for selecting D-PTSU, the objectives for the operations of D-PTSU, and how the D-PTSU will be operated from the points of view of the agency operator of the facility, maintenance personnel, emergency responders, transit operators, local agencies, and any other relevant stakeholders. The ConOps and its more detailed supporting documents and references, provide the "road map" for how the D-PTSU will be operated by the agency. A typical ConOps for a D-PTSU will contain the following sections:

1. Executive Summary called the "Scope" that provides an overview of the contents of the ConOps.
2. Introduction laying out the objectives for operations of D-PTSU, performance measures, and identifying partners and stakeholders.
3. Background describing the setting, listing assumptions and constraints, and listing the resource documents used in preparation of the ConOps.
4. Operations of the D-PTSU from the points of views of the partners/stakeholders. Scenarios may be used to help flesh out the operating parameters for each partner.
    a. Transportation management center (TMC) operations.
    b. Maintenance operations.
    c. Emergency responder operations.
    d. Transit operations.
    e. Local agency interface.
    f. Other.

Additional information on the preparation of a ConOps can be found in the Federal Highway Administration (FHWA) report: *Developing and Using a Concept of Operations in Transportation Management Systems*, FHWA-HOP-07-001.

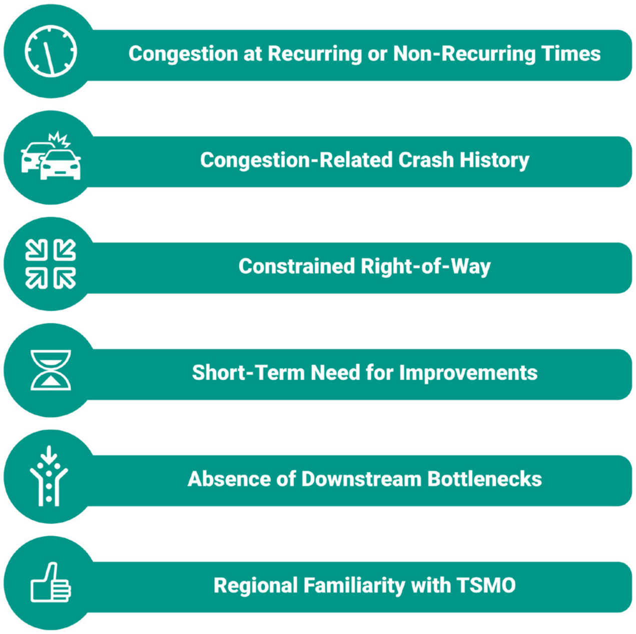
The remainder of this chapter will walk readers through the key decisions unique to D-PTSU that should be made in the course of preparing the ConOps for D-PTSU. The key decisions include:

1. The level of D-PTSU.
2. Selection of decision parameters for opening and closing D-PTSU.
3. Development of decision support framework for opening and closing D-PTSU.
4. Determining if and when D-PTSU should become a conversion to a full-time lane.

The following two chapters then describe various methods that an agency might employ to select the decision parameters for opening and closing D-PTSU. These initial values can be included in the initial ConOps draft and should be refined later on as the agency gains operating experience with D-PTSU.

CANDIDATE PART-TIME SHOULDER USE FACILITIES

As discussed in chapter 1 of this report and more broadly in the 2016 FHWA report on the Use of Freeway Shoulders for Travel, PTSU—whether dynamic or static—is not appropriate for all freeways. Figure 7 lists characteristics of facilities particularly well-suited for PTSU operations.



Source: FHWA

Figure 7. Diagram. Considerations in choosing part-time shoulder use.

SELECTING THE LEVEL OF DYNAMIC PART-TIME SHOULDER USE

As part of the development of the ConOps, the agency should conduct a self-assessment of its capabilities for operating D-PTSU. The ConOps should document this self-assessment and provide the rationale for the selected level of D-PTSU to be implemented.

When it comes to opening and closing the shoulder on D-PTSU facilities, agency practices fall within a spectrum of options rather than a single operational model. This spectrum encompasses unique attributes of traffic patterns, driver populations, and agency capabilities from facility to facility. The levels presented in table 6 can help agencies understand what characteristics their PTSU facilities may initially have and what characteristics they may eventually have as they mature. The levels do not represent rigid categories, but are intended to capture the range of existing PTSU practices or those that can be planned. As agencies move to a higher level, better operations results are expected, but each higher level also requires more resource, staffing, and funding commitment by the agency. Generally speaking, agencies opening their first PTSU facility may want to start with level 1 or 2 operations and progress to higher levels over time as they become more comfortable and skilled with D-PTSU operation. In general, higher levels are more beneficial over the long term, although on shorter facilities it is possible that the benefits of a higher level of PTSU do not outweigh the costs.

Table 6. Levels of part-time shoulder use.

Level	Title	Description
0	No part-time shoulder use (PTSU)	Shoulder is never opened to traffic.
1	Static PTSU	Shoulder is only opened to traffic at predictable, fixed hours of day and days of week.
2	Dynamic PTSU with core hours and scheduled variation	Shoulder is opened to traffic during recurring “core” hours and days of the week and may also be opened outside of those core hours in a scheduled, pre-determined manner for special events or seasonal variations.
3	Dynamic PTSU with core hours and unscheduled variation	Shoulder is opened to traffic during recurring “core” hours and days of the week and may also be opened outside of those core hours in response to realtime or anticipated traffic conditions.
4	Fully Dynamic PTSU	Shoulder is opened and closed purely in response to or in anticipation of factors such as traffic congestion, demand surges, events, incidents, weather, maintenance needs, incident management needs, or enforcement needs. There are no “core” hours and days of the week when the shoulder is always opened regardless of traffic conditions.

For any level of PTSU (except for level 1 with static signs), a shoulder may be closed during “core” hours of operations for many reasons; for example, if the shoulder is physically blocked (e.g., by a disabled vehicle), if an agency deems it is unsafe to open the shoulder (e.g., during a snowstorm), or if another stakeholder requests it (e.g., law enforcement in response to an incident in adjacent general purpose lanes). Further discussion on each level follows.

Level 1 (Static PTSU) can serve as a precursor to dynamic PTSU. Some agencies have operated a static PTSU facility for the first few months of operations and then moved to dynamic operations as they and other stakeholders became more comfortable with PTSU. S-PTSU needs the same physical roadway conditions needed for D-PTSU, such as, for example, shoulder width, pavement quality, pavement markings, or offsets to fixed objects.

Level 2 (Dynamic PTSU with core hours and scheduled variation) is similar to S-PTSU on most days of the year. Variations to core hours of operations are known and communicated in advance to stakeholders such as law enforcement and emergency responders. For example, with Level 2 D-PTSU, the shoulder may be opened on weekends or earlier on a Friday afternoon than other weekday afternoons due to a special event. Such an opening/closing schedule could be predetermined and could be reflected in interagency agreements, memorandums of understanding, or legal statutes that authorize PTSU at certain times.

Level 3 (Dynamic PTSU with core hours and unscheduled variation) is more responsive to traffic conditions than Level 2 D-PTSU. In a Level 3 deployment, the shoulder is opened on an ad-hoc basis if traffic conditions merit. Core hours of operations would remain so that the shoulder is always open regardless of traffic conditions (unless it is physically blocked, or an agency deems it is unsafe to open the shoulder). Users of the shoulder (e.g., maintenance workers, emergency responders, and law enforcement) should be aware that they will need to adapt to the shoulder being open on short notice at any given time. Operating agencies will need appropriate TMC and incident management personal in place at all hours.

Level 4 (Fully Dynamic PTSU) deployments open the shoulder in response to realtime and projected traffic conditions alone and do not maintain core hours of operations. Historical volumes, speeds, and other data may influence when an agency chooses to open and close the shoulder, but there is no “commitment” or “expectation” to open during certain hours if conditions on a given day do not merit it. Many European agencies, including the Hessen state in Germany, use Level 4 D-PTSU. Level 4 D-PTSU is also well suited for freeways with non-recurring congestion such as rural intercity routes and rural recreational routes where core hours of operations could not be determined.

These levels of D-PTSU are somewhat analogous to the Capability Maturity Model (CMM) used to characterize a region or an agency’s abilities and experience with transportation systems management and operations (TSMO). It is generally easier for an agency with PTSU experience to implement Level 4 D-PTSU than it is for an agency without PTSU experience. The D-PTSU levels and CMM levels are not intended to correspond to one another (i.e., it is not implied that Level 3 D-PTSU is most appropriate for a CMM Level 3 agency).

SELECTING SHOULDER OPERATIONS DECISION PARAMETERS

One of the key pieces of information to be included in the ConOps is the set of performance measures and thresholds that will be initially used to determine when to open and close the shoulder to traffic. These initial values may then be refined later as the agency operator gains experience with the D-PTSU and as demand patterns evolve on the facility.

Full shoulders provide safety benefits for the traveling public on a freeway facility. Shoulders provide a place for disabled vehicles, enforcement, maintenance, and temporary snow storage that is away from the travel lanes. Shoulders should not be used for travel unless the benefits (safety and delay improvements) of opening the shoulder to travel exceed those of keeping the shoulder closed.

Research and international operating experience (see chapter 2) suggest that shortly before the beginning of traffic congestion (breakdown of smooth traffic flow on the freeway) is an appropriate point for dynamically opening a shoulder to travel. “Breakdown,” as defined in the Highway Capacity Manual, is “The transition from noncongested conditions to congested conditions typically observed as a speed drop accompanied by queue formation.” (TRB 2016) The appropriate point for closing the shoulder is when it will not cause congestion in the full-time lanes of the freeway. This is the basic philosophy behind establishing decision parameters for when the shoulder should be dynamically opened and closed. Chapters 4 and 5 cover specific traffic operations decision parameters for opening and closing the shoulder in greater detail.

Breakdown is the transition from noncongested to congested conditions typically observed as a speed drop accompanied by queue formation.

Other considerations related to policies or physical condition of the roadway may override the traffic operations decision parameters. For example:

- Obstructions on the shoulder such as debris, snow, ice, disabled vehicles, enforcement personnel, and maintenance equipment may prevent or delay the agency from opening the shoulder lane to traffic.
- Agreements with emergency responders or law enforcement may limit times that the shoulder can be opened.
- Legislation may place statutory limits on when and/or how frequently the shoulder may be opened.
- Opening the shoulder typically requires one or more dedicated TMC staff to be present, and these personnel may not be available 24 hours a day.
- Environmental approval of projects may be contingent upon the shoulder remaining closed at some times to minimize air quality, noise impacts, and associated mitigations.

Nationally and internationally, the process of opening and closing the shoulder has historically been mostly up to the discretion and experience of operators in the TMC. Some TMC operators will have predictive algorithms or control systems to support their decisionmaking process in the transportation management center, while others make decisions without software by reviewing incoming data. On level 3 and 4 D-PTSU facilities, operators have historically opened the shoulder lane based on the thresholds of traffic volumes, speeds, or core hours of operations prior to the expected breakdown.

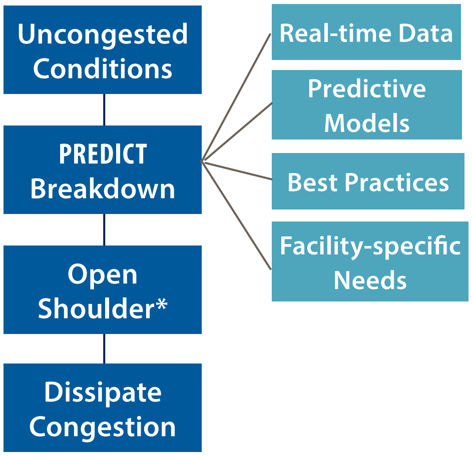
Interviews with agency operators indicated they currently use one or more of the following traffic operations decision parameters to determine when to open the shoulder lane to travel:

- Traffic volume greater than or equal to 1,400-1,500 vehicles per hour per lane (veh/h/ln).
- Vehicle speeds less than or equal to 40-55 mi/h. These speeds are different in the United States, Europe, and South Korea and change from facility to facility.
- Consistent peak periods from historical traffic volume information.
- Special events.
- Congestion caused from crashes.
- Operator's discretion, based on experience.

Agencies generally use one or more of the following decision parameters to determine when they should close the shoulder to travel:

- Traffic volume less than 1,400-1,500 veh/h/ln (if shoulder were to be closed).
- Vehicle speeds greater than 40-55 mi/h.
- After the peak periods.
- Crashes and obstructions on the shoulder.
- Disabled vehicles.
- Extreme roadway and weather conditions (the shoulder is not opened or closed if open).
- Operator's discretion, based on experience.

As shown in figure 8, an agency may use several metrics for predicting traffic breakdown and therefore determining when to open the shoulder to travel. Metrics include historical data on when congestion has occurred in the past, traffic model predictions of congestion (breakdown), best practices from other agencies operating similar facilities, as well as conditions and needs specific to the local facility.

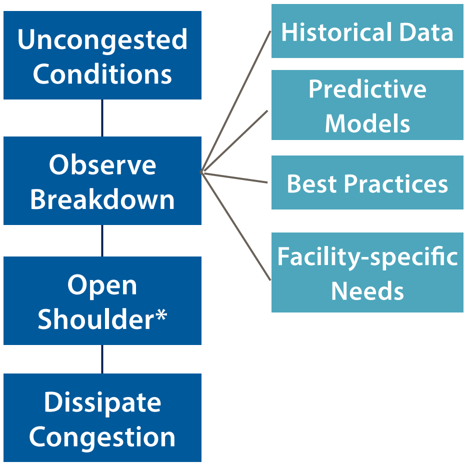


* Assuming there are no issues with maintenance , law enforcement, environmental conditions. etc.

Source: FHWA

Figure 8. Diagram. Decision parameters for opening a shoulder to travel based on predicting breakdown.

If an agency is unsuccessful at predicting a specific breakdown event or lacks the realtime data and/or experience to do so, opening a shoulder shortly after the onset of breakdown is usually sufficient to dissipate congestion on a freeway in several minutes. The added capacity of PTSU is substantial and nearly equal to the capacity of an additional general-purpose lane in some cases. Figure 9 shows the steps to be followed to open the shoulder shortly after the onset of breakdown.



* Assuming there are no issues with maintenance, law enforcement, environmental conditions. etc.

Source: FHWA

Figure 9. Diagram. Decision parameters for opening a shoulder to travel based on an observed breakdown.

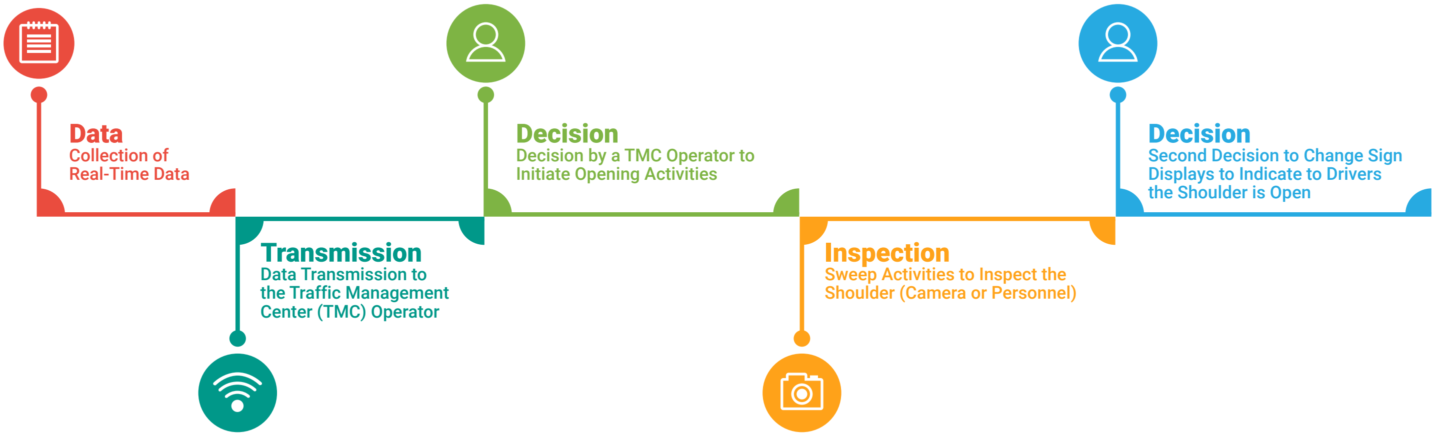
Chapter 4 of this report presents methods an agency could use to establish their own decision parameters. As part of the preparation of this report, each method was used with data and models from typical urban freeways, and these results effectively provide initial decision parameters an agency could use as a starting point before developing their own.

DEVELOPING THE DECISION SUPPORT FRAMEWORK

The decision of when to open and close the shoulder to traffic in realtime necessarily depends on more than just volume and speed decision parameters. The agency operator should also consider the needs of the other stakeholders (maintenance, emergency responders, transit, and local agencies). The ConOps should therefore provide the agency operator with a decision support framework to determine when to open and close the shoulder to traffic. A decision support framework (DSF) for dynamic part-time shoulder use consists of decision trees designed to answer two questions for a facility operator in realtime:

- Should I begin the process of opening the shoulder to traffic now?
- Should I begin the process of closing the shoulder to traffic now?

Opening a shoulder is not an instantaneous process, as shown in figure 10. It requires collection of realtime data, data transmission to the Transportation Management Center (TMC) and processing, a decision by a TMC operator to initiate opening activities, sweep activities to inspect the shoulder (with cameras or field personnel), and a second decision after the sweep to change sign displays to indicate to drivers that the shoulder is open. Interviews with U.S. and foreign agencies with PTSU facilities indicated that the sweep time generally takes 15 to 20 minutes. In other words, an operator needs to decide that they want to open a shoulder 15 to 20 minutes before it actually opens.



Source: FHWA

Figure 10. Diagram. Events preceding the opening of a dynamic shoulder.

A DSF for D-PTSU focuses on one tactical measure: congestion. However, the basic DSF could be readily expanded to include more strategic measures of agency objectives, such as safety, mobile source emissions, noise, and transit.

The DSF presented in this report is split into two decision trees: recommending when to open the shoulder to traffic and recommending when to close the shoulder to traffic. Each one has some parameters (such as minimum time to keep a shoulder open) that can be pre-determined by an agency.

Documenting the Assumptions Used in Developing the Decision Support Framework

The DSF should state its assumptions. These may be variations on any or all of the following:

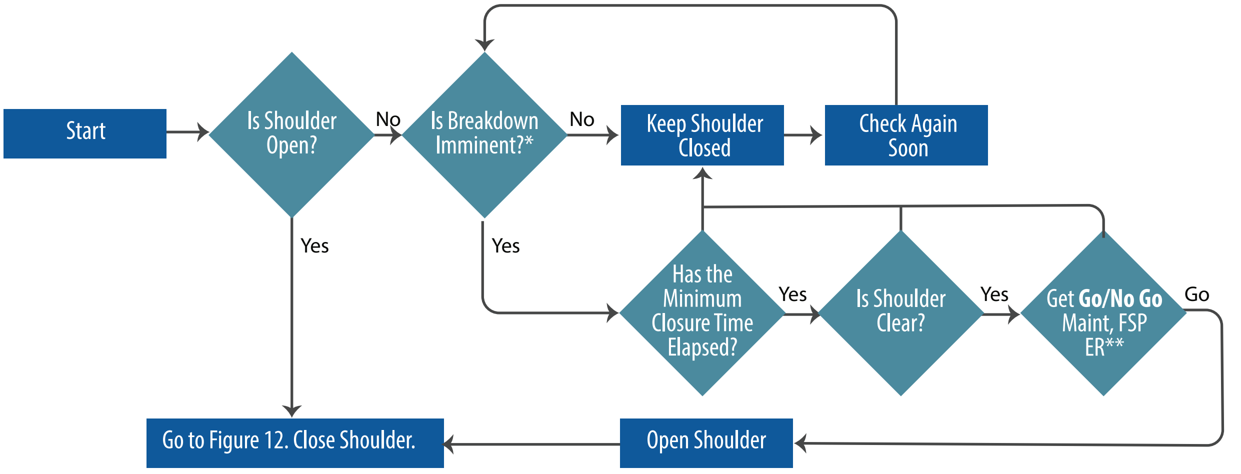
- Dynamic lane controls are in place so that the agency can remotely open and close the shoulder within a few minutes notice.
- The decisions to open and close the shoulder ultimately must be made by a human being before being implemented.
- Video or loop detectors are in place and 100 percent operational to monitor lane-by-lane occupancy and speed throughout the facility continuously, including on the shoulder.
- The DSF can be refined in later versions to include logic checks to account for detector breakdowns, discrepancies between upstream and downstream detectors, and detection errors.
- Video surveillance or field personnel are available to verify that, before opening a shoulder, it is clear.

- Communication links are instantly available to contact maintenance personnel, emergency responders, and freeway service patrol to obtain go/no-go recommendations from them before opening a shoulder lane.
- Maintenance personnel, emergency responders, and freeway service patrol (FSP) managers have a means of knowing the status of the shoulder (open or closed) in realtime, their personnel geo-locations, and the conditions on the freeway.

Note that these example assumptions are effectively the prerequisites for Level 3 (i.e., D-PTSU with core hours supplemented by the capability of providing unscheduled shoulder opening) and Level 4 (i.e., fully dynamic PTSU) operations. Level 1 (i.e., S-PTSU) or Level 2 (i.e., D-PTSU with core hours and scheduled variations) could be implemented without some of these assumptions because the opening time of the shoulder would be pre-determined.

An Example Lane Opening Decision Tree

The agency's ConOps for D-PTSU should include a decision tree that its operators can follow when determining whether or not to open the shoulder to traffic. Figure 11 provides an example of a conceptual decision tree that an agency might use for opening the shoulder to traffic. This particular example presumes that the agency will not open the shoulder unless congestion is present or imminent. It presumes that the agency will not open the shoulder in any case until it has ascertained that the shoulder is free of obstructions and the agency has obtained the approval of maintenance, the FSP, and law enforcement/emergency responders (ER). These presumptions should be explicitly stated in the ConOps. Agencies may require approval from other specific stakeholders as well. If so, these additional considerations should be included in the ConOps decision tree.



*Can use Volumes, Speeds or Occupancy. Should also test if breakdown has already occurred.

**Check with Maintenance, Freeway Service Patrol, Emergency Responders.

Source: FHWA

Figure 11. Diagram. Example shoulder opening decision tree.

This diagram shows the events for which an agency should determine a specific duration when preparing its ConOps for the D-PTSU:

- The minimum closure time to keep the shoulder closed, once already closed.
- The minimum time between re-checks of shoulder status.

The first decision diamond box (Is Shoulder Open?) that should be included in the ConOps decision tree verifies that the question of opening the shoulder makes sense. If the shoulder is already open, there is no need to go through the rest of the decision tree.

The second decision diamond box (Is Breakdown Imminent?) is the most critical and complex question. There are several options for implementing this decision box that the agency should consider when preparing its ConOps for the D-PTSU:

- The agency could choose to proactively anticipate congestion and proactively open the shoulder, like the process shown in figure 11.
- The agency could wait until congestion is present, then open the shoulder in response. This could be done if the agency's predictive capabilities are limited or if congestion unexpectedly occurs. The amount of additional capacity added with PTSU is usually sufficient to dissipate congestion within a few minutes of the opening of the shoulder.
- In addition to congestion, the agency may also have air quality, noise, or other multimodal objectives for D-PTSU. In these cases, using off-line modeling would identify how those objectives are related to field measurements of speed and volume and identify how to set the appropriate thresholds for opening the shoulder lane.

The decision parameter values will vary between localities and between facilities. Chapter 4 provides different methods of choosing decision parameters and presents results of decision parameters-related research conducted for this project.

The third decision diamond ("Has the Minimum Closure Time Elapsed?") is to prevent frequent opening and closing of the shoulder, which could be confusing to drivers and other stakeholders (e.g., police, emergency responders). Recently closed shoulders should not be reopened too soon. In practice, D-PTSU agencies generally open the shoulder during the morning peak, the afternoon peak, or both, depending on the peaking characteristics of the facility. However, if volume fluctuates throughout the day at near-capacity levels—as might be the case on a weekend or on a rural freeway—an agency would likely want to establish a minimum time for each operating state (open/closed), such as 30 or 60 minutes.

The fourth decision diamond ("Is the Shoulder Clear?") is a safety check to make sure the shoulder is clear of obstructions (e.g., breakdowns, maintenance operations) before it is opened to traffic.

The fifth and final decision diamond ("Get Go/No Go Maint, FSP, ER") requires the operator to verify with its D-PTSU stakeholders (maintenance, FSP, law enforcement, and emergency responders) that their personnel and equipment are not on the shoulder before it is opened to traffic.

After making the decision to "Keep Shoulder Closed," figure 11 shows the next step as "Check Again Soon." This is likely a short duration of time – such as 1 to 5 minutes – because the effort for a TMC operator to check traffic conditions is relatively low. This is particularly true if software in the TMC is automatically providing a suggestion to the operator ("Keep Shoulder Closed" or "Begin Opening Shoulder") as opposed to the operator manually reviewing speed and/or volume data.

Note that the example lane opening decision tree does not address the option of partial lane openings for long facilities. It also does not address the issues of conflicting sensor results on different segments of the facility. For example, the lane opening volume decision parameter may be met in one section but not in any of the other sections. The decision tree included in the ConOps should address these additional possibilities, when they are applicable.

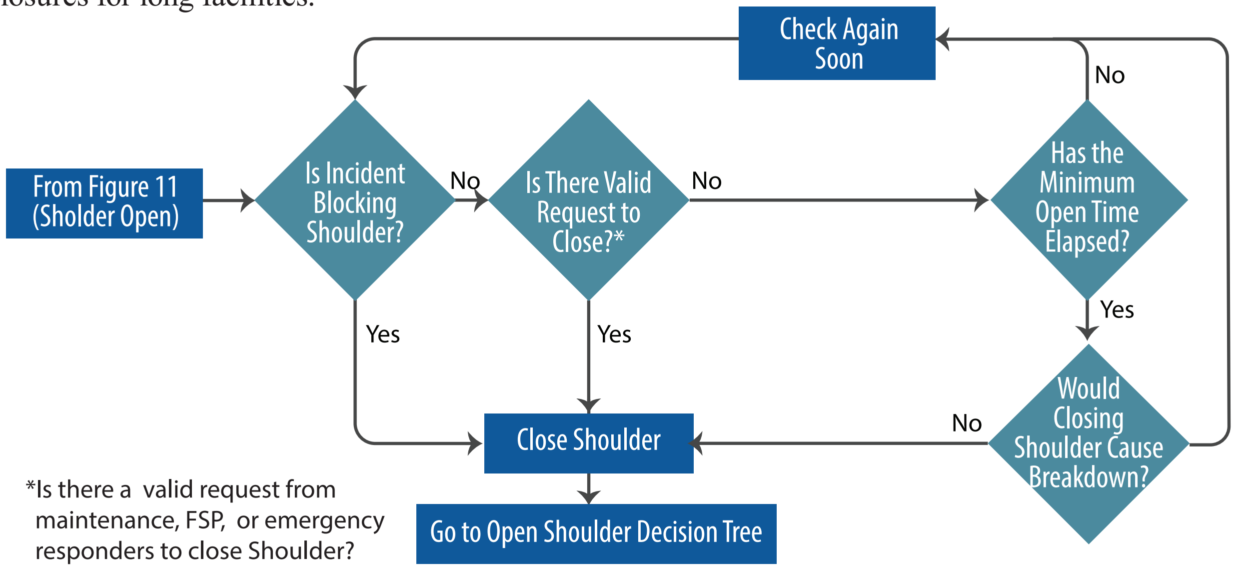
Example Lane Closing Decision Tree

Figure 12 provides an example of a lane closing decision tree. This particular example presumes that the agency will close the shoulder lane when one or more or of the following conditions are met:

- The instant a blockage or incident is detected in the shoulder lane.
- Upon request of maintenance personnel, freeway service patrol, or emergency responders.
- If the lane has been open a minimum amount of time set by the agency **and** calculations or typical performance show that the lane can be closed without causing congestion.

The ConOps should document the presumptions upon which the lane closing decision tree is based.

In the case of an incident or maintenance need, it would be possible on a sufficiently long facility to close only a portion of the shoulder and not the entire length of it. The congestion threshold can be expanded to incorporate environmental and other concerns in addition to congestion. The ConOps should address these additional concerns as well as resolve conflicting detector data (such as when one section meets the volume threshold, but the others do not) and additional options for partial lane closures for long facilities.



*Is there a valid request from maintenance, FSP, or emergency responders to close Shoulder?

Source: FHWA

Figure 12. Diagram. Example shoulder closing decision tree.

This diagram shows two suggested parameters which should be user-agency adjustable:

- The minimum closure time to keep the shoulder open once it is already open.
- The minimum time between re-checks of shoulder status.

The first decision diamond ("Is Incident Blocking Shoulder?") provides the decision parameters for immediately closing the shoulder should an incident occur that would block it.

The second decision diamond ("Is there a Valid Request to Close?") provides for requests coming from maintenance, law enforcement, emergency responders, or the FSP for closure of the shoulder to traffic. The request is evaluated against the criteria mutually agreed to by the various departments to determine if the shoulder should be closed. There may be a delay in closing the shoulder if the request is not urgent and the shoulder has not been open a long time.

The third decision diamond ("Has the Minimum Open Time Elapsed?") prevents frequent openings and closings of the shoulder. The agency policy sets the minimum number of minutes.

The fourth decision diamond ("Would Closing Shoulder Cause Breakdown?") is the most common reason for determining whether closing the shoulder is appropriate. The operator's experience with the facility or a predictive model is needed to determine the effect on the operations of the remaining lanes when closing the shoulder. Typically, operators have an understanding of daily traffic patterns on a freeway and when decreased volume will be sustained long enough to justify closing the shoulder.

CONSIDERATIONS FOR PERMANENT SHOULDER CONVERSION

The D-PTSU ConOps may also consider addressing the potential future scenario of shoulder openings being so frequent that full-time shoulder use may be an option. The FHWA report on the *Use of Narrow Lanes and Narrow Shoulders on Freeways* (Neudorff, Jenior, Dowling, & Nevers, 2016) describes a performance-based analytical framework to help agencies identify if and when it may be appropriate to go to full-time shoulder use (in effect, an additional lane and narrow shoulders, which may or may not be accompanied by narrow lanes).

Much of the information contained in the primer is presented in the broader context of both performance-based planning and programming and performance-based practical design. The primer contents include case studies on the use of narrow shoulders and lanes, issues and approaches for analyzing the operational and safety impacts of narrow lanes and narrow shoulders, and the role of TSMO in supporting narrow lane and narrow shoulder operations.

In essence, the decision point for going from part-time shoulder use to full-time shoulder use occurs when the life-cycle benefit-cost ratio of full-time shoulder use exceeds that of part-time shoulder use. The benefit-cost analysis takes into account both safety effects and traffic operations effects, as described in the FHWA report. The safety effects (changes in crash frequencies, types, and severities) of PTSU are not fully researched and understood at this time, but in general there is likely a negative safety effect of opening the shoulder in a low volume period where it does provide a congestion reduction benefit. If a shoulder is open for many hours during a typical day and thus serves as a lane for recurring extended periods, it may be appropriate to convert the shoulder to a full-time lane.

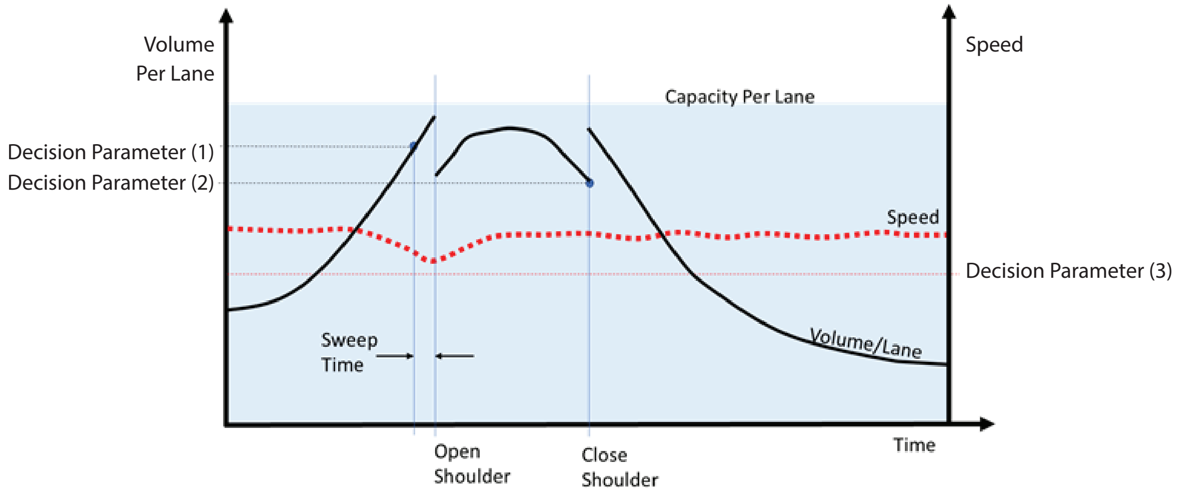
CHAPTER 4. DECISION PARAMETERS FOR OPENING THE SHOULDER

This chapter describes methods for determining when the shoulder of a dynamic part-time shoulder use (D-PTSU) freeway should be opened to traffic. The traffic operations decision parameters for temporarily opening a shoulder to traffic will vary from facility to facility, and this chapter describes how an agency can go about determining the appropriate decision parameters and thresholds for opening the shoulder.

The methodology to determine the appropriate conditions for opening the shoulder and the operational decision parameters should consider the following:

- Variations in capacity—roadway capacity is not a fixed value and changes based on vehicle speeds, vehicle mix, driver population, and environmental conditions.
- The time required to initiate and complete the shoulder opening process (i.e., the sweep time).
- The rate of increase in the traffic flows leading up to the peak period.
- The geometry of the specific facility, such as grades and heavy merges, diverges, or weaving.
- The extent to which these thresholds will vary with time of day, day of week, time of the year, weather conditions, and the combination of all these conditions.

Figure 13 illustrates the application of an agency's speed and volume thresholds, generally developed in a concept of operations (ConOps) document, to determine when to open and close the shoulder lane during a typical peak period. In this example, the agency has a volume threshold (decision parameter 1) and a speed threshold (decision parameter 3) to open the shoulder. A second, lower volume threshold, decision parameter 2, exists for closing the shoulder. In reality, both the opening and closing decision parameters could also be functions of speed and volume combinations rather than each of these in isolation as shown in this example.



Source: FHWA

Figure 13. Diagram. Example application of speed and volume decision parameters.

In this example the volume threshold to open the shoulder is initiated first, before the speed threshold. Different values and a different speed-flow relationship for the freeway could have resulted in the reverse condition.

There is a delay—*the sweep time*—between the times when the threshold to open the shoulder is reached (decision parameter 1) and when the shoulder is opened to traffic. This is the time required for the shoulder to be inspected to verify it is free of debris and disabled vehicles. The sweep time is also used to notify stakeholders such as law enforcement that the shoulder will be opening. Thus, a decision parameter ideally anticipates the actual onset of congestion. In this example, decision parameter 1 is well below the capacity.

The volume per lane drops suddenly when the shoulder is opened because the same flow divided by more lanes results in a drop in volume per lane. The volume per lane then jumps suddenly when the shoulder is closed. The closing threshold volume (decision parameter 2) is set low enough that the shoulder closure does not suddenly cause new congestion in the remaining lanes. This is why it is desirable to have a slightly lower volume threshold (decision parameter 2) for closing the shoulder than for opening it.

Since opening the shoulder in this example prevents the onset of significant congestion, a speed threshold for closing the shoulder would not apply (the speed recovers rapidly after the shoulder is opened, after which the speed does not provide a useful indication of when the shoulder can be closed). Consequently, the volume threshold (decision parameter 2) is used to determine when the shoulder can be closed without inadvertently creating congestion on the freeway.

METHODS FOR SELECTING SHOULDER USE TYPE AND DECISION PARAMETERS

Five data-driven methods exist for selecting and optimizing the opening time of a D-PTSU facility. While they are primarily presented in this chapter in the context of making decisions day-to-day, they could also be used during ConOps development to establish hours of operations for static part-time shoulder use (S-PTSU) or core hours of operations for D-PTSU. Some methods are more applicable to day-to-day use, and others are more applicable to use at the ConOps stage. The five basic methods include:

I. **Demand-to-Capacity Patterns** – Using sensors or traffic counts on the facility, an operating agency assesses historical *demand profiles* to determine levels of congestion relative to the available facility base capacity as well as the expected capacity with shoulder use.

II. **Empirical Performance Data** – Using *whole-year travel time reliability data*, an operating agency explores the frequency and pattern of breakdown events to identify times when the facility experiences congestion.

III. **Macroscopic Decision Parameter Optimization** – Using the Highway Capacity Manual (HCM) *freeway facilities method*, an operating agency examines different types of decision parameters (speed vs. volume-based) and decision parameter values for a facility. It does this using an iterative approach to determine the optimum decision parameter for the facility, a process that can be automated through software.

IV. **Microscopic Decision Parameter Refinement** – Using *calibrated microsimulation tools*, an operating agency simulates the facility in question with the initial proposed decision parameter algorithm. It uses the simulation assessment to verify the concepts developed through the macroscopic optimization, which can be refined for the facility-specific geometry and traffic patterns.

V. **Monitoring and Adjustment** - On a Level 3 or Level 4 D-PTSU facility, which are defined as a dynamic PTSU with core hours and unscheduled variation and a fully dynamic PTSU, respectively, the operating agency uses *realtime operating experience* to adjust the decision parameter values and open or close the shoulder at different thresholds. By monitoring shoulder operations for the first few weeks after implementation of the thresholds, the operator adjusts the thresholds and decision parameters as necessary to meet the agency's objectives for operating the facility. Monitoring should be continued but can be less intensive once the operator has acquired experience with the operations of D-PTSU.

The details of these methods are described later in this chapter, after linking the methods to specific use cases and analysis questions in the following section.

USE CASES FOR SHOULDER USE AND DECISION PARAMETER SELECTION

The selection and adequacy of the aforementioned methods is a function of the intended goals of the agency or operator. Three common use cases are introduced below that represent frequent questions an agency may have related to PTSU:

1. Would D-PTSU be an appropriate strategy in a location where no PTSU (even static) is currently in place?
2. Should D-PTSU be considered in a location where S-PTSU is in place?
3. How can an agency better optimize the operations of an existing D-PTSU installation?

For each use case, one or more of the methods are used to inform agency decisionmaking.

Would Dynamic Part-Time Shoulder Use be an Appropriate Strategy in a Location Where No Part-Time Shoulder Use (Even Static) Is Currently in Place?

An agency exploring the use of D-PTSU on a facility needs first to develop an understanding of congestion patterns on the facility (spatial and temporal extents of congestion) as well as the underlying causes of congestion. This use case is best approached with a combination Method I – Demand-to-Capacity Patterns and Method II – Empirical Performance Data.

To explore the viability of D-PTSU, an agency can look at demand-to-capacity (d/c) ratios, including fluctuations in d/c ratios. From this, d/c combinations where PTSU is most effective, which are typically shorter periods of congestion, can be identified.

Combining d/c analysis with an investigation of empirical performance data identifies the distribution of breakdowns across days of week and time of day, and determines when a dynamic system may provide benefit over a static system.

That said, many agencies are choosing to skip static part-time shoulder use (S-PTSU) and are starting at a Level 2 D-PTSU system or above. This provides flexibility in dealing with incidents, inclement weather, and planned special events.

Should Dynamic Part-Time Shoulder Use Be Considered in a Location Where Static Part-Time Shoulder Use Is in Place?

Similar to the previous use case, this question is best approached with a combination of Method I – Demand-to-Capacity Patterns and Method II – Empirical Performance Data. The applicability of S-PTSU versus D-PTSU is a function of the distribution of breakdown events. Are periods of high d/c ratios uniformly distributed and predictable, or scattered across the day, on weekends, and as a function of seasonal variability? An S-PTSU system may be a reasonable choice when congestion is highly predictable (e.g., 7-9 a.m. every weekday), while a D-PTSU system applies when congestion patterns are more random. A reliability analysis (Method II) helps in this assessment: the less reliable a facility, the more useful it is to move towards a dynamic system.

A related question is whether the operating hours of an S-PTSU system should be expanded (vs. migrating to D-PTSU). This question can similarly be answered using Methods I and II. If analysis finds that high d/c ratios and congestion that once occurred from 7-9 a.m. now extend until 10 a.m., then increasing the hours operations is a viable approach—assuming no other changes in the reliability of the system.

How Can an Agency Better Optimize the Operations of an Existing Dynamic Part-Time Shoulder Use Installation?

To answer this question, the three more advanced methods (Method III, IV, and V) are used to augment the analysis from Method I and II. A thorough understanding of congestion patterns and temporal and spatial distributions of congestion is still the starting point.

Once an agency decides to implement D-PTSU, Method III: Macoscopic Decision Parameter Optimization can be used to develop guidance on when to use volume-based versus speed-based decision parameters. Each has benefits and tradeoffs, which are described in the discussion of Method III below.

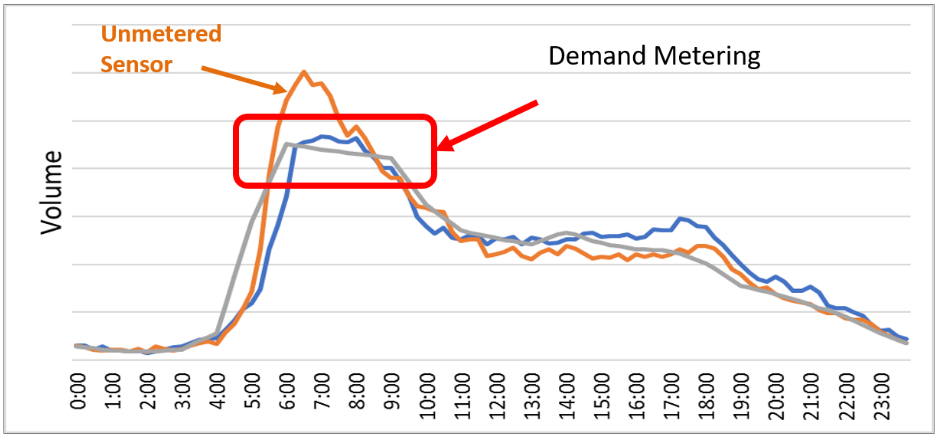
Method III can be based on a generic facility, which is how it is described in the discussion of Method III below for the purposes of this report. However, for a specific D-PTSU project, the method can be customized to replicate the specific geometry and demand patterns of the subject facility. As such, the FREEVAL method, which will be introduced in the discussion of Method III, can be used to model a specific facility. FREEVAL uses underlying algorithms to quickly and efficiently test different decision parameter combinations.

With the macroscopic results and a set of facility-specific decision parameters in place, an agency may chose to conduct a microsimulation analysis (Method IV: Microscopic Decision Parameter Refinement) to verify the effects. An example for this is illustrated in the discussion of that method later in this chapter.

Finally, Method V: Monitoring and Adjustment applies to existing facilities, with operators monitoring day-to-day operations of the D-PTSU system and making adjustments based on observed congestion patterns.

BOTTLENECK IDENTIFICATION

A key component of PTSU decisionmaking, regardless of the method used for determining decision parameters, is locating and understanding bottlenecks. In the experiments conducted as part of this report, bottlenecks were modeled as on ramps, but other freeway features such as uphill grades, bridges, tunnels, or lane drops could also be bottlenecks. In recent years, probe data sources provided by commercial vendors have become popular tools for identifying bottlenecks. However, sensors are needed to measure the capacity of bottlenecks and the demand, so sensor placement is key. Sensors may not measure the true demand if they are located downstream of an active bottleneck or within a queued segment, and should be located right at a bottleneck for accurate measurement of demand and capacity. Sensors that are impacted by congestion in these ways will only measure the throughput or "volume served" as opposed to the true demand. To avoid this metering effect, the selected sensor should be upstream of congestion and free of any queuing patterns. Alternatively, an unconstrained demand profile can be used to estimate demand from the known daily volumes in the bottleneck. To illustrate this point, figure 14 shows an example of two metered sensors as well as one unconstrained sensor from a congested freeway. While all three sensors have the same demand over a 24-hour period (same facility), the measured volume profiles plateau for the two sensors impacted by congestion.



Source: FHWA

Figure 14. Chart. Example of freeway sensor metering due to congestion.

METHOD I: DEMAND-TO-CAPACITY PATTERNS

The first step towards implementing or improving PTSU is to develop an understanding of d/c patterns. Congestion on freeways is caused by demand exceeding capacity, with unserved demand translating into a queue and congestion. For recurring congestion, it is common that (fixed) capacity at a bottleneck is exceeded by surges in demand during certain times of day. These time periods are generally good candidates for a (part-time) capacity enhancement treatment such as PTSU.

Alternatively, the d/c ratio may also exceed 1.0 when the denominator—the capacity—is temporarily reduced due to weather, an incident, a work zone, or other similar events. In these non-recurring congestion cases, PTSU is less likely to be applicable, given that the underlying reason capacity is compromised (incident, weather, etc.) is likely to affect the shoulder also.

In designing a PTSU system, agencies need to understand how high the true demand is relative to the available capacity. In the HCM, the "ideal" capacity of a basic freeway segment is 2,400 passenger cars per hour per lane (pc/h/ln) for a freeway with free-flow speed (FFS) of 70 mi/h and above, with that capacity being reduced by 50 pc/h/ln for each 5 mi/h drop in FFS. However, in a freeway facility context, the HCM also recognizes bottleneck capacities are often significantly lower than the values in table 7.

Table 7. Highway Capacity Manual summary of bottleneck capacity estimated in vehicles (per hour per lane).

Location	No. of Lanes	Average (Standard Deviation)		
		Breakdown {XE "Breakdown"} Flow	Maximum Prebreakdown Flow	Queue {XE "Queue"} Discharge Flow
Minneapolis, Minn.	2	1,876 (218)	2,181 (163)	1,644 (96)
Portland, Ore.	2	2,010 (246)	2,238 (161)	1,741 (146)
Toronto, Canada	3	2,090 (247)	2,330 (162)	1,865 (124)
Sacramento, Calif.	3	1,943 (199)	2,174 (107)	1,563 (142)
Sacramento, Calif.	4	1,750 (256)	2,018 (108)	1,567(115)
San Diego, Calif.	4	1,868 (160)	2,075 (113)	1,665 (85)
San Diego, Calif.	5	1,774 (160)	1,928 (70)	1,600 (66)

Source: Highway Capacity Manual, Sixth Edition. 2016. Exhibit 14-2, Transportation Research Board, Washington, DC.

Assuming a shoulder capacity of 1,600 passenger cars per hour (pc/h) and a freeway bottleneck capacity of 2,000-2,200 pc/h/ln, target d/c ratios for PTSU viability can be derived (table 8). Shoulder capacities vary greatly from facility to facility, and 1,600 pc/h is used here to represent a shoulder with a relatively high capacity that is still less than a general purpose lane. The table develops a blended cross-section capacity for a PTSU facility with two, three, or four general purpose lanes in one direction (not counting the shoulder). A comparison of this blended capacity with PTSU to the base capacity allows for the development of a target d/c ratio. If the demand profile of a facility stays below that target ratio (but exceeds 1.0 for parts of the day), PTSU may be a viable treatment.

Table 8. Target demand-to-capacity ratios for part-time shoulder use viability.

Base Number of Lanes	Base Capacity (pc/h/ln)	Capacity with PTSU added (pc/h/ln)	Ratio of PTSU vs. Base → PTSU d/c Ratio Target
2	4,000-4,400	5,600-6,000	1.40 – 1.36
3	6,000-6,600	7,600-8,200	1.27 – 1.24
4	8,000-8,800	9,600-10,400	1.20 – 1.18

d/c = demand-to-capacity (ratio). pc/h/ln = passenger cars per hour per lane. PTSU = part-time shoulder use.

The table suggests that PTSU can increase capacity by 35-40 percent for a two-lane freeway, 25-30 percent for a three-lane freeway, and 15-20 percent for a four-lane freeway. For facilities (or time periods) with d/c ratios greater than 1.4, 1.3, or 1.2 for two-, three-, and four-lane facilities, respectively, a PTSU system will not provide sufficient added capacity to relieve congestion. PTSU facilities have been removed after 25-30 years of operation because they were no longer providing adequate capacity. I-95/SR 128 in Massachusetts was widened by one additional lane in each direction to provide additional capacity at off-peak times, and I-66 in Virginia is currently being widened to provide multiple additional lanes in each direction.

PTSU can increase capacity by 35-40 percent for a two-lane freeway, 25-30 percent for a three-lane freeway, and 15-20 percent for a four-lane freeway. For facilities with pre-PTSU demand to capacity ratios greater than 1.4, 1.3, or 1.2 for two-, three-, and four-lane freeways, respectively, PTSU will not add sufficient capacity to relieve congestion.

At the same time, it is important to recognize that for facilities with a d/c ratio of 1.05 or below, a PTSU system may not be necessary, as other transportation system management and operations strategies such as ramp metering may provide a better benefit-cost ratio at those low degrees of oversaturation.

In applying these concepts to a PTSU evaluation, an agency should ask the following questions:

- When (in time) does demand exceed capacity?
- Where (in space, which segments) does demand exceed capacity?
- How high is the demand relative to available capacity?
- How long does demand exceed capacity?
- How much do these patterns change from day to day?

An understanding of these questions for a given facility will help develop an understanding of the underlying causes of congestion and an initial hypothesis about the expected benefits of a S-PTSU or D-PTSU system.

METHOD II: EMPIRICAL PERFORMANCE DATA

The selection of decision parameter thresholds and the type of decision parameter starts with a thorough understanding of the congestion patterns on the facility. Since PTSU is primarily a congestion-relief treatment, the agency needs to understand where and when congestion typically occurs on a facility. It is further critical to distinguish between recurring congestion (repetitive congestion pattern due to capacity constraints relative to demands) and non-recurring congestion (variable congestion patterns due to volume fluctuations, weather, incidents, work zones, and seasonal effects). To some degree, this also determines the added benefits of D-PTSU over S-PTSU for a given facility.

To fully understand congestion patterns, it is desirable for an agency to evaluate congestion patterns for a period of at least 1 year of data, can be with agency collected data, probe data, or a combination of both. Archival probe-based data sources could come from the National Performance Monitoring Resource Data Set (NPMRDS), or a commercial data provider. Using one year of data, it is possible to derive congestion patterns and identify periods where PTSU may offer congestion relief.

Understanding congestion patterns further requires an assessment of the facility (bottleneck) capacity, and the level of demand relative to that capacity (see Method I). For this assessment, traffic sensors on the facility are used to gather speed/flow/density data at the bottleneck, which is then used to determine bottleneck capacities.

The empirical performance method consists of four steps:

1. **Assess Whole-Year Congestion** – using archived data, determine congestion patterns, distinguish recurring and non-recurring congestion, and quantify temporal and spatial extents of congestion.
2. **Evaluate Breakdown Probabilities** – from local sensor data, apply probability methods at the bottleneck to identify breakdown events and quantify breakdown flow rates (i.e., segment capacity).
3. **Explore Breakdown Distributions** – use the results of the breakdown probability analysis to determine temporal distribution of breakdown events.
4. **Estimate Initial Decision Parameter Threshold** – use whole-year speed-flow data and HCM capacity concepts to develop initial threshold values for speed- and volume-based decision parameters.

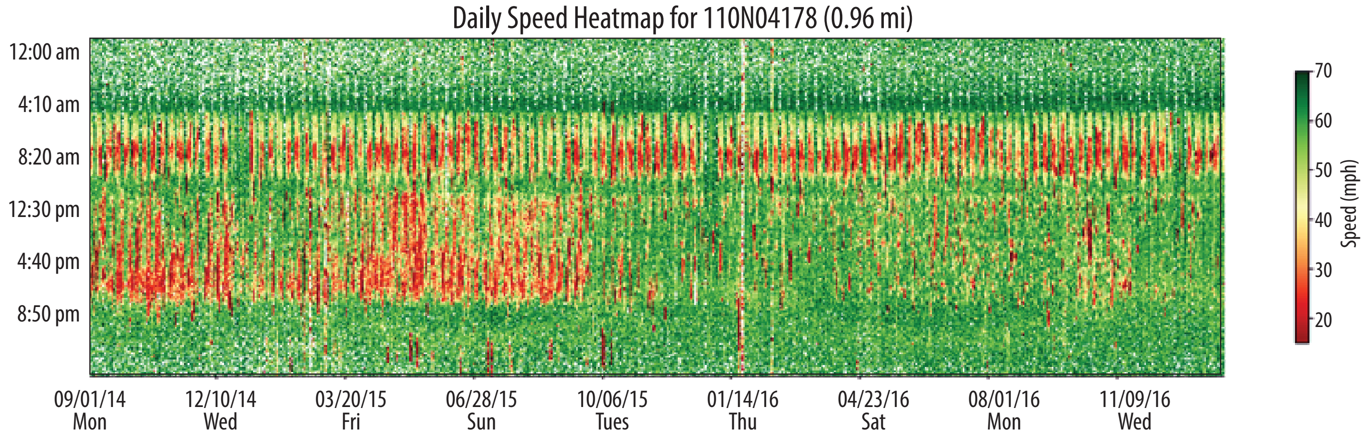
Assess Whole-Year Congestion

Analysis of a whole-year data set from sources like the NPMRDS provides insight about the temporal and spatial congestion patterns on a facility. The motivation for this analysis is to identify whether the congestion is recurring and predictable (e.g., every weekday morning from 7-9 a.m.), more random (e.g., sometimes breaks down in the afternoon, sometimes on the weekends), or some combination. In the context of identifying decision parameters, the more randomly the breakdown events are distributed, the more the decision parameter needs to be dynamic as opposed to static.

A whole-year speed and travel time dataset can be used to generate a heat map of corridor performance, which is used to understand congestion patterns. An example is given below for the eastbound portion of I-66 in northern Virginia, which was converted from a static (morning peak only) to a dynamic system in September 2015.[1] The example includes a portion of I-66 upstream of the PTSU segment, the PTSU segment itself, and a portion of I-66 downstream of the PTSU segment. Figure 15 shows a photo of the facility, while figure 15 shows a representative heat map from one of the segments.

Source: Kittelson & Associates, Inc.

Figure 15. Photo. Gantry with dynamic lane use signs I-66 in Northern Virginia.



Source: Probe Data Analysis Tool: Summary of Case Studies

Figure 16. Chart. Speed heat map for eastbound I-66 analysis segment from probe data.

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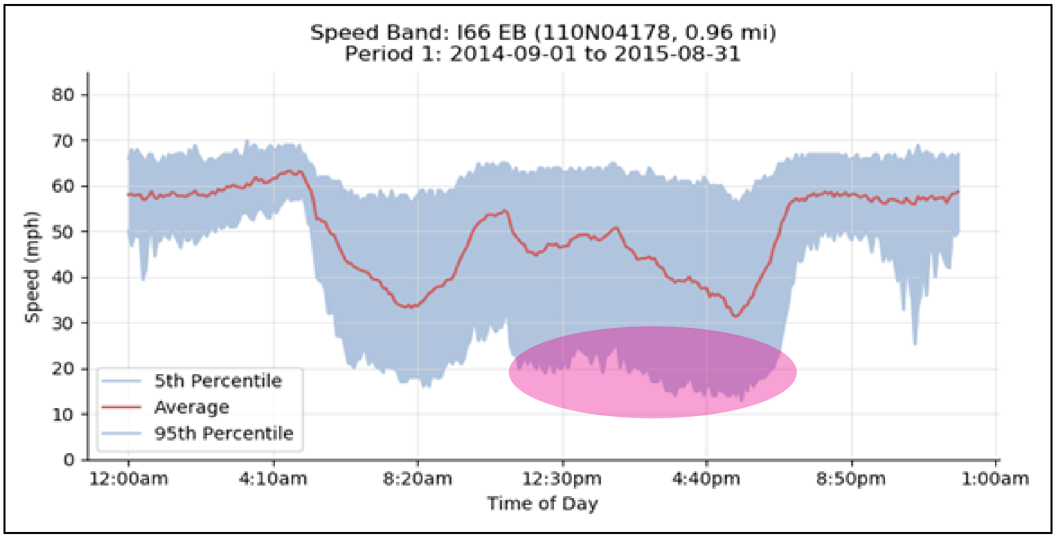
[1] PTSU was entirely removed from I-66 in 2018 as part of a major widening project.

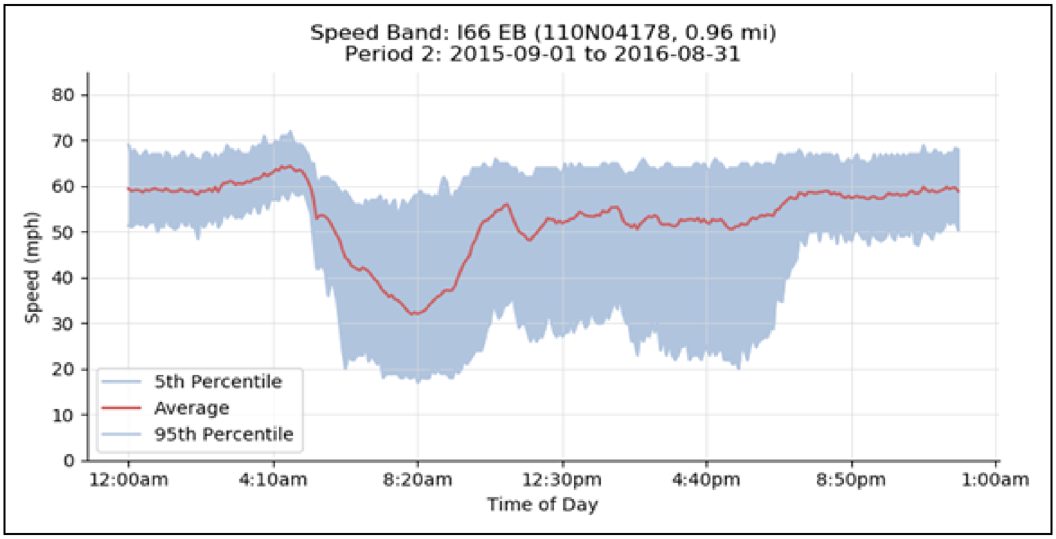
In figure 16, it is apparent that from September 2014 through around September 2015 there is heavy congestion during both the morning, midday, and afternoon hours. During the morning peak period, a S-PTSU system had already been in place. For the midday and afternoon peak hours, no PTSU was used, resulting in congestion on a subset of days. Since the congestion patterns in the midday and afternoon hours are not homogeneous, there is an indication that a dynamic system may provide some benefits (as opposed to just extending the S-PTSU operating hours). With the implementation of D-PTSU in September 2015, midday and afternoon peak congestion is notably reduced, while the morning peak period is unaffected. In a sense, the morning period acts as a control site for the effects of the D-PTSU system for other time periods.

Conversion of S-PTSU to D-PTSU on I-66 eastbound enabled the shoulder to be opened outside of the a.m. peak hour if the Virginia Department of Transportation desired. As a result, the average p.m. travel time for the eastbound PTSU segment decreased from 14.7 to 13.7 minutes, and the average weekend daytime travel time for the PTSU segment decreased from 14.5 to 13.1 minutes. Both results were statistically significant. (Suliman 2017)

In addition, the same probe data can be used to generate various visualizations on travel time reliability as well as to conduct a before-and-after analysis (once the system has been put in place, and to monitor operations). One example visualization is the “speed band” graphic shown in figure 17, which shows the average speed (red line) by time of day and the “reliability band” from the 5th to 95th percentile (shaded in blue). In interpreting these graphs, time periods when the average speed drops below free-flow speed are candidates for PTSU. The need for a dynamic system increases during time periods when the blue speed band is wider, while a static system may be sufficient during times when the reliability band is narrow. The figure also shows a before (figure 17a) and after (figure 17b) comparison, showing improvements in the average speed and reliability bands for midday and afternoon periods after the S-PTSU system was converted to D-PTSU. The area of afternoon reliability improvement is indicated with a pink circle. Overnight reliability improved as well following the S-PTSU to D-PTSU conversion, but this is likely due to overnight construction of D-PTSU infrastructure in the before condition.



a) Speed band for period 1.



b) Speed band for period 2.

Source: FHWA Probe Data Analysis Tool: Summary of Case Studies

Figure 17. Charts. Compound figure depicts speed band comparison for I-66 eastbound.

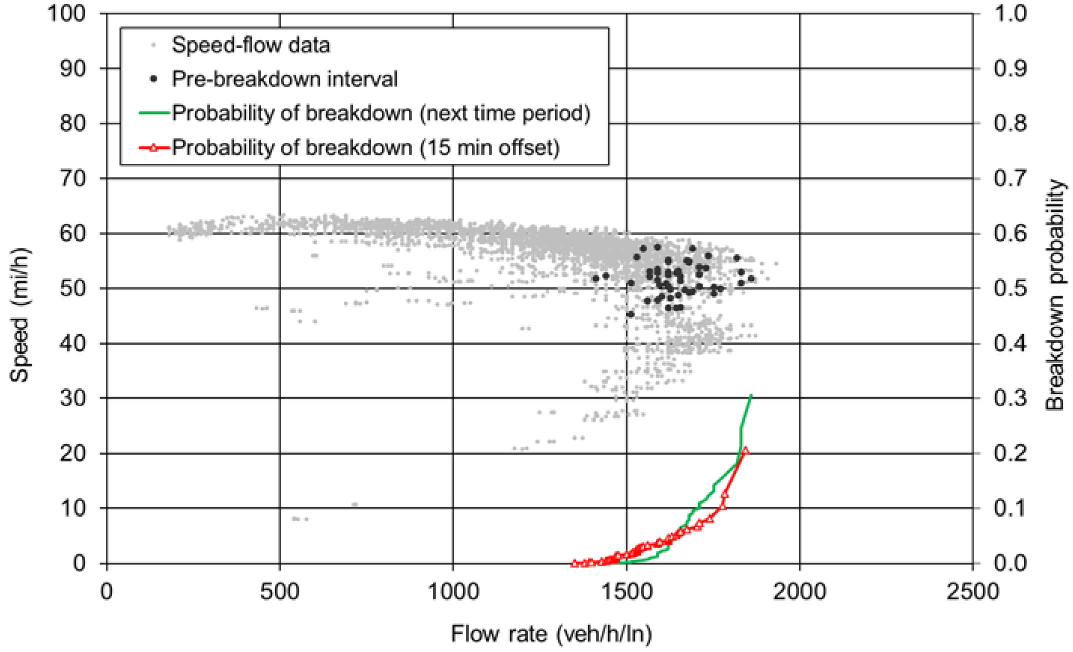
Evaluate Breakdown Probabilities

This step in the method requires the use of traffic sensors on the facility of question to gather speed/flow/density data on a lane-by-lane basis. Sensors should ideally be located just upstream of all existing and potential bottlenecks along the stretch of the facility where the shoulder will be opened to traffic. Generally, this will be immediately upstream of on-ramp merges. If the detectors are placed in (or just downstream of) the actual bottleneck, which is just downstream of the ramp merge, they will rarely, if ever, register speeds below the speed at capacity, nor will they count volumes greater than the capacity of the bottleneck.

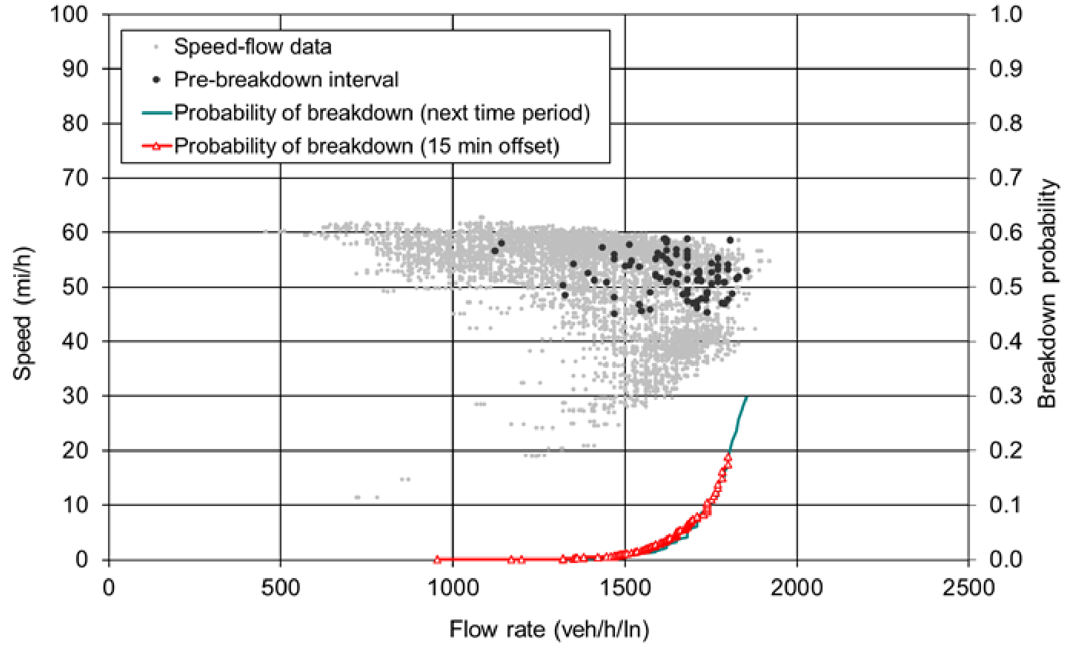
If archived data from an existing freeway is available, it can be used to determine the probability that traffic flow will break down (i.e., become congested) in the next time interval based upon speed and volume conditions in the present time interval. Two established techniques for conducting this analysis are the product limit method (PLM) and the maximum likelihood technique, which are both based on the statistics of sensor data. These methods must use volume and speed data collected upstream of a bottleneck to reliably predict congestion. Both methods are described in appendix C.

The probability of a traffic breakdown is a function of the flow rate. It represents the capacity distribution function of the freeway segment under investigation, assuming that capacity is a random variable rather than a constant value. The methods for stochastic capacity analysis are usually applied based on flow data aggregated in small time intervals (e.g., 5 minutes) in order to estimate the probability that traffic will break down in the next time interval. For deriving decision parameters for D-PTSU, however, it is typically necessary to predict the risk of a traffic breakdown about 15 minutes in advance because of the “sweep time” that is required to open the shoulder once a breakdown is expected. “Sweep time” includes the time for an agency to verify the shoulder is free of obstructions (by driving the route or inspecting it with closed-circuit television cameras) and conduct other protocols such as notifying law enforcement. The short-term development of traffic demand can either be predicted by time series analysis or be considered within the methods for traffic breakdown analysis by incorporating a time offset. In this case, the occurrence of a traffic breakdown is related to the volume measures (about) 15 minutes prior to breakdown rather than the volume immediately before breakdown.

Figure 18 shows analysis results using one the statistical techniques noted above—PLM—for the morning and afternoon peak period using a year of weekday data collected on a freeway in California. Data was downloaded from the California Department of Transportation’s Performance Measurement System (PeMS) and initially collected from permanent sensors on the roadway. As traffic breakdowns at low volumes are often caused by crashes or incidents, which cannot be predicted and therefore shouldn’t be part of a breakdown prediction model, only intervals at flow rates of more than 1,000 vehicles per hour per lane (veh/h/ln) were considered for estimating the breakdown probability. The estimation was carried out with and without a time offset of 15 minutes (three 5-minute intervals).



a) Morning peak (6 – 10 a.m.).



b) Afternoon peak (Noon – 6 p.m.).

Source: FHWA

Figure 18. Charts. Compound figure depicts sample Product Limit Method analysis for the morning and afternoon peak on a freeway in California.

In figure 18, the individual data points indicate speed and flow conditions from a 5-minute time period, with the black points indicating time periods just prior to breakdown. The two curves indicate the probably, for a given flow rate, that traffic flow will break down in the next 5-minute interval (green line with no symbols) or 15 minutes in the future (red line with triangle symbols). The lines stop where flow rates are approximately 1,800 veh/hr/ln and the resulting probably is 20-30 percent. In other words, because freeway capacity is not a constant value, there is no flow rate where breakdown always follows (in either next 5 minutes or 15 minutes into the future). The presence of gray data points (not followed by breakdown) at the same flow rate as black data points (followed by breakdown) is an illustration of this.

The results in figure 18 reveal a higher variance of the breakdown probability distributions with 15-minute time offset compared with the distribution without time offset. This can be explained by the uncertainty of the demand development during the time offset, which influences the variation of the breakdown prediction. However, the differences between the curves are small, particularly at low breakdown probabilities.

The distributions given in figure 18 represent the probability of a traffic breakdown following a single 5-minute interval with a certain traffic volume. During a period of several succeeding intervals at similar volumes, each incorporating the risk of a traffic breakdown, a higher total probability that traffic breaks down during that period arises. Therefore, and because of the stochastic variability of traffic breakdown occurrence, it is useful to apply volumes at low 5-minute breakdown probabilities (e.g., in the range of 1–5 percent) as decision parameters for opening the shoulder. In the example, the volumes at 1 percent and 5 percent probability of breakdown roughly amount to 1,500 and 1,650 veh/h/ln, respectively.

Explore Breakdown Distributions

The PLM estimation results in a list of breakdown events,[2] or specifically a flow rate observation just prior to the breakdown event. Each of these breakdown events represents a data point that can be used to asses when (time of day and day of week) breakdowns occur on the facility.

Figure 19 shows the distribution of breakdown events for the facility introduced above by day of week and time of day. The figure covers a 1-year analysis period of weekdays.

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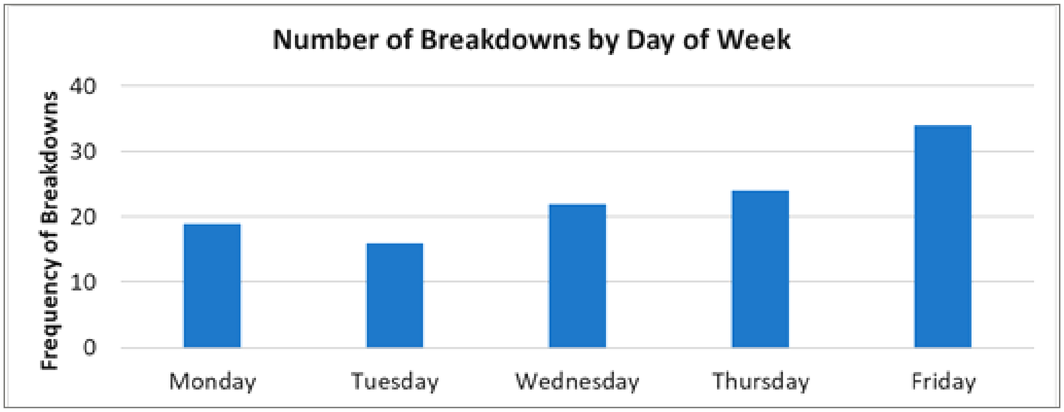
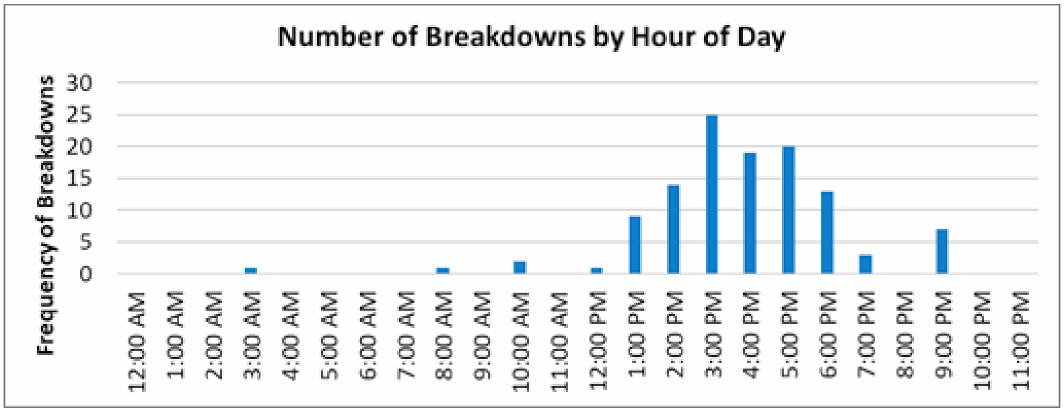
[2] The Highway Capacity Manual defines a breakdown as "the transition from noncongested conditions to congested conditions typically observed as a speed drop accompanied by queue formation." (See TRB 2016)



a) Breakdowns by day of week.



b) Breakdowns by hour of day.

Source: FHWA

Figure 19. Charts. Compound figure depicts temporal distribution of breakdown events.

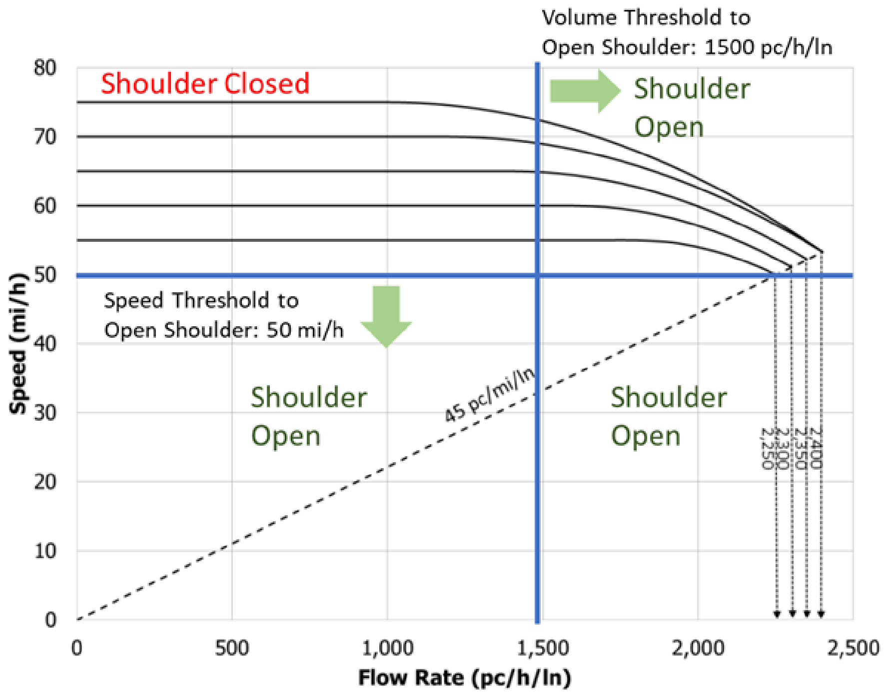
The following observations can be made from figure 18:

- Breakdowns occur slightly more often on Fridays.
- Breakdowns are not a daily event with only 16 (Tuesdays) to 34 (Fridays) days out of 52 weeks experiencing a breakdown event.
- The majority (90 percent) of breakdowns occur between 1 p.m. and 7 p.m.
- More than half (55 percent) of breakdowns occur between 3 p.m. and 6 p.m.
- Breakdowns occur occasionally during midday periods and in the evenings after 9 p.m.

Using these data to assess the viability of a PTSU system leads to the conclusion that a dynamic system may be viable. **Specifically, a 3-hour S-PTSU system, active from 3 p.m. to 6 p.m. would miss 45 percent of breakdown events in the figure 18 example. At the same time, a 6-hour S-PTSU system active from 1 p.m. to 6 p.m. would result in many unnecessary openings**. For example, from a total sample of 250 working days, only 9 breakdowns are observed to occur in the 1-2 p.m. hour and 14 occur during the 2-3 p.m. hour. Given the temporal variability and the fact that not all weekdays result in a breakdown, a D-PTSU system appears a reasonable option for this facility.

Estimate Initial Decision Parameter Threshold

Using the collected speed-flow data, the agency can develop an initial understanding of potential speed-based or volume-based decision parameters for the subject facility. The HCM can provide generalized findings from default speed-flow curves for basic freeway sections to select some initial starting values for opening the shoulder or assessing the feasibility and benefits of PTSU on a specific freeway or throughout a specific region (see example in figure 20).



Source: Highway Capacity Manual, Sixth Edition. 2016. Exhibit 12-7, Speed Flow Curve for Basic Freeway Section, Transportation Research Board, Washington, DC.

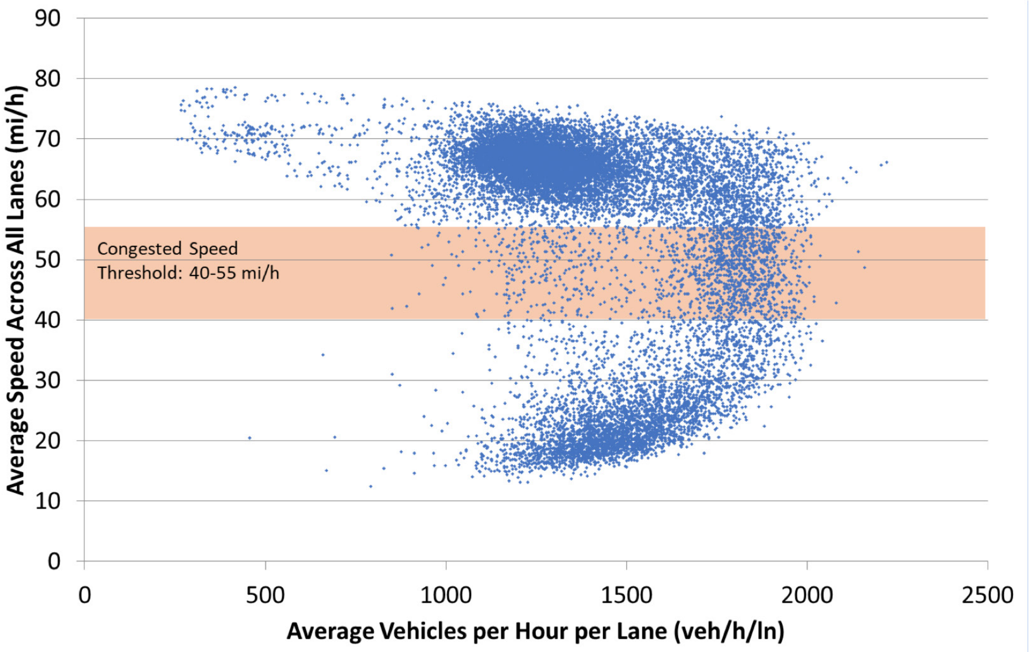
Figure 20. Chart. Using Highway Capacity Manual speed-flow curves to select thresholds.

In this example, after consulting the HCM speed-flow curves, the agency has selected 1,500 pc/h/ln as its shoulder opening volume threshold, and 50 mi/h as its shoulder opening speed threshold. The 50-mi/h threshold ensures that congestion will decision parameter consideration of opening the shoulder lane. The passenger cars threshold is set significantly below capacity so that the agency operator will have adequate advance notice to ensure that the shoulder is clear before opening the shoulder. As the operator gains experience, this volume threshold may be adjusted.

Note that the HCM passenger car threshold needs to be converted to the equivalent measure of veh/h/ln so that the operator can readily spot when volumes counted by a sensor exceed the threshold. The passenger car threshold is translated into equivalent vehicles per hour based on the HCM heavy vehicle adjustment factor (which varies with percentage heavy vehicles, terrain, and grade) and the peak hour factor for the facility. In the HCM, see equation 12-9, chapter 12, Basic Freeway Segments for the appropriate values.

Selection of Speed Threshold for Congestion. The HCM speed-flow diagram for basic freeway sections (see figure 20) suggests that a speed threshold of 50 mi/h would be appropriate for determining when a freeway is congested. In reality, breakdown speeds from facility to facility can vary from approximately 40 to 55 mi/h.

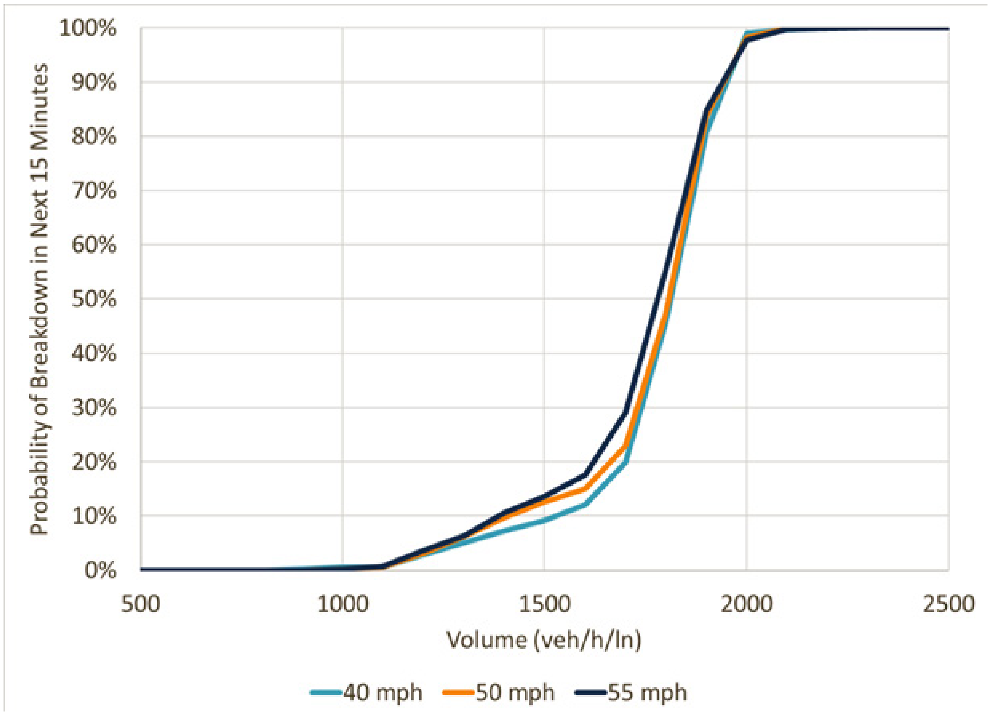
Figure 21 shows an example speed-flow plot that includes a year's worth of 5-minute data for the weekday morning peak period for a freeway in Northern California (approximately 16,000 data points). From this example it appears that speeds above 55 mi/h typically indicate uncongested operations on the freeway. Speeds below 40 mi/h typically indicate congested operations. Speeds in between 40 and 55 mi/h may or may not indicate congested (breakdown) operations.



Original figure © Richard Dowling, Alexander Skabardonis, David Reinke. 2008. "Predicting the Impacts of ITS on Freeway Queue Discharge Flow Variability." *Transportation Research Record* 2047. (See acknowledgments)

Figure 21. Chart. Identification of threshold for congested speeds.

Figure 22 shows the results of a more detailed examination of the data. For each sequence of four 5-minute periods, the first period was examined to determine if the speed was above the selected speed threshold, and if one of the following 5-minute periods fell below the same threshold. If so, the volume of the first 5-minute period was considered to be a pre-breakdown flow rate. All of the pre-breakdown flow rates were then grouped into 100 veh/h/ln bins in a spreadsheet to obtain a probability distribution for the pre-breakdown flow rate. This examination was repeated for three possible congested speed thresholds (40, 50, 55 mi/h). The results are plotted in figure 22. As can be seen in the figure, the distributions are relatively similar, regardless of the selected congested speed threshold. So, in this case the HCM speed threshold for congestion of 50 mi/h is appropriate for this facility and will be used in the remainder of this illustrative example.



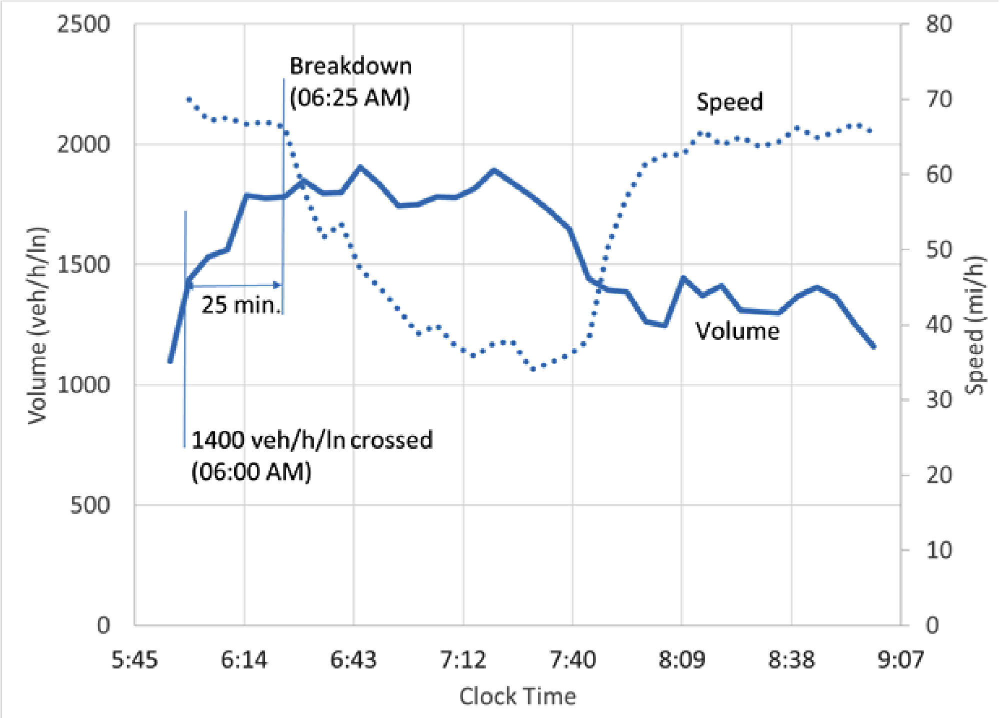
Source: FHWA

Figure 22. Chart. Probability of breakdown in next 15 minutes.

Selection of Volume Threshold for Opening Shoulder. The agency operator has two objectives for the selected volume threshold for opening the shoulder to traffic.

- The threshold should be high enough so that the agency is not opening the shoulder when congestion is not imminent.
- The threshold should be low enough so that the agency has adequate time to conduct a sweep and complete the opening process before the onset of congestion.

Examination of the cumulative probability curves in figure 22 suggests that at 1,750 veh/h/ln there is a 50 percent probability of breakdown in the next 15 minutes. However, at this threshold, will the agency have enough time to verify the shoulder is clear and open it before congestion is reached? To answer this question the volume and speed trends are examined for several representative days (see figure 22 for one example). From this examination it is determined that if the agency were to use a 1,750 veh/h/ln threshold, it would often have less than 5- or 10-minutes' warning before the onset of congestion. However, if the agency selects a volume threshold of 1,400 veh/hr/ln, it would often have 20 to 25-minutes warning of impending congestion. The amount of time needed to open the shoulder will vary from facility to facility, but most U.S. D-PTSU facilities take more than 5 or 10 minutes.

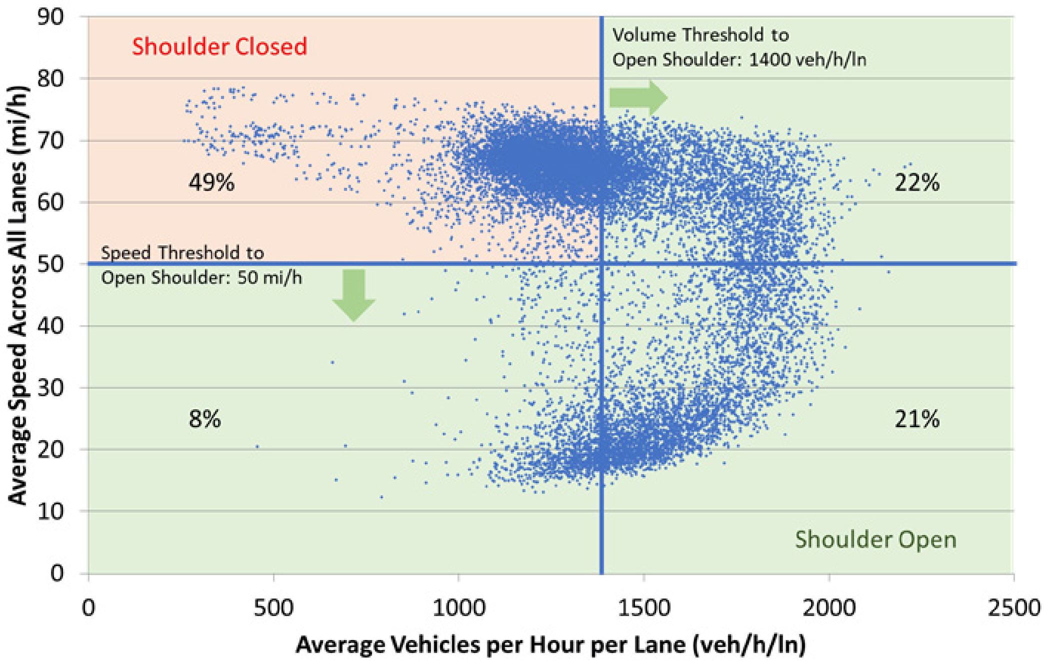


Source: FHWA

Figure 23. Chart. Example a.m. peak period speed-flow data for one day.

Use of Occupancy. Occupancy is defined by the HCM as 1) the proportion of roadway length covered by vehicles or 2) the proportion of time a roadway cross section is occupied by vehicles. Agencies with PTSU facilities interviewed as part of this project did not report the use of occupancy as a decision parameter, but it could be used as such. Unlike speed values, occupancy values change incrementally in lower-volume conditions and potentially provide an earlier indication of an approaching breakdown. Occupancy values are also less sensitive to fluctuations in capacity. For these reasons, may also wish to consider occupancy-based decision parameters.

Examination of Full Year Operations. Once the speed and volume thresholds for opening the shoulder have been selected, the agency might plot those thresholds against the speed-flow data to get an understanding of what percentage of the year the shoulder will be open to traffic. Figure 24 illustrates such a plot for a 50 mi/h speed threshold and a 1,400 veh/h/ln volume threshold. In this particular example, the shoulder would be closed for 49 percent and open for 51 percent of the time during the weekday morning peak periods over the course of a year.



Original figure © Richard Dowling, Alexander Skabardonis, David Reinke. 2008. “Predicting the Impacts of ITS on Freeway Queue Discharge Flow Variability.” *Transportation Research Record* 2047. (See acknowledgements)

Figure 24. Chart. Annual percent of time shoulder is open or closed in a.m. peak.

METHOD III: MACROSCOPIC DECISION PARAMETER OPTIMIZATION

The HCM 6th Edition freeway facilities methodology allows for analysis of access-controlled freeway and highway facilities in under-saturated and congested conditions over multiple analysis periods (up to 24 hours at a time). The methodology provides macroscopic operational analysis that combines the HCM’s basic freeway, merge/diverge, and weave segment methodologies, and further extends them to model queue spillback and queue dissipation across adjacent segments. The methodology has extensions for both reliability and active transportation and demand management strategies. Most importantly for this document, it includes guidance for modeling shoulder-use strategies that increase overall facility capacity in the PTSU segments.

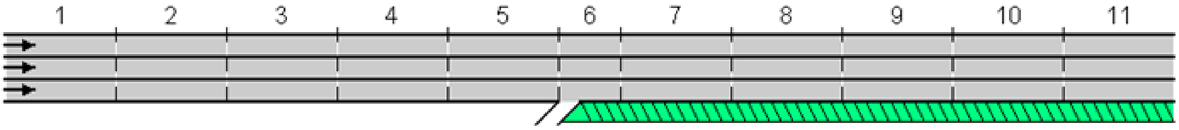
With the goal of determining the relative effectiveness of multiple decision parameter types under varying demand scenarios, the freeway facilities methodology provides a useful framework on which to develop, test, and compare sets of strategies. In comparison to more detailed analysis approaches like microsimulation, the method provides a more efficient analysis approach for analyzing hundreds or even thousands of scenarios. FREEVAL, which was developed as a part of the HCM 6th Edition update, is a free open-source implementation of the freeway facilities methodology. Several modifications to FREEVAL were made to conduct the research described in this chapter and enable more responsiveness to traffic conditions and more realistic durations for changing the number of lanes on the freeway (i.e., opening or closing the shoulder) and these are described in appendix C. FREEVAL and the HCM freeway facility were the basis for developing the guidance for D-PTSU decision parameter implementation described below.

In this report, the application of the FREEVAL methodology is introduced using a generic example facility with illustrative volume profiles. The results presented below provide useful insights in the tradeoffs of different decision parameters as a function of congestion levels (d/c ratios) and demand patterns (slope of demand curve). But in addition to these generic results, a facility-specific application of the method could be used to explore these tradeoffs and benefits of different D-PTSU decision parameters for a specific facility.

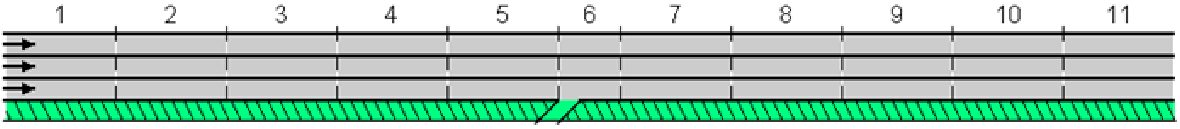
Experiment Design

The FREEVAL experiment was designed to test two different types of PTSU decision parameters: speed-based and volume-based. Operational performance of the facility was then determined for each decision parameter under multiple demand scenarios. Both the peak bottleneck demand as well as the rate (slope) of the demand increase were varied. In order to maintain consistency across geometries with differing numbers of lanes, peak bottleneck demand volume was considered in relation to the bottleneck capacity, and thus represented as the d/c ratio. In the results presented in this chapter, capacity values represent the capacity of the general purpose lanes only and not the shoulder. Thus, PTSU facilities are able to process d/c ratios greater than 1.0 when the shoulder is open.

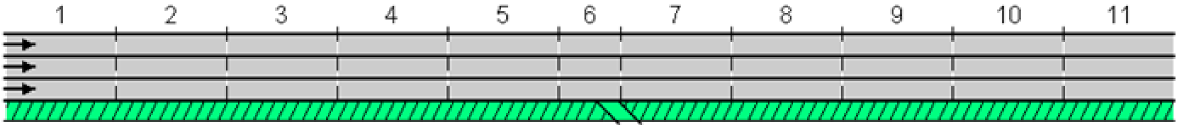
Three different geometric configurations for the facility, shown in figure 25, were considered in the experiment. The configurations differed either in the cause of the bottleneck (i.e., merge vs diverge) or the configuration of the shoulder use facility (i.e., beginning at an on-ramp or flowing through an on-ramp). Each geometry was also considered for two-lane, three-lane, and four-lane (per direction) facilities. The three configurations for facilities with three mainline lanes per direction are shown below, with a crosshatched green area showing a shoulder used as a part-time lane. The terminology "Type A" and "Type B" was created for purposes of this report.



a) Merge bottleneck with PTSU beginning at the ramp (Type A).



b) Merge bottleneck with PTSU extending through the ramp (Type B).



c) Diverge Bottleneck with PTSU extending through the ramp.

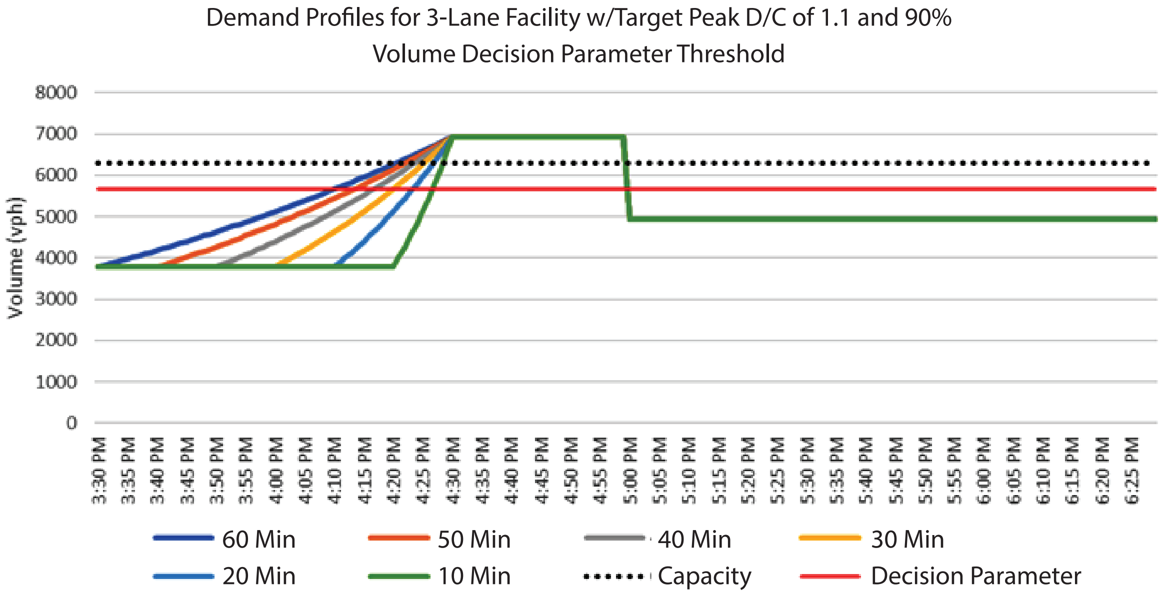
Source: FHWA

Figure 25. Diagrams. Compound figure illustrates ramp-freeway junction types in FREEVAL experiment.

All three facilities were subject to the following fixed assumptions:

- Full lane capacity, non-bottleneck (2,400 pc/lane/hour).
- Full lane capacity, bottleneck (2,100 pc/lane/hour).
- Free-flow speed (70 mi/h).
- Facility sweep time (20 minutes).
- Facility clearance time (20 minutes).
- Minimum duration shoulder must remain open (15 minutes).
- Heavy vehicle percentage (1 percent single-unit trucks, 1 percent tractor trailers).
- Length of time bottleneck is at peak demand (30 minutes).

The operational status of a corridor in the time frame leading up to a breakdown can vary significantly for different facilities. One primary cause of this is the rate at which the demand volumes increase from below capacity to above capacity. This is referred to as “slope offset” in this chapter. Some facilities experience rapid increases in demand, while others may see volumes increase more gradually. For example, demand tends to increase more rapidly in the morning peak than in the afternoon peak or on weekends. For the purpose of this experiment, this variation is modeled through different slope offsets for the demand profiles. Specifically, this experiment considered six different slopes. Figure 26 shows the demand profiles for a three-lane facility with a target peak d/c of 1.1 and a 90-percent volume decision parameter threshold.



Source: FHWA

Figure 26. Chart. Demand profiles for three-lane facility.

The profiles represent an increase of demand volumes from a d/c ratio well below 1.0 up to the max bottleneck d/c defined as an exponential function ($V = V_0{*}e^t$). Differing exponential slopes were created by offsetting (delaying) the start of the demand increase by increments of 10 minutes for a range of no offset (zero) up to 50 minutes. A slope offset of zero means the demand begins to increase immediately, but at a very gradual rate. A higher slope offset delays the starting point of demand increases, resulting in a steeper demand profile. A low slope offset (flatter slope) provides more time between a decision parameter volume being reached and the demand profile exceeding capacity, than a higher slope offset (steeper slope).The above chart shows an example of the six demand profiles for a three-lane facility with a peak bottleneck d/c of 1.0. For reference, a line showing where a 90 percent volume decision parameter threshold is met is also shown.

The slope of the demand curve was one of the six key parameters that was varied in the experiment: (1) the geometric configuration of the bottleneck as described above), (2) the number of main line lanes, (3) the capacity of the shoulder, (4) the peak bottleneck d/c ratio, (5) the demand profile slope described above, and (6) the decision parameter threshold itself. Table 9 summarizes the parameter variations of the experiments and a total resulting 5,670 scenarios analyzed.

Table 9. Parameter variations of experiments and total scenarios analyzed in FREEVAL.

Parameter	#	Values
Geometric bottleneck configuration	3	Type A Merge, Type B Merge, Diverge
Number of mainline lanes	3	2, 3 and 4 lanes
Shoulder capacity	3	1,200 pc/h/ln, 1,400 pc/h/ln, 1,600 pc/h/ln
Peak bottleneck demand-to-capacity ratio	5	1.02, 1.04, 1.06, 1.08, 1.10
Demand volume profile shape/slope	6	0 to 50-minute offsets
Decision parameter threshold	7	See below
Total Scenarios	5,670	3*3*3*5*6*7

pc/h/ln = passenger cars per hour per lane.

For the decision parameter threshold, both volume- and speed-based decision parameters were evaluated. In the case of a speed-based decision parameter, the shoulder was opened when observed speeds dropped below the specified value. For a volume-based decision parameter, the shoulder was opened when volumes were first observed above the specified value (given as a percentage of a bottleneck's known capacity). Table 10 shows the different thresholds considered for the two decision parameter types.

Table 10. Different thresholds for the two decision parameter types.

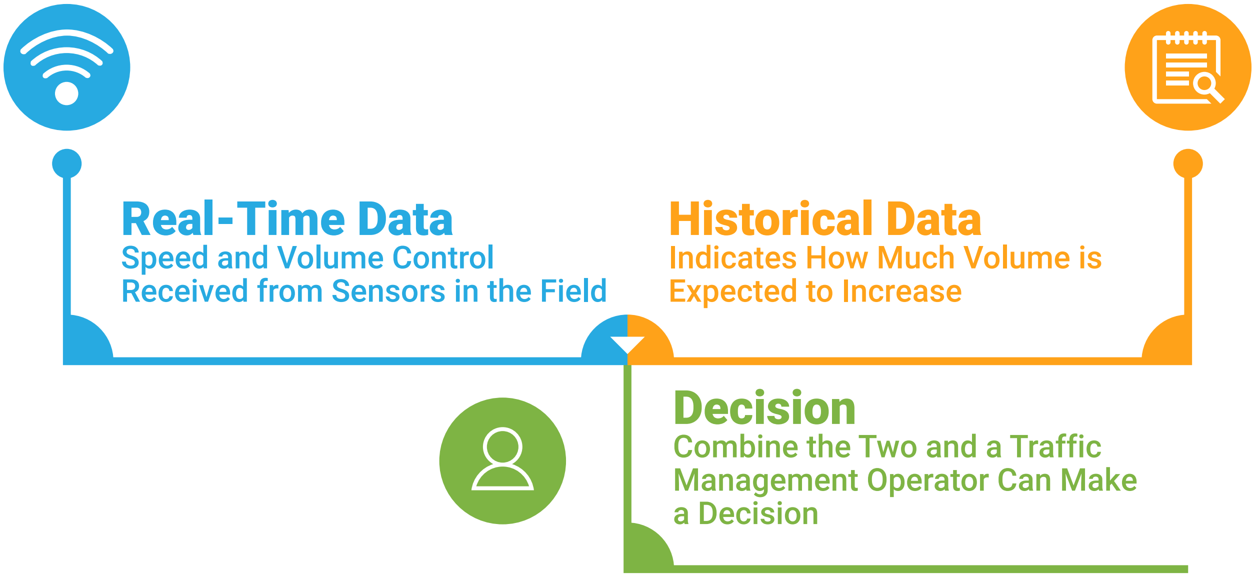
Decision Parameter Type	#	Threshold
Speed	3	45 mi/h, 50 mi/h, 55 mi/h
Volume (as a percentage of bottleneck capacity)	4	70%, 80%, 90%, 100%

Results

Once the necessary software modifications were made to enable the execution of the experiment in the FREEVAL computational engine, all scenarios were run and a set of performance metrics were recorded. **While the core HCM methodology provides a variety of performance metrics, the primary metric for this analysis is the delay experienced on the facility during the study period, which is recorded as the vehicle hours delay (VHD)**. Beyond delay, an additional key performance metric specific to this experiment is the number of analysis periods that the shoulder was opened for each scenario.

The rate of the volume increase leading up to the breakdown is crucial when identifying a decision parameter. Historical data of typical volume rate increases can be used to inform when how realtime conditions will change the coming minutes and whether shoulder-opening activities should be initiated or not.

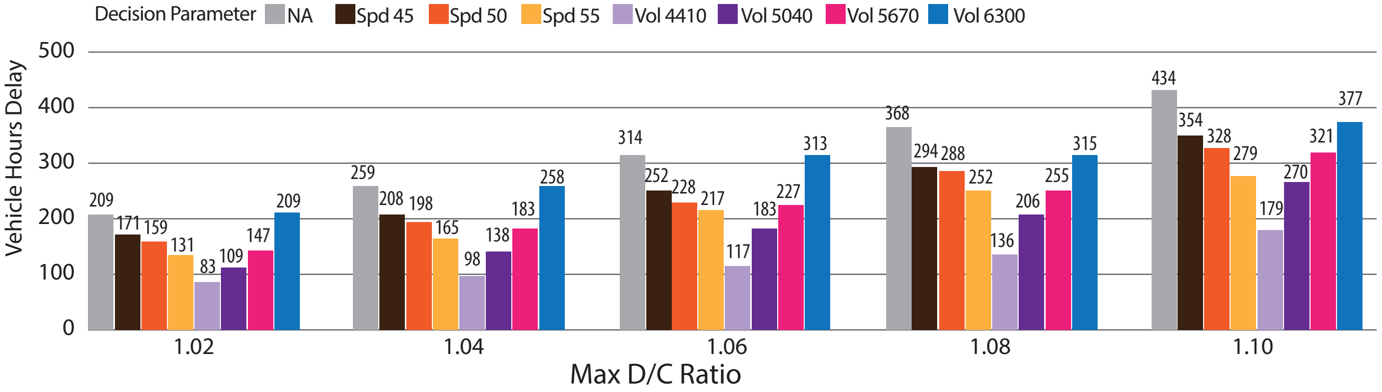
The primary result of the HCM experiment shows that the rate of the volume increase leading up to the breakdown is crucial. While varying parameters such as number of mainline lanes, peak d/c ratio, and shoulder capacity changed the magnitude of the values, the conclusions reached across the variations were all largely consistent. For instance, while higher peak bottleneck d/c ratios influenced the overall extent of delay experienced, the relative effects of the different shoulder-use decision parameters were essentially fixed across all five values. As a result, no matter how advanced realtime data collection on a facility may be, historical data provides valuable insight into whether an observed volume increase is expected to be sustained or not. Figure 27 illustrates this relationship.



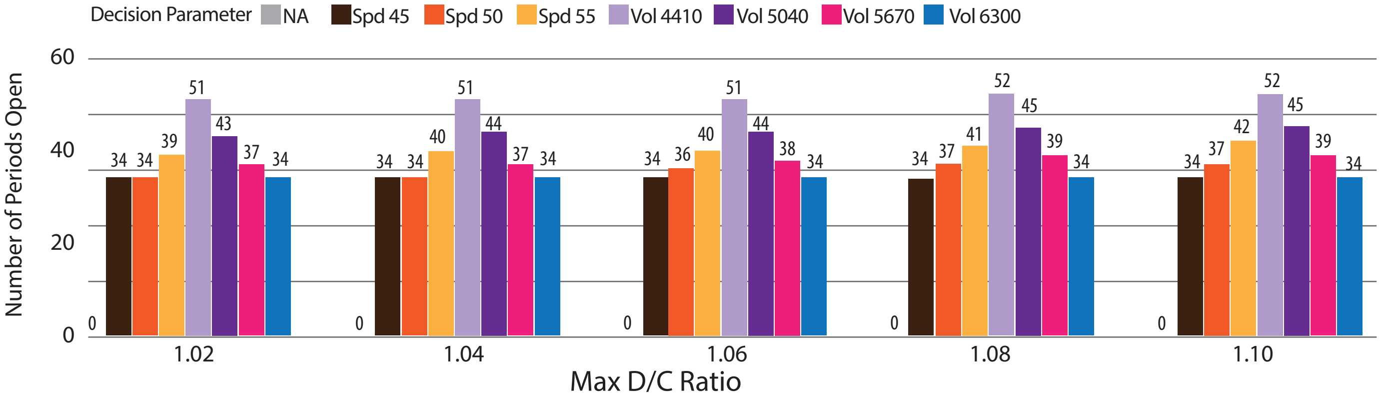
Source: FHWA

Figure 27. Chart. Use of realtime and historical data for part-time shoulder use decisionmaking.

Figure 28 demonstrates this for a three-lane Type A merge facility with a medium rate of demand increase (offset = 30 minutes). While the VHD values shown in the top half of the figure do vary across d/c ratios ranging from 1.02 up to 1.10, the relative delay experienced by each decision parameter scenario is similar for all cases. This is further reflected by examining the number of periods the shoulder is open in each case, which are almost identical across all five d/c values. This same trend is found for nearly all variations of facility geometry.



a) Vehicle hours of delay by decision parameter and max d/c.



b) Periods shoulder is open by decision parameter and max d/c.

Source: FHWA

Figure 28. Chart. Effects of varying peak bottleneck d/c ratios for a three-lane, Type A facility geometry and demand increase slope (offset = 30, medium).

The top chart shows vehicle hours of delay when different speed thresholds (gray/orange/tan bars) and volume thresholds (purple bars) determine when the shoulder is opened. Each group of bars represents a different d/c ratio, and volumes and geometry are consistent across all scenarios. The bottom chart shows the number of minutes in the hour the shoulder is open. In general, higher speed and lower volume thresholds result in the shoulder being opened longer and delay being lower. This represents a tradeoff for agencies to consider.

Generalized Results

As previously discussed, the capacity of freeway bottlenecks varies greatly, and the thresholds at which the PTSU opening process should begin to avoid the onset of a breakdown will vary. However, making a number of assumptions, tables indicating the minutes until breakdown occurs for various scenarios can be developed. A set of tables developed for this project can be found in appendix D, and one example is shown below in table 11.

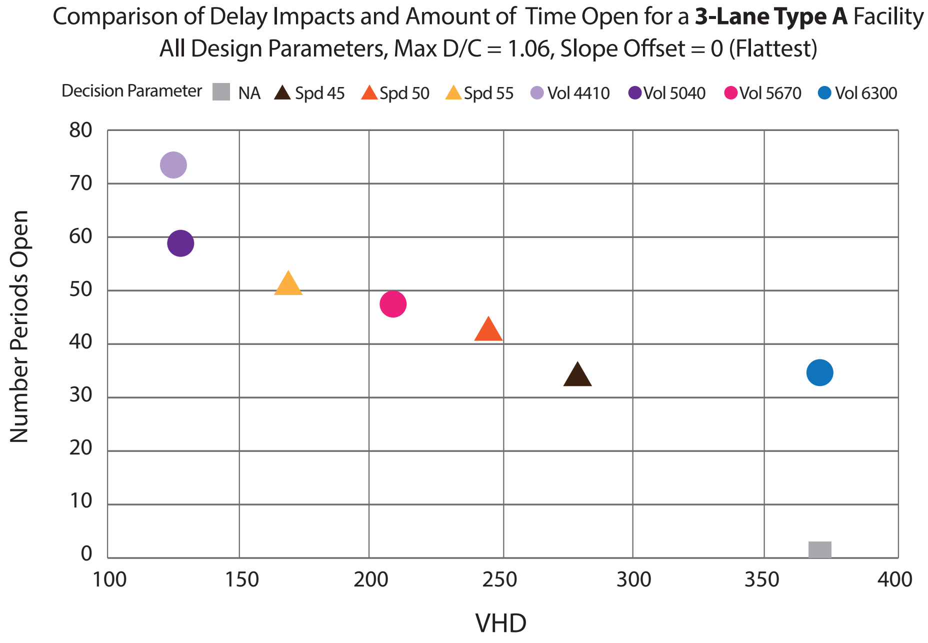
Table 11. Example of appendix D table—minutes until capacity is reached when per lane capacity is 1,900 veh/h/ln.

Bottleneck Per Lane Capacity	Minutes until Capacity Is Reached									
	Increase in Hourly Volume Rate In Past 5 Minutes									
1,900	10	20	30	40	50	60	70	80	90	100
Current Volume (veh/h/ln)										
0	190	95	64	48	38	32	*28	*24	*22	*†19
100	180	90	60	45	36	30	*26	*23	*20	*†18
200	170	85	57	43	34	*29	*25	*22	*†19	*†17
300	160	80	54	40	32	*27	*23	*20	*†18	*†16
400	150	75	50	38	*30	*25	*22	*†19	*†17	*†15
500	140	70	47	35	*28	*24	*20	*†18	*†16	*†14
600	130	65	44	33	*26	*22	*†19	*†17	*†15	*†13
700	120	60	40	*30	*24	*20	*†18	*†15	*†14	*†12
800	110	55	37	*28	*22	*†19	*†16	*†14	*†13	*†11
900	100	50	34	*25	*20	*†17	*†15	*†13	*†12	*†10
1,000	90	45	*30	*23	*†18	*†15	*†13	*†12	*†10	*†9
1,100	80	40	*27	*20	*†16	*†14	*†12	*†10	*†9	*†8
1,200	70	35	*24	*†18	*†14	*†12	*†10	*†9	*†8	*†7
1,300	60	*30	*20	*†15	*†12	*†10	*†9	*†8	*†7	*†6
1,400	50	*25	*†17	*†13	*†10	*†9	*†8	*†7	*†6	*†5
1,500	40	*20	*†14	*†10	*†8	*†7	*†6	*†5	*†5	*†4
1,600	30	*†15	*†10	*†8	*†6	*†5	*†5	*†4	*†4	*†3
1,700	*	*†10	*†7	*†5	*†4	*†4	*†3	*†3	*†3	*†2
1,800	*†10	*†5	*†4	*†3	*†2	*†2	*†2	*†2	*†2	*†1
1,900	*†0	*†0	*†0	*†0	*†0	*†0	*†0	*†0	*†0	*†0
2,000	--	--	--	--	--	--	--	--	--	--
2,100	--	--	--	--	--	--	--	--	--	--
2,200	--	--	--	--	--	--	--	--	--	--

veh/h/ln = vehicles per hour per lane.
-- = not applicable.
* Operator should consider initiating shoulder-opening activities.
† The freeway will reach capacity before the shoulder is opened.

Suppose a freeway has an hourly volume of 1,200 veh/h/ln, and the capacity of a downstream bottleneck is 1,900 veh/h/ln. Also suppose it takes 20 minutes to "sweep" the shoulder and complete the opening process once the decision to open the shoulder has been made. Find the "1,200"' row on the table. If the hourly volume rate increased 10 veh/h/ln in the last 5 minutes (first column of data in the table) and that rate of increase is assumed to continue, it will be 70 minutes until capacity is reached. Moving further to the right, the minutes until capacity is reached decrease. When they fall below 20 minutes, values are displayed in red to indicate the shoulder cannot be opened before capacity is reached due to the sweep time.

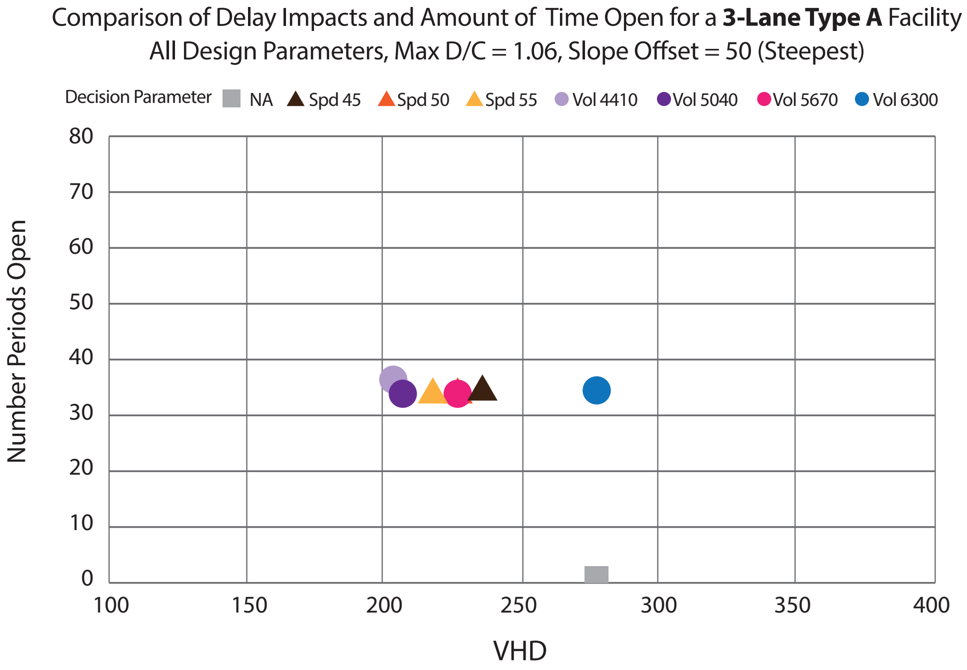
Figure 29 and figure 30 highlight some of the differences in behavior resulting from varying the rate of increase of the demand profile. Both figures compare the VHD with the number of periods the shoulder was opened for a three-lane merge Type A bottleneck with a peak bottleneck d/c ratio of 1.06. Figure 29 plots the metrics for the facility under the slowest rate of demand volume increase (offset = zero). Notice that the chart shows a wide degree of spread across various decision parameter types and thresholds. In contrast, figure 30 shows results for the same facility but under the fastest rate of demand increase (offset = fifty minutes). Unlike in figure 28, the points are all clustered together, with little variation in results regardless of decision parameter type or threshold. Taken together, this indicates that the choice of decision parameter type or threshold is less important for facilities that experience sudden or rapid increases in demand volume. Alternatively, when the volumes increase to an over-capacity condition more slowly, the choice of decision parameter type and threshold plays a much larger role in the overall performance of PTSU.



Source: FHWA

Figure 29. Chart. Comparison of vehicle hours delay and number of periods the shoulder is open for a three-lane Type A merge facility for a peak demand-to-capacity ratio of 1.06 and no slope offset.

Overall, the results from the HCM experiment have two primary findings. First, it is possible to develop general guidance largely based on the rate of increase in demand experienced in the time leading up to capacity being exceeded. Facilities with more gradual rates of change should focus more on decision parameter type and threshold, while those with rapid demand increases will see fewer practical differences between different types of decision parameters. This in turn leads to the second takeaway, which is that if field-observed data for both the ratio of peak demand versus capacity and the rate of increase in demand leading up to breakdown are known, they will likely be very indicative of the performance of PTSU and should be used to inform decisionmaking to determine decision parameter type and threshold.



Source: FHWA

Figure 30. Chart. Comparison of vehicle hours delay and number of periods the shoulder is open for a three-lane Type A merge facility for a peak demand-to-capacity ratio of 1.06 and a 50-minute slope offset.

METHOD IV: MICROSCOPIC DECISION PARAMETER REFINEMENT

Microsimulation offers a way to evaluate and refine a D-PTSU decision parameter scheme prior to implementation in the field. While the macroscopic optimization in Method III is geared at efficiently running a large number of potential decision parameter events and combinations, Method IV is designed to test a select few decision parameter strategies in a more dynamic simulation environment.

Microsimulation models individual vehicle movements using a series of behavioral rules or algorithms, including car-following, lane changing, gap acceptance, and others. Microsimulation tools are frequently used to evaluate freeway systems, proposed interchange geometric changes, and active traffic and demand management strategies.

Microsimulation tools can be used to model S-PTSU and D-PTSU systems, with the latter using whatever desired combination of decision parameter events and decision algorithms of interest through the use of Component Object Model (COM) scripting. Using COM, many microsimulation tools can use customized and agency-specific decision algorithms.

In a typical work flow, an agency may employ Methods I and II to understand the congestion and demand patterns on the subject facility, and then use Method III to test a range of potential decision parameter options and combinations. Method IV then applies the developed decision parameter logic to the subject facility in a dynamic simulation context.

Similar to the discussion of Method III, the microscopic decision parameter refinement is best applied to the specific facility on which an agency is considering PTSU. In this section, the method is applied to a generic facility that mirrors the Method III experiment to illustrate the application of the method. The section first discusses experimental design for the microsimulation analysis and then summarizes key simulation findings. The same steps can be applied to both a microsimulation analysis of other geometric configurations as well as decision parameter algorithms.

Experiment Design

The microsimulation experiment was designed to test two different types of D-PTSU decision parameters (i.e., speed-based and volume-based). Operational performance of the facility was then determined for each decision parameter under multiple demand scenarios. This experiment used the VISSIM microsimulation tool, but other tools are viable as long as they can model freeway operations and allow the use of custom logic scripts through COM.

Scenario Demand Variations: The same vehicle demand and rate (slope of the demand increase) discussed for the FREEVAL experiments (figure 25) was used for the simulation scenarios. This was to maintain consistency between the FREEVAL and simulation experiments, which will allow for results comparison.

Decision Parameter Variations: Four decision parameter types were considered. These include two speed decision parameter scenarios (45 mi/h and 55 mi/h) and two volume decision parameter scenarios (70 percent and 80 percent of bottleneck capacity). A base scenario without the D-PTSU (i.e., no decision parameter, no opening of shoulder) was also analyzed to provide baseline comparison. It should be noted that only a select number of decision parameter scenarios were analyzed in microsimulation, compared to the FREEVAL experiments, due to the increased time involved in developing and analyzing simulation models.

Geometric Configuration: Only the merge bottleneck with Type B geometry (i.e., merge bottleneck with PTSU flowing through the ramp, see the discussion on Method III above) was considered in the simulation. A three-lane geometry (not including the shoulder) for the mainline was considered for the facility with PTSU.

Table 12 summarizes the parameter variations of the experiments and resulting total number of scenarios analyzed in the simulation.

Table 12. Parameter variations of experiments analyzed in microsimulation.

Parameter	#	Values
Geometric bottleneck and shoulder configuration	1	Type B Merge
Number of mainline lanes	1	3 lanes
Shoulder capacity	1	1,600 vph
Decision parameter variations	5	No Decision parameter, Speed=45mi/h, Speed=55 mi/h, Vol=0.7*d/c, Vol=0.8*d/c
Peak bottleneck d/c ratio	5	1.02, 1.04, 1.06, 1.08, 1.10
Demand volume profile shape/slope	6	0 to 50-minute offsets
Total Scenarios	150	1*1*1*5*5*6

d/c = demand to capacity (ratio). vph = vehicles per hour.

The following fixed assumptions were made for the simulation experiments:

- Full lane, non-bottleneck capacity was assumed as 2,400 pc/h/ln.
- Full lane, bottleneck capacity was assumed as 2,100 pc/h/ln.
- Shoulder capacity was assumed as 1,600 pc/h/ln.
- A free-flow speed of 65 mi/h was assumed.
- Facility sweep time to open the shoulder was set to 20 minutes.
- Minimum duration for the shoulder to stay open was set to 15 minutes.
- A 2 percent heavy vehicle presence was considered.

It should be noted that capacity in simulation is not a value that can be pre-defined by the user. Therefore, the research team conducted sensitivity testing of the car-following behavior parameters (VISSIM’s Wiedemann 99) to reasonably represent the capacities of freeway mainline, freeway bottleneck, and shoulder lane. The team then extracted capacities from the model by developing flow-density curves by varying vehicle demand to create various flow regimes.

Realtime Microscopic Analysis

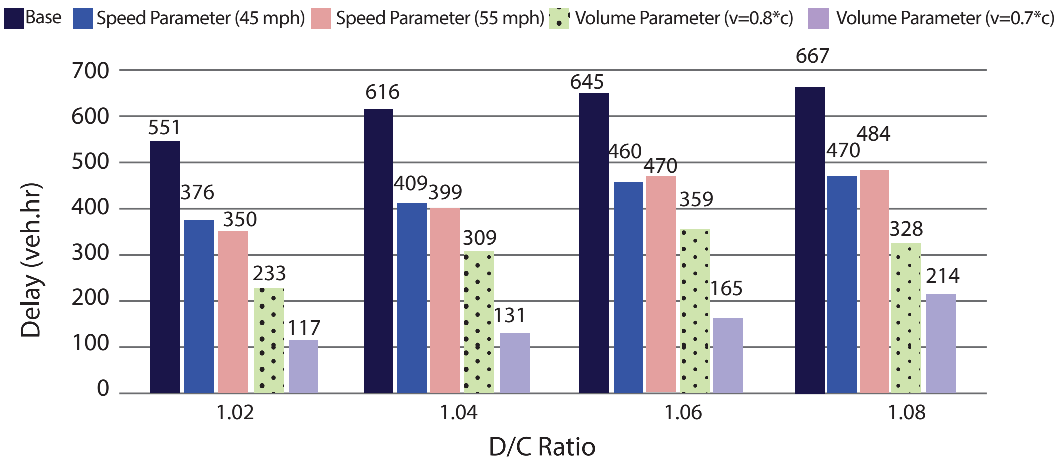
Once a PTSU facility is operational, microsimulation can be used in realtime to inform and optimize PTSU decisionmaking by facility operators. Once a microsimulation model is constructed and calibrated, it can be fed data from field sensors and traffic variables such as speeds, volumes, and vehicle mixes can be updated in real time. This “sensor in the loop” approach enables data to be analyzed, rather than merely observed, by TMC staff, and it enables microsimulation to be linked to realtime, rather than historical, traffic conditions. With this data, microsimulation can be used as a predictor of traffic conditions in the near term (1 hour or less). This would effectively replace a lookup table such as the example in table 11. Integrated corridor management (ICM) is an emerging active traffic management strategy which often implements changes across multiple modes and routes. Pilot ICM installations in Dallas and San Diego have incorporated realtime data into microsimulation in this manner.

VISSIM Results and Conclusions

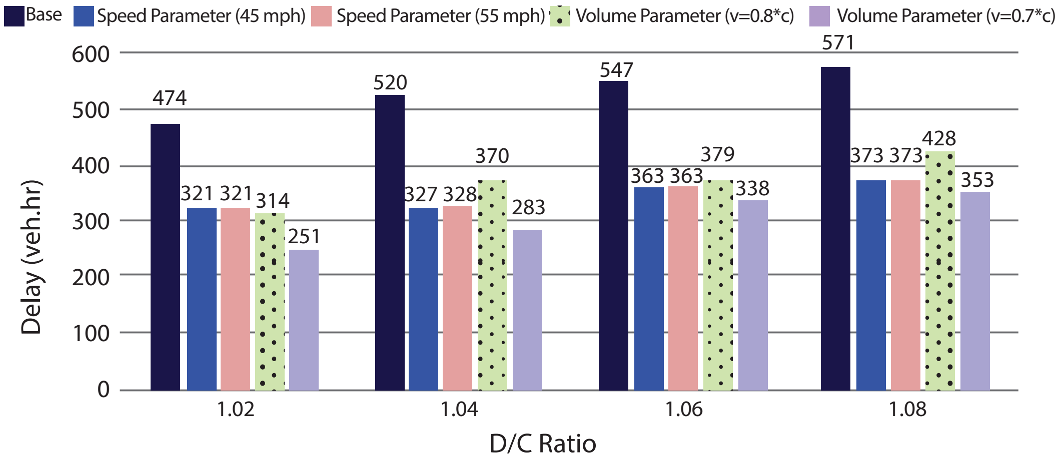
The following measures of effectiveness were used in VISSIM to summarize results:

- Total network delay.
- Network delay reduction as a function of shoulder duration open.
- Vehicle throughput, both for the mainline and the shoulder.

Figure 31 illustrates network delay comparison under various decision parameters and maximum d/c ratios for slope offset 0 and slope offset 40. As previously described, slope offset represents the number of minutes between the start of the experiment and the start of volume increase. In both experiments, the same peak volume was reached at the same time, so higher slope offset values represent a more rapid rate of volume increase. While results from only two slopes are shown here, simulation results for other slopes indicated similar findings.



a) Network Delay: Slope Offset = 0; Shoulder Capacity = 1,600 veh/hr.



b) Network Delay: Slope Offset = 40; Shoulder Capacity = 1,600 veh/hr.

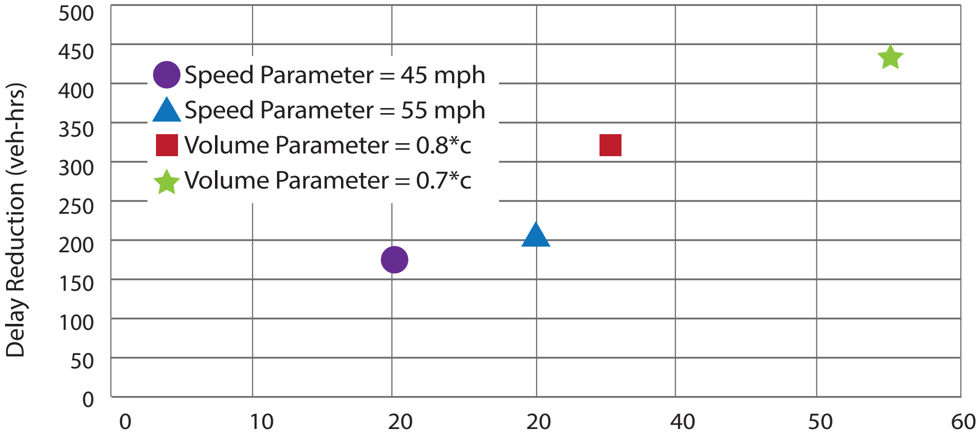
Source: FHWA

Figure 31. Charts. Compound figure depicts network delay comparison under various decision parameter variations and maximum demand to capacity ratios.

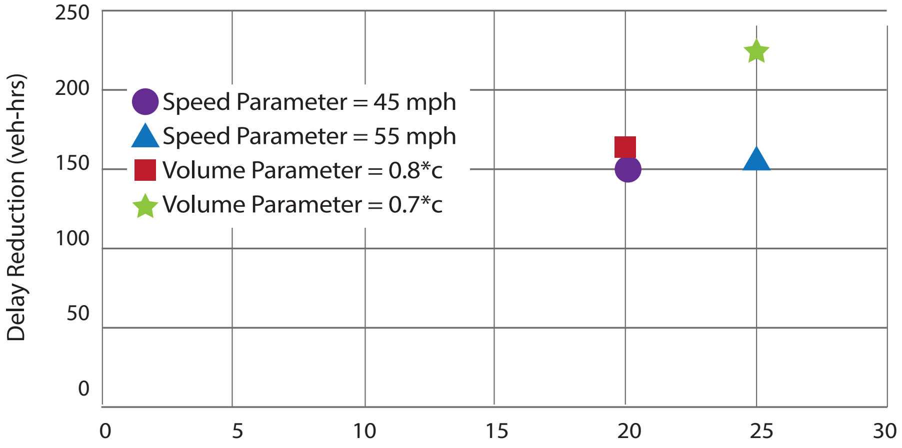
Key network delay findings include:

- For lower slope offset demand variations (e.g., slope = 0, indicating a more gradual volume increase to oversaturation), the volume-based decision parameter outperforms the speed decision parameter and results in considerably lower network delay. In addition, setting up a lower volume decision parameter threshold further reduces network delay by opening the shoulder early before the bottleneck conditions start.
- For the higher slope offset demand variations (e.g., slope = 40, indicating a more abrupt volume increase from below capacity to above capacity), a speed-based decision parameter tends to perform the same and even better in certain conditions.

Figure 32 shows network delay reduction and shoulder open duration under various decision parameter variations and slope offsets for max d/c = 1.02.



a) Maximum demand to capacity ratio = 1.02; Slope Offset = 0.



b) Maximum demand to capacity ratio = 1.02; Slope Offset = 40.

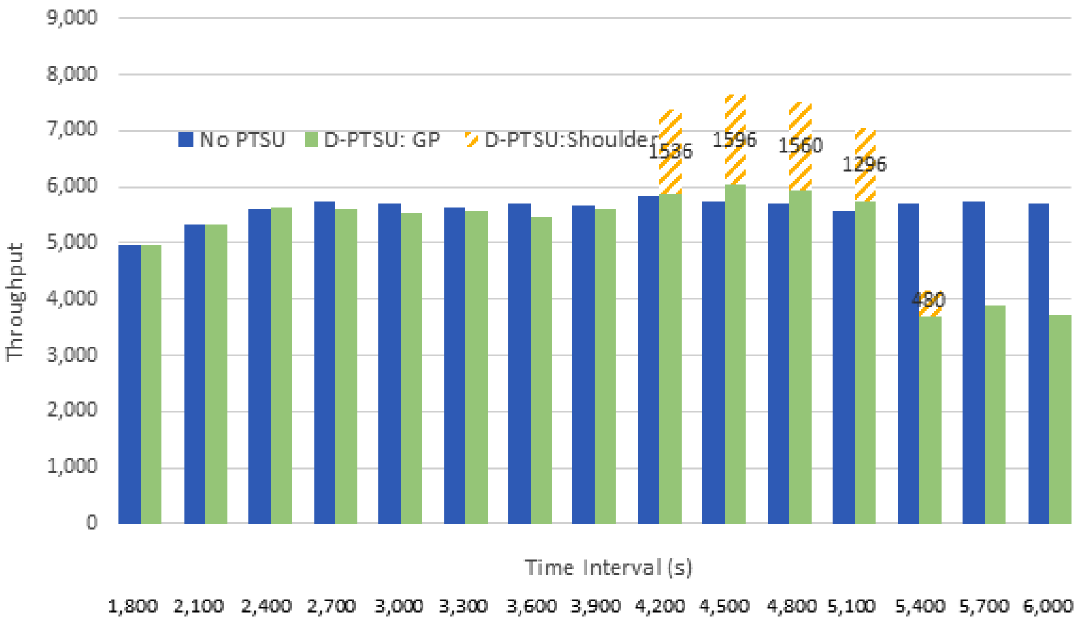
Source: FHWA

Figure 32. Charts. Compound figure compares delay reduction and shoulder open duration under various decision parameter variations for different maximum demand to capacity ratios and slope offsets.

Key findings include:

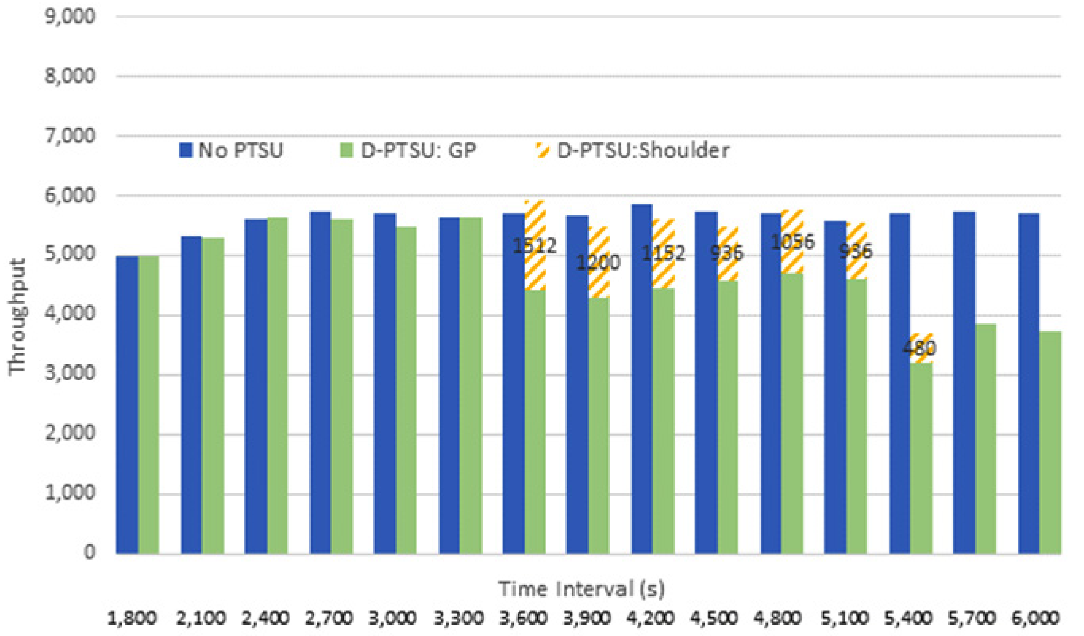
- With the lower slopes (e.g., slope = 0), similar to the network delay findings, the volume-based decision parameter outperforms the speed-based decision parameter by reacting to the volume increase faster and opening up shoulder before the bottleneck conditions are realized. This can particularly be observed from the volume decision parameter = 0.8*d/c scenario, as the shoulder was open for only 5 minutes longer than the speed decision parameter = 55 mi/h scenario (35 minutes vs. 30 minutes), yet substantial delay reductions are achieved.
- With the higher slopes (e.g., slope = 40), the speed-based decision parameter tends to perform similarly to the volume-based decision parameter scenario. For example, the speed decision parameter = 45 mi/h scenario is almost identical to the volume decision parameter = 0.8*d/c scenario. While the findings are counter-intuitive, this can be attributed to the specific demand scenarios that were designed and tested in the experiments. With the abrupt volume jump prior to the breakdown under the high slopes, the volume decision parameter scenarios are unable to respond before the traffic flow breakdowns happen, resulting in performance similar to the speed-based decision parameter scenarios.

Figure 33 illustrates vehicle throughput under slope offset = 0 and maximum d/c ratio = 1.04 under the speed decision parameter = 45 mi/h and the volume decision parameter = 0.8*d/c scenarios. The below figures provides an example of how the volume decision parameter responds quicker to the pre-breakdown conditions by opening the shoulder sufficiently prior to the breakdown and providing additional capacity for a longer period. This can also be observed from the speed decision parameter results as the obtained shoulder throughput was close to capacity (1,600 vehicles per hour) during almost every interval that the shoulder was open, indicating oversaturated conditions had already been reached by the time the shoulder was opened. Finally, throughput results for the speed decision parameter scenario validate the shoulder capacity assumption of 1,600 vehicles per hour used in the simulation.



D-PTSU = dynamic part-time shoulder use. GP = general purpose (lanes). PTSU = part-time shoulder use.

a) Vehicle throughput where slope offset = 0, maximum demand to capacity ratio = 1.04, the speed decision parameter = 45 mi/h, and shoulder capacity = 1,600 veh/hr.



D-PTSU = dynamic part-time shoulder use. GP = general purpose (lanes). PTSU = part-time shoulder use.

b) Throughput: Slope Offset = 0; Max d/c = 1.04; Volume Decision parameter = 0.8*d/c; Shoulder Capacity = 1,600 veh/hr.

Source: FHWA

Figure 33. Charts. Compound figure depicts vehicle throughput for slope offset = 0, maximum d/c = 1.04 under speed decision parameter = 55 mi/h and volume decision parameter = 0.8*d/c scenarios.

METHOD V: MONITORING AND ADJUSTMENT

The fifth and final method acknowledges the value of continuously monitoring a D-PTSU system once it is in operation. Facility operators learn their facility from observing day-to-day operations and develop an understanding for when to open and close based on the incoming data they are seeing. Whether the system being monitored is a Level 2, 3, or 4 D-PTSU, there is value in monitoring the operations and adjusting thresholds based on experience. The concepts and data analysis methods described in this chapter can reasonably be applied to existing D-PTSU systems to assist with the assessment of ongoing operations.

CONCLUSIONS

This chapter presented a method for evaluating the viability of a D-PTSU system for a given facility and provided guidance for exploring and comparing different options for using decision parameters to open the system. In the decision to select an appropriate decision parameter for a D-PTSU facility, three primary choices are available:

1. **Fixed time-of-day parameters,** which pre-determine the hours of operations.
2. **Volume-based decision parameters,** which are proactive and geared toward preventing breakdown from happening in the first place.
3. **Speed-based decision parameters,** which are reactive to breakdown having occurred.

It is recommended that both a speed and a volume threshold be selected for opening the shoulder lane.

The analysis suggests that it is most effective to select both a volume threshold and a speed threshold for opening the shoulder to traffic. This ensures that the low-volume, low-speed conditions typical of congested operations will result in the shoulder being opened, even if the volume threshold may not have been reached. Inclement weather and other conditions can cause speeds to drop below the speed threshold even though volume thresholds have not been reached, reducing the capacity of the facility below its normal, fair weather condition. This situation can also occur when there is a downstream incident backing up traffic into the section with PTSU; however, the agency operator will also want to consider whether there is any value to opening the shoulder when the bottleneck is downstream of the PTSU section. Additionally, an operator can use its discretion and not open the shoulder if they determine weather or other realtime conditions make it unsafe to open the shoulder.

Using sensor technology, **speed-based decision parameters** are easier to implement, since they are directly tied to a bottleneck sensor. If sensor speed shows decision parameter speed, the shoulder is opened. This requires the use of realtime sensor data, which is best achieved using sensor technology deployed in the field. While probe-based speed data are available to many agencies, they are limited in application for two primary reasons: (a) they are generally not available in realtime, and (b) they are aggregate speeds from a sample of vehicles over a distance rather than speeds measured instantaneously at a point.

Due to the nature of the speed-flow-density relationship, a speed-based decision parameter will typically occur "too late" to prevent breakdown. As was discussed in Methods I and II, a decision parameter speed of 45 mi/h, for example, corresponds to a 100 percent probability of breakdown. However, the macroscopic decision parameter optimization experiment described in this section found that in some cases, a speed-based decision parameter is still the best option as it balances delay impact with the "wasted" time during which the shoulder is open, which can lead to safety concerns.

Volume-based decision parameters are more difficult to implement, since the decision parameter volume is a function of the bottleneck capacity. However, they are better at predicting future traffic conditions. The volume-based decision parameter should be set at a flow rate at which the breakdown probability is still very low, with that breakdown probability obtained from the PLM or maximum likelihood method presented in Method II.

Since bottleneck capacity is not fixed but rather depends on site-specific attributes (geometry, vehicle mix, weaving, etc.), it is recommended that a site-specific assessment of breakdown probability be performed. In the Method II example, 95 percent breakdown occurs at a flow rate of 1,570 vehicles per hour per lane. As a result, the decision parameter volume needs to be set at some percentage of that breakdown capacity.

Because a shoulder cannot be opened instantaneously, the rate of volume increase in the minutes beyond the present time is key. Historical data and knowledge of a specific facility can provide into this issue.

In selecting a volume-based decision parameters, the slope of the demand curve, which describes the rate-of-increase in traffic volume leading up to breakdown, is another key consideration. Given the same decision parameter volume, a flatter slope provides more time between a decision parameter volume and breakdown flow rate, relative to a steeper slope.

The volume-based decision parameter also needs to take into account the amount of sweep time needed between reaching the volume threshold for activating PTSU and the time the shoulder can actually be opened. Specifically, the decision parameter volume needs to be set such that it provides sufficient time between reaching the decision threshold and the breakdown occurring, which is a function of facility length (longer facilities take longer to sweep), sweep technology (camera tour is faster than manually driving it), rate of change of traffic growth (steeper slopes give less time than flatter slopes), and, ultimately, the bottleneck capacity.

At the same time, agencies need to be careful not to set decision parameter volumes too low for two primary reasons:

1. Opening the shoulder too early results in increases in capacity before it is needed, resulting in potentially higher speeds, and potentially reduced safety.
2. A decision parameter volume that is set too low can result in false positives; i.e., traffic volumes are increasing but will never reach capacity.

Based on the macroscopic experiment, it is recommended that an “optimum” volume threshold for the decision to initiate PTSU be set at about 70-80 percent of breakdown flow rate.

Occupancy could also be used as a decision parameter in addition to or in place of speed and/or volume. Agencies interviewed for this project did not report the use of occupancy-based decision parameters, but it could provide an indication of forthcoming breakdown.

In summary, the three primary decision parameter types—fixed time-of-day, speed-based, and volume-based—are most applicable under the following conditions:

- If breakdowns are frequent and predictable (e.g., every morning between 7 a.m. and 9 a.m., but rare during other times of the day), a **fixed time-of-day decision parameter may be sufficient.** If there are no breakdowns outside of the peak, there are few benefits to be gained from a dynamic system, and consequently there may be limited value in investing further resources in dynamic decision parameter technology.
- **Volume-based decision parameters** are most reliable for realtime prediction of oncoming breakdowns. Volume increases as the onset of breakdown approaches, and this incremental change often enables an analyst to predict the breakdown soon enough to initiate a sweep and open the shoulder prior to reaching breakdown conditions. Volume-based decision parameters are most straightforward to apply on freeways with frequent and reasonably predictable congestion patterns, where the rate of volume increase, the driver population, the heavy vehicle percentage, and other parameters of the traffic stream are similar day to day (e.g., breakdown every morning peak).
- **Speed-based decision parameters are less reliable indicators of oncoming breakdowns.** In general, speed does not substantially decrease until just prior to the onset of breakdown, and there may be insufficient time to conduct a sweep prior to breakdown if a speed-based decision parameter is used. However, volume-based decision parameters should be supplemented by speed-based decision parameters. If a volume-based decision parameter fails to detect the onset of breakdown but speeds begin to decrease, then it may still be appropriate to begin a sweep and open the shoulder. The capacity gained through D-PTSU often relieves the congestion quickly and enables the freeway to “recover” from short-term breakdown. Volume-based decision parameters are most likely to “miss” an oncoming breakdown—and a supplemental speed-based decision parameter is likely to be activated—on freeways where breakdown is a not a routine, predictable occurrence.

To account for both breakdown types, those originating from daily demand patterns and those originating from random fluctuation, it is useful to have both decision parameter types included in a D-PTSU system. Having both a volume-based and a speed-based decision parameter will also provide operators with the most flexibility in adjusting decision parameter thresholds during the ongoing monitoring of a D-PTSU system.

CHAPTER 5. CLOSING THE SHOULDER

This chapter describes reactive and predictive methods for determining when a shoulder should be closed to traffic. It discusses traffic-related and non-traffic-related (i.e., maintenance, weather, incidents, emergency response, and safety) decision parameters.

REALTIME AND PREDICTED TRAFFIC CONDITIONS

To maximize the safety benefits dynamic part-time shoulder use (D-PTSU), it is desirable to close the shoulder to traffic as soon as it is no longer needed to prevent congestion. At the same time, it is NOT desirable to cause congestion on the remaining lanes of the freeway when the shoulder is closed.

The shoulder should be closed based upon predicted traffic operations after closure. In essence, a lane is being removed and the operator needs to ensure that the remaining lanes can carry the added traffic that shifts off of the shoulder.

If opening the shoulder eliminates congestion on the remaining lanes of the freeway, then a threshold based on speed alone will not be useful for determining when the shoulder can be closed without creating congestion on the remaining lanes of the freeway.

A volume threshold works best for determining when a shoulder can be closed without congesting the remaining lanes. As an initial threshold, the agency might set its volume target such that when the shoulder is closed, the resulting volumes per lane in the general-purpose lanes do not exceed the agency's target for opening the shoulder. As long as volumes are consistently decreasing at this time, this will eliminate unnecessary feedback in the decision support framework and avoid starting a process to re-open the shoulder as soon as it is closed.

As with shoulder opening thresholds, any computed shoulder closure threshold should be adjusted as the agency operator gains experience with the operations of their specific facility. Freeway operations should be monitored closely until the operator is comfortable with the shoulder opening and closing thresholds, and then monitored regularly but less frequently for changes in conditions that may warrant further adjustment of the thresholds.

MAINTENANCE, INCIDENTS, AND EMERGENCY RESPONSE

Incidents, weather, and the maintenance and emergency responses needed to address those conditions may all require closure of the shoulder before volumes decrease to a level where closure would normally occur. Agency policies and agreements with emergency responders will more precisely determine how and under what conditions the shoulder will be closed to traffic for reasons other than sufficiently low traffic volumes. In general, shoulders are closed as quickly as possible in these situations; this ability is an advantage of D-PTSU over static part-time shoulder use.

SAFETY CONSIDERATIONS

Part-time shoulder use is founded upon the belief that shoulders are an inherently good and useful feature of a freeway to retain. They provide both a margin of error for vehicles to depart a travel lane without departing the roadway as well as a refuge for disabled vehicles. When shoulders are opened for travel, it is during congested periods, and the temporary loss of the shoulder is presumably offset by the reduction in congestion-related crashes. Before-after studies of PTSU implementation have found varying results with regard to full-day safety. National Cooperative Highway Research Program Project 17-89 Safety Performance of Part-time Shoulder Use on Freeways, is currently underway and scheduled to be completed in 2020. It is anticipated that the results of this research will further inform this discussion.

APPENDIX A. PART-TIME SHOULDER USE QUESTIONS

1. **Planning and Preliminary Engineering**
    a. Is there any regional opposition to part-time shoulder use (PTSU)?
    b. Will physical roadway conditions permit PTSU?
    c. Is the shoulder pavement strong enough to carry traffic?
    d. Will the right or left shoulder be used?
    e. Is the segment long enough to provide meaningful congestion relief?
    f. Will the PTSU be bus-only, static, or dynamic?
    g. Has an operating scheme been selected?
    h. Will vehicle use restrictions (such as a prohibition on large/commercial trucks) be used?
    i. Is realtime monitoring and incident response in place?
    j. Does the corridor have supporting transportation systems management and operations (TSMO) and Traffic Incident Management (TIM) capabilities in place?
    k. Does PTSU significantly reduce cost compared to a traditional capacity expansion?
    l. Has project been incorporated into Transportation Improvement Program (TIP) and long-range plan?
    m. If an area has a congestion management process (CMP), is shoulder use a compatible strategy?

2. **Mobility Analysis**
    a. What is a reasonable estimate of capacity for the shoulder?
    b. What tools will be used for operations analysis?
    c. Will part-time shoulder use improve reliability?

3. **Safety Analysis**
    a. What types of crashes are occurring today?
    b. Are there congestion-related crashes that PTSU could reduce?

4. **Environmental Analysis**
    a. Is there concern about the project within the community?
    b. Should air quality analysis be conducted?
    c. Is the project in a non-attainment or maintenance area?
    d. Is the project in a state that requires greenhouse gas analysis?

e. Will any sensitive noise receptors be impacted?
f. Should noise analysis be conducted?
g. Will there be physical widening that potentially impacts water resources, plants and animals, cultural and historic sites, etc.?
h. Does the project meet the criteria for a categorical exclusion?

5. Costs and Benefits Analysis

a. Are operations and maintenance costs being included in cost estimates?
b. What benefits will occur and how are they being monetized?
c. Does the benefit-cost analysis take into account the ability to deploy PTSU much quicker than adding capacity?

6. Roadway Design

a. Are there good locations to begin and end shoulder use that don't create bottlenecks themselves or safety issues?
b. Has compliance with Controlling Criteria been assessed?
c. How wide will the shoulder be?
d. Are there bridges or other areas where the shoulder will be narrower?
e. Has vertical clearance under bridges been checked?
f. Have drainage patterns been checked? Sometimes the shoulder is used to store water or facilitate drainage with irregular cross slopes.
g. Has stopping sight distance been checked on curves adjacent to barriers?
h. Have fixed object offsets been checked? Guardrails, signs, and other objects may need to be moved further away from the roadway.
i. Have clear zones been checked? New guardrails may need to be installed
j. Are there objects such as bridge piers that cannot be moved, and how will shoulder traffic pass through these areas?
k. Are ramps taper-style or parallel-style and will any need to be modified?
l. Are there any two-lane entrance or exit ramps that exist today?
m. Are there system interchanges?
n. Will PTSU pass through larger interchanges or terminate on a ramp?
o. Are modifications needed at any ramp-freeway junctions?
p. Will safety turnouts be provided and have locations been established?
q. Should a second edge line be added on the outside of the shoulder?

r. Are dynamic signs needed, whether they be supplemental or primary?

s. Is signing and pavement marking compliant with the Manual on Uniform Traffic Control Devices (MUTCD)?

t. What ITS infrastructure should be added to aid facility operators or provide mitigating strategies?

u. Will other TSMO strategies be implemented as a mitigation for design exceptions?

7. Implementation

a. What design exceptions are needed and have they been processed? At a minimum, an exception for shoulder width is necessary.

b. Is an MUTCD Request for Experiment necessary?

c. Are stakeholders such as police and emergency responders engaged?

d. Have state-specific legal issues such as laws prohibiting driving on the shoulder been addressed?

e. Is public outreach plan established?

8. Maintenance and Operations

a. Are communication mechanisms in place between police, emergency responders, and facility operators?

b. Is an incident management plan in place?

c. Do police have a plan for conducting enforcement?

d. Is there a plan for plowing snow from the shoulder?

e. Is there a maintenance plan for aggressive debris removal from the shoulder since it will be used for travel at times?

f. Will there be other unique maintenance needs and have they been addressed?

g. What specific actions will occur each time the shoulder is opened or closed?

h. Have responders established preferred response procedures to incidents when the shoulder is open to traffic?

i. Have a protocols been established to decide to close the shoulder during certain incidents?

APPENDIX B. DYNAMIC PART-TIME SHOULDER USE APPLICATIONS FACT SHEETS

I-70 FREEWAY, IDAHO SPRINGS, COLORADO

NAME OF THE FACILITY

I-70

OPERATING AGENCY

Colorado Department of Transportation (CDOT)

BACKGROUND

CDOT created the I-70 Mountain Express Lane from a wide shoulder that, only during peak recreational travel periods, operates as a third travel lane in the eastbound direction. This dynamic part-time shoulder lane is dynamically priced and located on the left side of I-70 from US 40/Empire (Exit 232) to Idaho Springs (Exit 241).

LENGTH/NUMBER OF LANES

This roadway section is 13 miles long and operates as dynamic part-time shoulder use (D-PTSU) when extra capacity is needed. This roadway section maintains two (2) lanes plus the D-PTSU on the left.

The lane width for the dynamic shoulder lane is 11 feet. A white solid line separates the travel lanes from the dynamic shoulder and a yellow solid stripe separates the shoulder lane from the median. This shoulder helps relieve the traffic congestion during the holidays and ski season from the Eisenhower/Johnson Memorial Tunnels to the top of Floyd Hill.

Figure 34 shows the map of the D-PTSU in Colorado on I-70.

DATE OF IMPLEMENTATION/STATUS

December 2015

CORE TIME PERIODS OF OPERATION

Holidays/Weekends: 9 a.m. – 6 p.m. or 9 a.m. – 8 p.m.

CRITERIA FOR OPENING THE SHOULDER

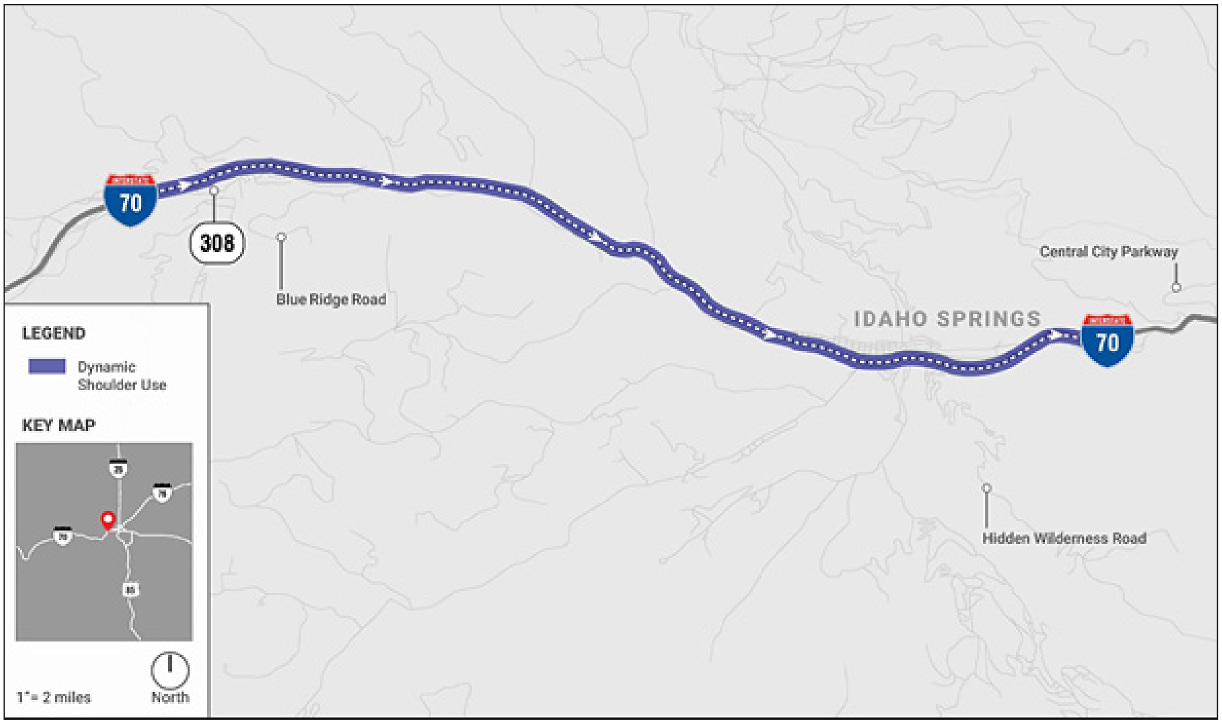
The criteria for opening the shoulder was initially traffic volume and the type of the day. During the Christmas week, ski season (i.e., every weekend from Thanksgiving to April 15th), and during some summer weekends, the dynamic shoulder was opened at 9 a.m. in the morning. CDOT has recently begun to open the shoulder at 9 a.m. on all Saturdays and Sundays for consistency.

The days to open the shoulder are largely based on historical data and trends from the previous years. CDOT initially used algorithms that charge the toll price based on traffic density. However, CDOT decided to use fixed price later. The toll rate is $5 on Saturday, $6 on Sunday and occasionally gets increased to $7 as the shoulder lane reaches capacity.

CDOT coordinates with maintenance pickup truck drivers and the operator at the traffic operations center (TOC) (which uses closed-circuit television cameras) to make sure that the shoulder section is free of obstacles, and any debris before opening the shoulder for traffic. After performing these checks, which take about 20 minutes, the dynamic shoulder lane is opened for traffic.

Figure 35 shows the shoulder being open for traffic.

Figure 36 shows the shoulder being closed for traffic.



Source: Kittelson & Associates

Figure 34. Map. Dynamic part-time shoulder use in Colorado.

Source: CDOT, 2018

Figure 35. Photo. Example of dynamic part-time shoulder use open.

Source: CDOT

Figure 36. Photo. Example of dynamic part-time shoulder use closed.

OTHER ATM TREATMENTS PRESENT

- Variable message signs.
- Lane use signals.
- Variable speed limit signs.
- Variable travel time information sign.
- Ramp meters.
- Supporting intelligent transportation system (ITS) devices.
    - Closed circuit television cameras.
    - Microware vehicle radar detectors.
    - Travel time indicators.
    - Weigh in motion system.

IMPACT ASSESSMENT/RESULTS

CDOT noted that with the introduction of the dynamic shoulder use on I-70, there was a 14 percent increase in the throughput, 38 percent improvement in the travel times in general purpose lanes, and 18 percent increase in the speeds across all lanes of eastbound I-70 during high traffic volumes on the weekends. (CDOT, 2017).

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Colorado Department of Transportation (CDOT) (2018). Eastbound I-70 Peak Period Shoulder Lane, CDOT Website. https://www.codot.gov/projects/I70mtnppsl

Interstate Guide (2016). A Dynamic Message Sign for the I-70 Mountain Express Lane on Interstate 70 Eastbound at Dumont. Photo taken: August 2016. https://www.interstate-guide.com/i-070.html

US-23 FREEWAY, ANN ARBOR, MICHIGAN

NAME OF THE FACILITY

US 23

OPERATING AGENCY

Michigan Department of Transportation (MDOT)

BACKGROUND

The US 23 roadway section in Washtenaw and Livingston counties between M-14 (Exit 41) to M-36 (Exit 54) is the “FlexRoute.” FlexRoute refers to dynamic part-time shoulder use (D-PTSU) on the left side of the roadway in both directions. It is open to traffic in the southbound direction in the a.m. period, and northbound direction in the p.m. period.

LENGTH/NUMBER OF LANES

This roadway section is 8.5 miles long in each direction and operates as a D-PTSU lane when extra capacity is needed. This roadway section maintains existing two (2) lanes, plus the dynamic shoulder on the left.

The lane widths for the dynamic shoulder lane and general travel lanes vary from 11 feet to 12 feet. A single solid yellow stripe is used on both sides of the shoulder lane. The corridor has 70 mi/h speed limit, but the speeds reduce to 60 mi/h when the dynamic shoulder is open to traffic.

Figure 37 shows the map of the FlexRoute dynamic shoulder lane in Michigan on US 23.

DATE OF IMPLEMENTATION/STATUS

November 13, 2017

CORE TIME PERIODS OF OPERATION

Weekdays: 6 a.m. – 9:30 a.m. (Southbound direction), 3 p.m. – 7 p.m. (Northbound direction). Time periods vary during winter season and during special events.

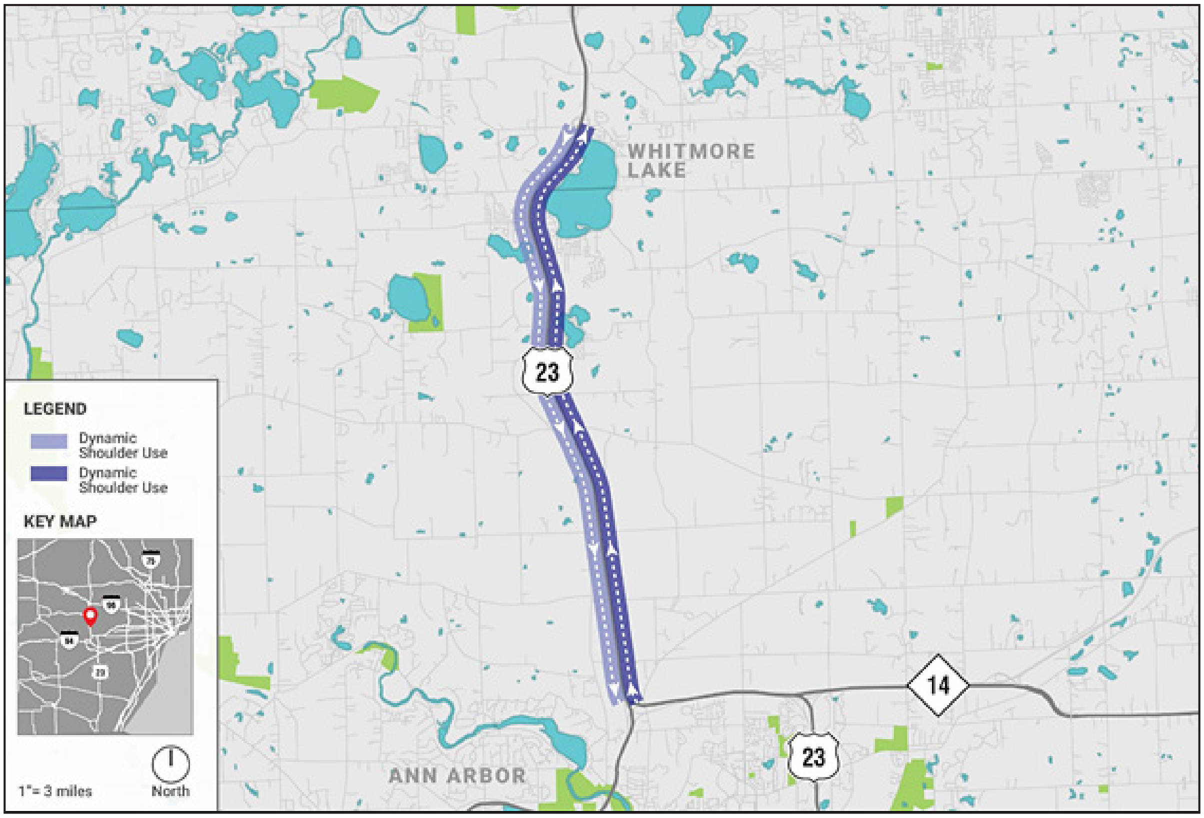
CRITERIA FOR OPENING THE SHOULDER

Parsons/Delcan software is used to make recommendations related to dynamic shoulder open/close operation. The criteria for opening the shoulder is based on traffic volume and vehicles speeds. Roadway section with a traffic volume of greater than or equal to 1400 vehicles per hour per lane (veh/h/ln), and vehicle speeds less than or equal to 60 mi/h are used as threshold values for opening the shoulder.

Historical volume information and algorithms are used for making the decision of opening the shoulder. Since this facility has only been open for several months, operators are still adjusting their procedures and often keeping hours of operation similar to the core (i.e., peak) periods. Once the shoulder is opened, it should stay open for a minimum of 20 minutes before it can be closed for traffic.

MDOT coordinates with the freeway service patrol and operators to make sure that the shoulder section is free of obstacles and any debris before opening it for traffic. It is sometimes difficult for operators to check the roadway surface conditions with cameras because of lack of visibility.

Figure 38 and figure 39 show the shoulder lane in construction and being open for traffic respectively.



Source: Kittelson & Associates

Figure 37. Map. Dynamic part-time shoulder use in Michigan.

Source: MDOT

Figure 38. Photo. Dynamic shoulder lane in construction.

OTHER ATM TREATMENTS PRESENT

- Lane control signs.
- Large/small dynamic message signs.
- Microwave vehicle detection.
- Low-light cameras.

These signs are located every 0.5–1 mile over every lane.

IMPACT ASSESSMENT/RESULTS

MDOT is collecting operational and safety performance measures every month (i.e., travel times, traffic speeds, planning time index, and crashes). However, because the system has only been in operation for a few months, MDOT does not have enough data to carry out any analysis at this time.

Source: MDOT

Figure 39. Photo. Rendering showing dynamic shoulder lane open.

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I-35W FREEWAY, MINNEAPOLIS, MINNESOTA

NAME OF THE FACILITY

I-35W

OPERATING AGENCY

Minnesota Department of Transportation (MnDOT).

BACKGROUND

Due to the geometric constraints of I-35W northbound between 42nd Street and downtown Minneapolis, the left shoulder was converted to be a dynamic shoulder lane. PTSU was removed in 2018 as part of a major widening project.

LENGTH/NUMBER OF LANES

This roadway section was 3 miles long and operated as a dynamic shoulder lane when extra capacity was needed. This roadway section had four (4) general purpose lanes plus the dynamic shoulder use (D-PTSU) on the left.

The D-PTSU effectively extended the use of an upstream, high-occupancy toll (HOT) lane to downtown Minneapolis without adding a full-time lane by making use of the existing space. The lane widths for the D-PTSU and general purpose lanes varied from 11 feet to 12 feet, with a buffer of 2 feet between dynamic shoulder lane and general purpose lanes. This separation was by a single solid yellow stripe. An additional yellow stripe was placed along the median barrier to the left of the shoulder lane to improve visibility.

Figure 40 shows the map of the D-PTSU in Minneapolis on I-35W.

DATE OF IMPLEMENTATION/STATUS

2009 through June 2018.

CORE TIME PERIODS OF OPERATION

Weekdays: 6 a.m. – 10 a.m., 3 p.m. – 7 a.m.
Saturday: 11 a.m. – 7 p.m.
Sunday: 10 a.m. – 6 p.m.

CRITERIA FOR OPENING THE SHOULDER

The criteria for opening the shoulder were traffic volume and speed of vehicles on the roadway. MnDOT generally operated the dynamic shoulder lane during the same time periods. Reasons for this included: driver expectancy, and connection to a HOT lane which had fixed times of operation.

The dynamic shoulder lane was generally opened every weekday at 6 a.m., when the HOT lane becomes operational (i.e., toll collection begins). MnDOT coordinated with freeway service patrol to make sure that the shoulder section was free of obstacles and any debris before opening it for traffic.

The dynamic shoulder lane was opened on weekends based on the level of traffic congestion going towards the downtown area. The frequency of this increased over time and it was eventually open most weekends.

Figure 41 shows the shoulder being open for traffic.

CRITERIA FOR CLOSING THE SHOULDER

The criteria for closing the shoulder were mainly traffic volume, and vehicle speeds, but traffic safety component was usually considered as well. When a situation arose that seemed to compromise traffic safety, the shoulder lane was closed for travel.

The D-PTSU was closed around 7 p.m. usually, but this operation was more variable in nature. The operator discretion was strongly considered while making the decision to close the shoulder for traffic.

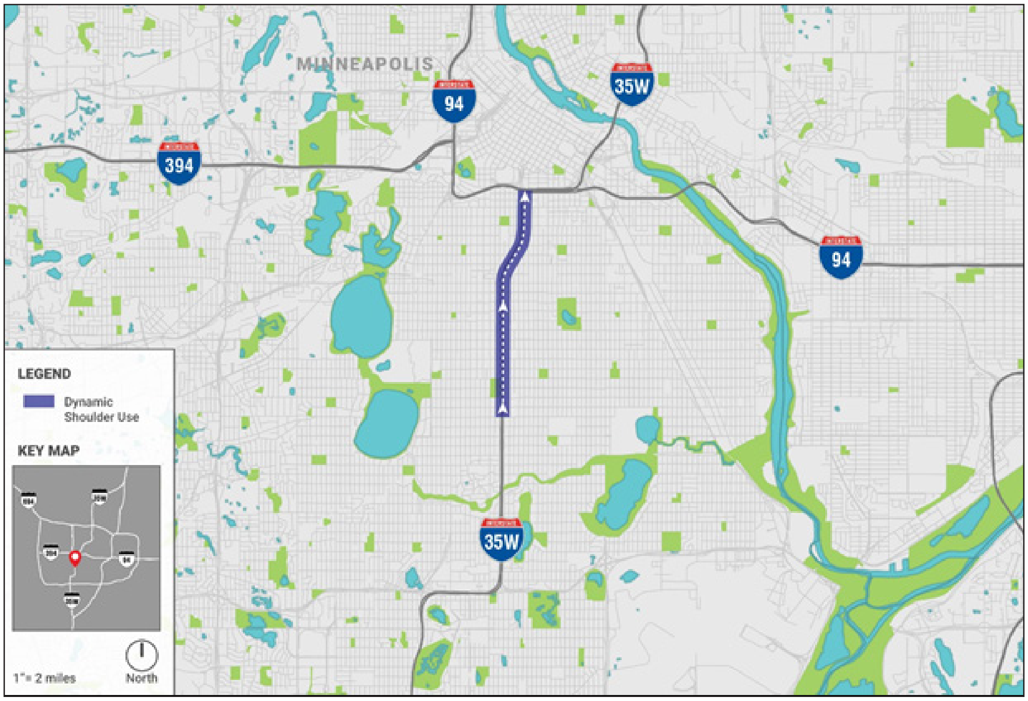
Specifically, during major events in downtown, the operator based on his/her own discretion closed the shoulder based on the closing time of the event.

Figure 42 shows the shoulder being closed for traffic.

OTHER ATM TREATMENTS PRESENT

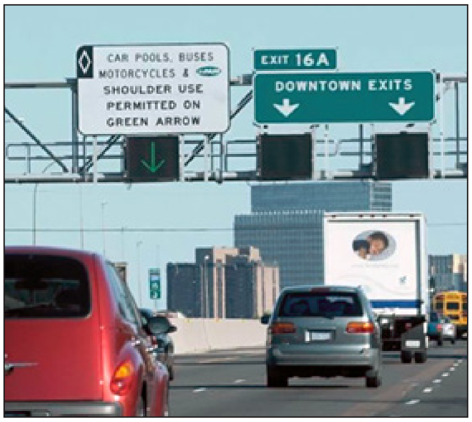
- Intelligent lane control signs.
  - Advisory variable speed limits (when shoulder is open for travel).
  - Static sign is placed at the beginning of the dynamic lane. Lane status: Electronic display signs over traffic lanes.
  - D-PTSU closed– respective merge signs; D-PTSU closed/open-In pavement lighting.
- MnPASS electronic toll collection devices.

These signs were located every 0.5 miles over every lane.



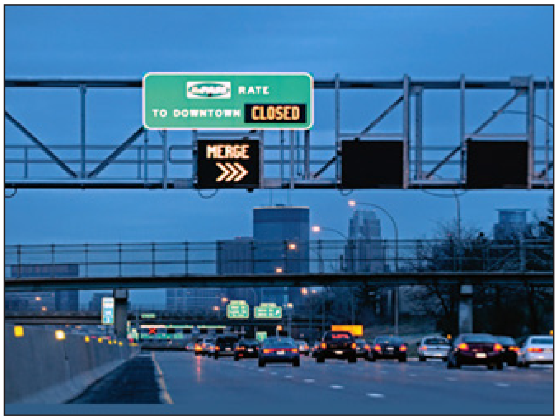
Source: Kittelson & Associates

Figure 40. Map. Dynamic part-time shoulder use in Minneapolis, Minnesota.



Source: FHWA

Figure 41. Photo. Dynamic shoulder lane open.



Source: MnDOT

Figure 42. Photo. Dynamic shoulder lane closed.

IMPACT ASSESSMENT/RESULTS

MnDOT observed that following the implementation of D-PTSU, the rear-end crash frequency increased in certain roadway sections in the D-PTSU region. The University of Minnesota conducted a safety study to assess if the increase in crashes is random, due to congestion, or due to the presence of the D-PTSU system.

It was determined that the observed change in crash frequency was attributed to the change in traffic volume and traffic patterns. This analysis also indicated no direct effect on the likelihood of rear-end crashes due to the operation of dynamic shoulder lane (Davis, 2017).

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I-66 FREEWAY, FAIRFAX COUNTY, VIRGINIA

NAME OF THE FACILITY

I-66

OPERATING AGENCY

Virginia Department of Transportation (VDOT).

BACKGROUND

I-66 was originally time of day based (i.e., static part-time shoulder) and was opened first in 1992. The roadway section was converted to dynamic part-time shoulder use (D-PTSU) in 2015. The roadway section extended from US-50 (Exit 57) to I-495 (Exit 64). PTSU was removed in 2018 as part of a major widening project adding multiple lanes in each direction.

LENGTH/NUMBER OF LANES

This roadway section was 6.5 miles in length and operated with a right-side dynamic shoulder lane when extra capacity was needed. This roadway section maintained three (3) general purpose lanes plus a left high occupancy vehicle lane (HOV-2).

The lane width for the dynamic shoulder lane was 12 feet. The eastbound direction had an average annual daily traffic (AADT) of 88,000 vehicles/day, and westbound direction had an AADT of 86,500 vehicles/day.

Figure 43 shows the map of the D-PTSU in Virginia on I-66.

DATE OF IMPLEMENTATION/STATUS

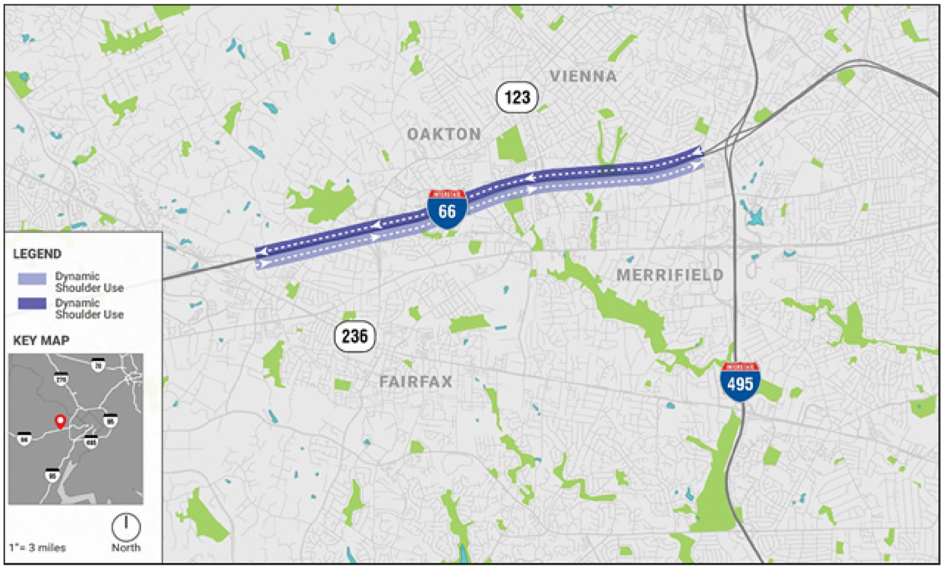
September 15, 2015 through July 20, 2018.

CORE TIME PERIODS OF OPERATION

Weekdays 5:30 a.m. – 11 a.m. eastbound and 2 p.m. – 8 p.m. westbound. Off-peak use and weekend use were common.

CRITERIA FOR OPENING THE SHOULDER

The criteria for opening the shoulder was traffic volume and vehicles speeds on the roadway. Roadway sections with a traffic volume of greater than or equal to 1,400 vehicles per hour per lane (veh/h/ln), and vehicle speeds less than or equal to 55 mi/h were used as threshold values for opening the shoulder. Historical volume information and algorithms were used for making this decision.



Source: Kittelson & Associates

Figure 43. Map. Dynamic part-time shoulder use in Virginia.

Source: VDOT

Figure 44. Photo. Dynamic shoulder lane open.

Source: VDOT

Figure 45. Photo. Dynamic shoulder lane closed.

Once the threshold was reached and shoulder was opened, it stayed open for a minimum of 5 minutes before it could be closed.

VDOT coordinated with freeway service patrol, and operators in the TOC to make sure that the shoulder section was free of obstacles, and any debris before opening the shoulder for traffic. The operators looked at observed queues, and cameras to check the roadway conditions.

Figure 44 shows the shoulder open to traffic.

CRITERIA FOR CLOSING THE SHOULDER

The criteria for closing the shoulder were mainly traffic volume, and vehicle speeds, but traffic safety component was usually considered as well. The shoulder lane was closed for traffic if the traffic volume fell below 1,400 veh/h/ln, and speeds were greater than 55 mi/h. When a situation arose that seemed to compromise traffic safety, and during heavy snow days, or during holidays when HOV facilities were not open, the shoulder lane was closed for travel.

During special events and/or holidays, the operator based on his/her own discretion closed the shoulder for traffic.

Figure 45 shows the shoulder being closed to traffic.

OTHER ATM TREATMENTS PRESENT

- Advisory variable speed limits (when shoulder is open for travel).
- Queue warning systems.
- Lane use control signs.

IMPACT ASSESSMENT/RESULTS

Virginia Department of Transportation (VDOT) stated that the crash frequency on the dynamic shoulder use segment was reduced by 8 percent after its implementation. The rear-end crashes reduced by 13 percent and the injury crashes reduced by 6 percent. However, there is no significant change in the crash frequency along the entire corridor of I-66.

The crash modification factors (CMFs) for the D-PTSU segment all crashes are 0.75, 0.71, and 0.69 for total, multiple-vehicle, and rear-end crashes respectively. Similarly, the CMFs for the DSU segment fatal and injury crashes are 0.69, 0.59, and 0.61 for total fatal and injury, multiple-vehicle, and rear-end crashes respectively (Suliman, 2017).

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REFERENCES

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I-405 FREEWAY, LYNNWOOD, WASHINGTON

NAME OF THE FACILITY

I-405

OPERATING AGENCY

Washington Department of Transportation (WSDOT).

BACKGROUND

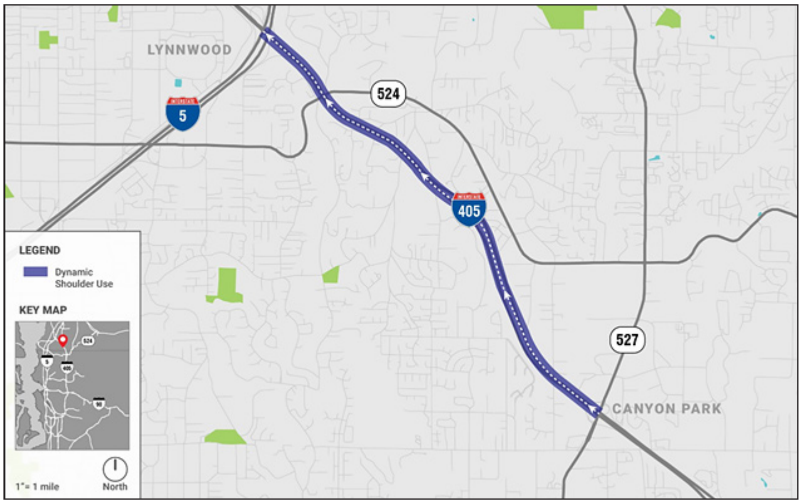
An existing right shoulder on I-405 was converted to dynamic shoulder lane that extends from SR 527 interchange in Bothell to the I-5 interchange in Lynnwood. This is the first implementation of dynamic part-time shoulder use (D-PTSU) in the State of Washington.

LENGTH/NUMBER OF LANES

This roadway section is 1.8 miles long and operates as a dynamic shoulder lane when extra capacity is needed. This roadway section maintains three (3) lanes (two regular and one express toll lane) plus the D-PTSU on the right.

The lane width for the dynamic shoulder lane is 13 feet. There is heavy traffic during the afternoon peak hour in the general purpose lanes that creates congestion south of SR 527 during the peak periods. A white solid line separates the travel lanes from the dynamic shoulder.

Figure 46 shows the map of the D-PTSU in Washington on I-405.



Source: Kittelson & Associates

Figure 46. Map. Dynamic part-time shoulder use in Washington.

Source: WSDOT

Figure 47. Photo. Dynamic shoulder lane open.

Source: WSDOT

Figure 48. Photo. Dynamic shoulder lane closed.

DATE OF IMPLEMENTATION/STATUS

April 24, 2017

CORE TIME PERIODS OF OPERATION

Weekdays (Monday – Wednesday): 2 p.m.–7 p.m.
Weekdays (Thursday – Friday): 11 a.m.–7 p.m.

CRITERIA FOR OPENING THE SHOULDER

The criteria for opening the shoulder is traffic volume. Roadway section with a traffic volume greater than or equal to 1,400–1,500 vehicles per hour per lane is used as threshold value for opening the shoulder. Historical volume information is used for making that decision.

Once the threshold is reached and shoulder is opened, it will stay open until 7 p.m., even if the traffic volume reduces a little before 7 p.m. During special events/occasions, the dynamic shoulder lane is open after 7 p.m. (i.e., when needed).

WSDOT coordinates with two maintenance officers (i.e., electronic maintenance and regular maintenance) to make sure that the shoulder section is free of obstacles, and any debris before opening the shoulder for traffic. Checks for clearance on the shoulder section are done by cameras and incident response team. After performing these checks, the dynamic shoulder lane is opened for traffic. However, WSDOT is planning for the process to become less manual and more automated.

Figure 47 shows the shoulder being open for traffic.

CRITERIA FOR CLOSING THE SHOULDER

WSDOT does not open and close the shoulder for shorter durations. Once a shoulder is opened, operators at the traffic operating center (TOC) wait until 7 p.m. or after 7 p.m. (if needed) to close the shoulder.

The shoulder is not opened with regularity during weekends or and holidays. However, the shoulder is opened during the weekend for special circumstances like crashes.

Figure 48 shows the shoulder being closed temporarily for traffic due to an obstacle on the shoulder.

OTHER ATM TREATMENTS PRESENT

- Electronic lane control signs.
- Side mounted message signs.
- Supplemental messages and queue warning systems.

IMPACT ASSESSMENT/RESULTS

WSDOT is still optimizing the thresholds for opening and closing of dynamic shoulder section. WSDOT is collecting data and will perform opertational and safety studies when they have enough data to carry out the analysis.

In the first five months of dynamic shoulder operation, there were 11 incidents reported on the roadway section, of which four were crashes, 6 were disabled vehicles, and one was an unclassified incident. However, this data is not sufficient to identify trends in road safety performance.

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A 3, A 5 FREEWAYS, HESSEN, GERMANY

NAME OF THE FACILITY

A 3, A 5

OPERATING AGENCY

Hessen.

BACKGROUND

Due to the increase in the traffic congestion on motorways especially during peak hours, some federal states in Germany implemented dynamic part-time shoulder use (D-PTSU). This measure effectively increases the capacity of frequently congested freeway sections during peak hours.

Other federal states in Germany have also implemented D-PTSU, and the information is provided in the “D-PTSU in other Federal States” section below.

LENGTH/NUMBER OF LANES

The currently existing D-PTSU segments in Hessen State of Germany are a total of 57 miles long. These D-PTSU sections operate as a travel lane when extra capacity is needed.

The typical width of dynamic shoulder lanes is 11.5 ft, which is the minimum standard width of lanes that are used by heavy goods vehicle according to the German motorway design guidelines. The speed limit must not exceed 62 mi/h while the D-PTSU is in operation. The dynamic shoulder lanes are separated from the general-purpose lanes by a white solid line.

Source: Geistefeldt, 2012

Figure 49. Photo. Dynamic shoulder lane open.

DATE OF IMPLEMENTATION/STATUS

1996-2017

CORE TIME PERIODS OF OPERATION

Based on the traffic patterns of each facility, typically during morning and/or afternoon peak hours.

CRITERIA FOR OPENING THE SHOULDER

The main criterion for opening the shoulder is traffic volume on the roadway. The decision to open a shoulder is made by the operator at the traffic operation center (TOC), supported by the control system. The control system proposes to open the shoulder based on the defined parameters for traffic volume, sufficiently prior to the expected breakdown. The operator at the TOC relies on the movable cameras covering the entire section of the D-PTSU segment to make sure that the shoulder is free of obstacles and any debris before opening it for traffic.

Figure 49 shows a dynamic shoulder use segment being open for traffic.

CRITERIA FOR CLOSING THE SHOULDER

Similar to the criterion for opening the shoulder, the criterion for closing the shoulder is traffic volume. Once the traffic density is reduced, based on the operator's discretion, the shoulder will be closed for traffic. In case of accidents or broken-down vehicles, the shoulder is immediately closed by the operator.

Dynamic part-time shoulder use segments are not opened during heavy snow and extreme weather or road conditions when D-PTSU cannot be safely used. However, these situations are extremely rare in Germany.

OTHER ATM TREATMENTS PRESENT

- Lane control systems.
- Variable speed limits.
- Variable message signs.
- Movable cameras.
- Back of queue, incident, and weather warnings.

IMPACT ASSESSMENT/RESULTS

A study conducted by the Traffic Centre Hessen reported that there is a 20-25 percent increase in the capacity of a three-lane carriageway, when the roadway segments before and after the implementation of dynamic shoulder use are compared in terms of operations (Geistefeldt, 2012). This permits traffic volumes of over 7,000 vehicles per hour without traffic breakdown.

In Hessen, internal analyses revealed that the dynamic shoulder use on Hessen motorways does not affect road safety. Through the research team questionnaire, Bavaria and North

Rhine-Westphalia stated that there were no reported negative effects of hard shoulder use on road safety.

A safety study on motorway A3 in Hessen, and on A7 in Schleswig-Holstein concluded that the total crash rate on the main roadway section increased slightly, whereas the total crash rate of congestion-related crashes on the upstream segment tended to be lower after the implementation of D-PTSU (Jones, Knopp, Fitzpatrick, & et.al., 2011).

D-PTSU IN OTHER FEDERAL STATES

There are D-PTSU implementations on A 4, A 7, A 8, A 9, A 45, A 57, A 63, A 73, A 99 facilities in other federal states of Germany. These states include: Baden-Wuerttemberg, Bavaria, Lower Saxony, North-Rhine Westphalia, and Rhineland-Palatinate.

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Jones, J. C., Knopp, M. C., Fitzpatrick, K., & et. al. (2011). Freeway Geometric Design for Active Traffic Management in Europe. Washington D.C.: U.S. Department of Transortation, Federal Highway Administration.

FREEWAYS, THE NETHERLANDS

NAME OF THE FACILITY

A1, A2, A4, A7, A8, A9, A10, A12, A13, A15, A20, A27, A28, A50

OPERATING AGENCY

Rijkswaterstaat, Centre for Transport and Navigation.

BACKGROUND

Due to the increase in the traffic congestion on roadways, the Centre for Transport and Navigation in The Netherlands implemented dynamic part-time shoulder use (D-PTSU) to resolve the traffic flow bottlenecks in the short term. There are two types of D-PTSU – right and left. Both act as dynamic shoulder lanes that are used as travel lanes during the peak periods of congestion.

LENGTH/NUMBER OF LANES

The existing dynamic shoulder lanes on the right comprise of 20 D-PTSU sections totaling a length of 100.66 miles of roadway segments. The existing dynamic shoulder lanes on the left comprise of 19 D-PTSU sections totaling a length of about 99.35 miles in total. These roadway sections operate as a dynamic shoulder lane on the right or left, when extra capacity is needed.

The dynamic part-time shoulder lanes on the right are separated from the general-purpose lanes by a white solid line. Similarly, the dynamic shoulder lanes on the left are separated from general-purpose lanes by a white dotted line that is different from the ones that separate the two general-purpose travel lanes.

DATE OF IMPLEMENTATION/STATUS

1999-2015 (D-PTSU segments are still being constructed and/or planned in 2017-18).

CORE TIME PERIODS OF OPERATION

Based on the algorithm and varies from facility to facility.

CRITERIA FOR OPENING THE SHOULDER

The criteria for opening the shoulder is traffic volume on the roadway. Vehicle speeds are not considered while making the decision to open a shoulder. If the traffic volume of a roadway exceeds 1,400–1,500 vehicles per hour per lane, then software triggers a warning for opening the shoulder. There is an option in the software that allows the agency to set a warning 15-20 minutes before the need to open the shoulder is predicted.

Rijkswaterstaat coordinates with the operator at the traffic operations center (TOC), who relies on video cameras covering the entire section of the roadway (i.e., the D-PTSU section) to make sure that the shoulder is free of obstacles and any debris before opening it for traffic.

Figure 50 and figure 51 show the shoulder on the right and left being open for traffic respectively.

CRITERIA FOR CLOSING THE SHOULDER

Similar to the criteria for opening the shoulder, the criteria for closing the shoulder is traffic volume. Once the traffic density is reduced, the software gives a warning to close the shoulder and the shoulder will be closed for traffic.

There are three types of facility operations: a) D-PTSU only used in the morning or evening peak hours, b) D-PTSU used both in the morning and evening peak hours, and c) D-PTSU that open in the morning, remain open all day, and close at night. The shoulder is closed in all these scenarios after the warning from the software, during incidents, or at the operator discretion.

OTHER ATM TREATMENTS PRESENT

- Variable message signs.
- Cameras.
- Automatic incident detection.

Source: © Tineke Dÿkstra Fotografie

Figure 50. Photo. Dynamic shoulder lane open on the right.

Source: © Justin Geistefeldt

Figure 51. Photo. Dynamic shoulder lane open on the left.

IMPACT ASSESSMENT/RESULTS

A safety study was done in 2007, and the area of analysis included 1.24 miles upstream, and 0.62 miles downstream of the segment in addition to the D-PTSU section. After analyzing 14 dynamic shoulder lanes individually, the researchers concluded that the level of road safety on road sections with dynamic shoulder lanes increased (after the D-PTSU segment was open). In other words, the crash frequency reduced, and this may be attributed to the improved traffic flow on the roadway (Rijkswaterstaat, 2007).

This study stated that the implementation of D-PTSU resulted in a reduction in the number of congestion-related (i.e., rear-end) crashes during the peak periods. In addition, the number of fatalities decreased for 12 out of the 14 D-PTSU segments. One fatal crash was directly attributed to the presence of the dynamic shoulder lane.

Of the 14 D-PTSU sections, 8 were D-PTSU on the right, and 6 were D-PTSU on the left. For the dynamic shoulder lanes on the right, the rear-end crash frequency decreased when compared to the before period for 6 sections. However, for the dynamic shoulder lanes on the left, the crash frequency remained approximately the same when compared to the before period.

This finding is consistent with the recent safety study done in 2015, where the driving speed on the right shoulder is on average lower than on regular lanes, and on the left shoulder significantly higher than regular lanes, thereby increasing the crash frequency/risk in the left shoulder. However, the smaller or no merge/diverge conflicts on the left shoulder compared to the right shoulder decreases the risk of crash occurrence on the left shoulder (Drolenga, 2015).

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Drolenga, J. (2015). Differentiatie Verkeersveiligheid Spitsstroken. Grontmij.

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M13 FREEWAY, COPENHAGEN, DENMARK

NAME OF THE FACILITY

M13

OPERATING AGENCY

Vejdirektoratet, Danish Road Directorate

BACKGROUND

Due to the increase in the traffic congestion on motorways, Danish Ministry of Transport implemented the first trial of dynamic part-time shoulder use (D-PTSU) in Denmark. This shoulder lane is part of a roadway section on Hillerod motorway between junction 8 and junction 6.

LENGTH/NUMBER OF LANES

This roadway section is 1.24 miles long and operates as a dynamic shoulder lane on the right, when extra capacity is needed, especially in the morning rush hour. This roadway section has two lanes in each direction of the road with an average annual daily traffic of approximately 66,000 veh/day.

Initially, a dotted line was used to separate the general purpose lane from the shoulder. Recently, this was replaced by a solid line.

DATE OF IMPLEMENTATION/STATUS

December 2013

CORE TIME PERIODS OF OPERATION

Weekdays: 6:15 a.m. – 10 a.m. (+/- 10-15 minutes)

Weekends/holidays: not at all, or only for a couple of hours (if needed).

CRITERIA FOR OPENING THE SHOULDER

The criteria for opening the shoulder is traffic volume and speed of vehicles on the roadway. The decrease in speed from 68 mi/h to 59 mi/h is generally a good indicator for the shoulder to be opened. Danish Road Directorate generally operates the D-PTSU during the same time periods. Traffic congestion starts around 6:15 a.m. every morning during weekdays.

Hence the D-PTSU will be opened 5-10 minutes before that.

Danish Road Directorate coordinates with the operator at the traffic operations center (TOC), who rely on video cameras covering the entire section of the roadway to make sure that the shoulder section is free of obstacles and any debris before opening it for traffic.

The dynamic shoulder lane is not opened on weekends/holidays because of no or minimum traffic congestion. If there is a need, the HSR lane is opened only for a couple of hours.

Figure 52 shows the shoulder being open for traffic.

CRITERIA FOR CLOSING THE SHOULDER

Once the traffic congestion is cleared, the criteria for closing the shoulder are mainly traffic volume, vehicle speeds, but traffic safety component is usually considered as well.

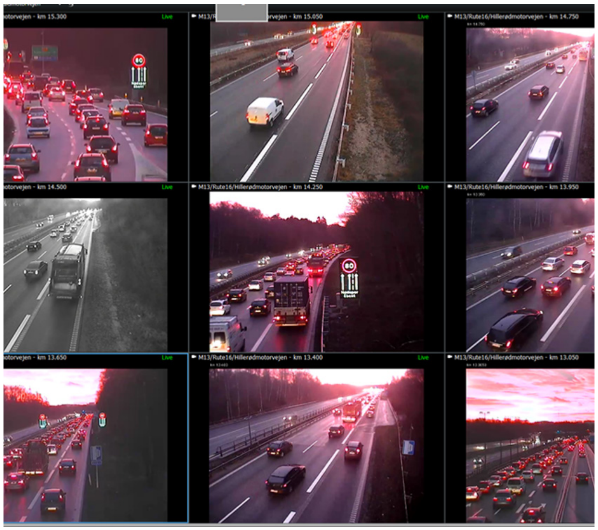
Generally, the dynamic shoulder lane is closed after 10 a.m. when the traffic congestion ends on the roadway section. This operation is more variable in nature. The operator discretion is strongly considered while making the decision to close the shoulder for traffic.

Figure 2 shows the shoulder being monitored in the TOC by the operator.

Note: Algorithms are used as a decision support/guideline. Danish Road Directorate have a list of policies and guidelines where they describe how to handle different situations.

Source: Danish Road Directorate (Vejdirektoratet)

Figure 52. Photo. Dynamic shoulder lane open.



Source: Danish Road Directorate (Vejdirektoratet)

Figure 53. Photo. Dynamic shoulder lane being monitored.

OTHER ATM TREATMENTS PRESENT

- Variable message signs.
- Pan-tilt-zoom (PTZ) cameras, fixed cameras with infrared lighting.
- Automatic incident detection.

IMPACT ASSESSMENT/RESULTS

Before the D-PTSU was implemented, there were often 2.48 to 4.35-mile-long queues and the vehicle speeds were below 31 mi/h for about one and half hour every day.

The average travel time has reduced by 1-3 minutes on a 9.32-mile-long section from Allerod to Motorring 3, and 5 minutes towards junction 6 (7.45-mile section). The traffic volume on the motorway after the DSU was opened has increased by 18 percent, and much of the traffic has shifted from local roads onto the motorway (Danish Road Directorate, 2016).

However, the study findings also noted that the effects of traffic safety have not been analyzed yet, and so far there is no indication either on positive or negative effects.

CONTACT INFORMATION

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REFERENCES

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FREEWAYS, SOUTH KOREA

NAME OF THE FACILITY

- Gyeongbu Expressway (Route 1).
- Seoul Belt/Ring Expressway (Route 100).
- Yeongdong Expressway (Route 50).
- Seohaean Expressway (Route 15, 50, 110).
- Namhae Expressway (Route 10, 102).
- Jungbu Naeryuk Expressway (Route 45).
- Jungang Expressway (Route 55).

A total of 7 highways and 26 sections.

OPERATING AGENCY

South Korea Expressway Corporation

BACKGROUND

Due to the increase in traffic congestion on roadways especially during peak hours, South Korea implemented dynamic part-time shoulder use (D-PTSU).

LENGTH/NUMBER OF LANES

The D-PTSU segments are a total of 118 miles long in South Korea. The number of lanes varies across the facilities.

DATE OF IMPLEMENTATION/STATUS

2007

CORE TIME PERIODS OF OPERATION

Based on the traffic patterns of each facility.

CRITERIA FOR OPENING THE SHOULDER

The criteria for opening the shoulder is the vehicle speed on the roadway. In 2007, the shoulder was opened when the average traffic speed reached less than 43 mi/h and stayed at or below that speed for 15 minutes. However, in 2013, the criteria for average travel speed was changed to 37 mi/h.

The operator at the traffic operation center (TOC) relies on the cameras covering the entire section of the D-PTSU segment to make sure that the shoulder is free of obstacles and any debris before opening it for traffic.

CRITERIA FOR CLOSING THE SHOULDER

Similar to the criteria for opening the shoulder, the criteria for closing the shoulder is vehicle speeds. Once the traffic density is reduced, and the average travel speeds increase, the shoulder will be closed for traffic at the operator's discretion.

In other circumstances, such as a potential safety issue, the shoulder lane is immediately closed by the operator.

OTHER ATM TREATMENTS PRESENT

- Lane control systems.
- Variable message signs.
- Closed-circuit television (CCTV) cameras.
- Vehicle detective system.
- Emergency turnouts.

IMPACT ASSESSMENT/RESULTS

No information available.

APPENDIX C. DECISION PARAMETER DEVELOPMENT METHODS

This appendix provides technical details to supplement chapter 4 and provides additional information on two decision parameter methods discussed in chapter 4.

B1. BREAKDOWN PROBABILITY ESTIMATION WITH METHOD II - EMPERICAL PERFORMANCE DATA

An empirical approach is adapted from the literature, (Brilon, Geistefeldt, & Regler, 2005) which identifies the probability of traffic flow breakdown based on the assumption that capacity is intrinsically stochastic. The method is based on the statistics of censored data. It delivers an estimation of the capacity distribution function $F_c(q)$, representing the probability of a traffic breakdown in dependence on the flow rate q:

$$F_c(q) = P(c \leq q) = 1 - P(c > q)$$

Figure 54. Equation. The capacity distribution function.

where:

$F_c(q)$ is the capacity distribution function, representing the breakdown probability at traffic volume q.

q is the traffic volume in vehicles per hour per lane (veh/h/ln).

c is the capacity (veh/h/ln), i.e., the traffic volume beyond which traffic flow will break down into congested conditions.

$P(c>q)$ is the probability that the capacity is greater than the observed volume.

In the light of the difficulty in selecting an appropriate fixed value for capacity, one could select values based on a “tolerable probability of breakdown.” (Elefteriadou, 2014)

Traffic flow observations deliver pairs of average speeds and volumes in selected time intervals (e.g., 5 minutes). In intervals prior to a traffic breakdown that results in a speed drop below a specified threshold speed in the next time interval, capacity can be measured directly. In intervals not followed by a breakdown, capacity must have been greater than the observed volume. These observations are called “censored” observations. To estimate distribution functions based on samples that include censored data, both non-parametric and parametric methods can be used.

A non-parametric method to estimate the distribution function of lifetime variables is the product limit method (PLM). (Elefteriadou, et al., 2009) The PLM is based on work by Kaplan and Meier, which uses lifetime data analysis techniques for estimating the time until failure of mechanical parts or the duration of human life (Kaplan & Meier, 1958). Brilon et al. (2005) used this method in the context of freeway breakdown to estimate the capacity in a true stochastic sense. The product-limit estimator for the capacity or breakdown probability distribution is given by:

$$F_c(q) = P(c \leq q) = 1 - \prod_{i:q_i \leq q} \frac{k_i - d_i}{k_i}, i \in B$$

Figure 55. Equation. The product-limit estimator for the capacity or breakdown probability distribution. (Elefteriadou, 2014)

where:

q is the traffic volume (veh/h/ln).

q_i is the traffic volume in interval i.

$P(q_i>q)$ is the probability that the observed breakdown volume is greater than the observed volume.

The product-limit estimator for the probability of observed breakdown volume being greater than the observed volume is given by:

$$P(q_i > q) = \prod_{i:q_i \leq q} \frac{k_i - d_i}{k_i}, i \in B$$

Figure 56. Equation. The product-limit estimator for the probability of observed breakdown volume being greater than the observed volume.

where:

q is the observed traffic volume (veh/h/ln).

q_i is the observed traffic volume at interval i, which is the one prior to the drop in speeds; i.e., defined as the observed breakdown flow (veh/h/ln).

k_i is the number of intervals with a traffic volume of $q \geq q_i$.

d_i is the number of breakdowns at a volume of q_i.

B is the set of breakdown intervals $\{B_1, B_2, \ldots.\}$.

However, if each observed volume that causes a breakdown is considered separately; i.e., only one observation of breakdown for every volume q_i ; $d_i = 1$, then the product-limit estimator is given by:

$$F_c(q) = P(c \leq q) = 1 - \prod_{i:q_i \leq q} \frac{k_i - 1}{k_i}, i \in B$$

Figure 57. Equation. Product-limit estimator for observed volume that causes a breakdown but is considered separately.

with all the terms defined as previously.

For a parametric estimation of the breakdown probability distribution, the function type of the distribution must be predetermined. The distribution parameters can be estimated by applying the maximum likelihood technique. For capacity analysis, the likelihood function is:

$$\boldsymbol{L = \prod_{i=1}^{n}\left\{f_c(q_i)^{\delta_i} \cdot [1 - F_c(q_i)]^{\delta_i}\right\}}$$

Figure 58. Equation. The likelihood function for capacity analysis.

where:

$f_c(q_i)$ is the statistical density function of the capacity c.
$F_c(q_i)$ is the cumulative distribution function of the capacity c.

n is the number of intervals.

$\delta_I = 1$, if interval i contains an uncensored value.
$\delta_I = 0$, if interval i contains a censored value.

To simplify the computation, it is useful to maximize the log-likelihood function instead of the likelihood function L.

Calculating the breakdown probability distribution will provide agencies with guidance on observing and measuring (1) maximum pre-breakdown throughput, and (2) breakdown flow at the agencies' desirable probability of breakdown value.

Agencies with new dynamic part-time shoulder use (D-PTSU) facilities, including conversions from static part-time shoulder use (S-PTSU), may want to open the shoulder less frequently and be more tolerant of congestion. Agencies more experienced with D-PTSU may want to be more aggressive opening the shoulder and do so even with a lower probability of congestion if it were not opened.

B2. FREEVAL MODIFICATIONS TO SUPPORT D-PTSU ANALYSIS WITH METHOD III – MACROSCOPIC DECISION PARAMETER OPTIMIZATION

The computational procedure in the Highway Capacity Manual (HCM) freeway facilities methodology is defined in terms of two distinct operational regimes. The first regime handles conditions where all segments are operating under capacity and is referred to as the "undersaturated" method. The second applies when at least one segment is operating over capacity or at level of service (LOS) F and is referred to as the "oversaturated" method.

The undersaturated method provides operational analysis in 15-minute increments. This increment is fixed as required by the set of underlying regressions on which the method is based. Alternatively, the oversaturated method is based on the cell transmission model, an approach which allows time steps of any length. The HCM fixes the oversaturated computational time step length at 15 seconds in accordance with certain assumptions of the methodology. Further, in order not to overwhelm users with extensive outputs, but to provide consistency within the undersaturated approach, the analysis using the oversaturated method is always aggregated up to the same 15-minute resolution as the undersaturated methods.

In the context of this project, there are two primary considerations relating to the use of the HCM method. First, the analysis is focused on operational conditions where demand is likely to exceed capacity and result in a breakdown that the PTSU strategy will attempt to mitigate or even eliminate. Since congested conditions are those of primary interest, it is assumed that the oversaturated method will be used for the entirety of the analysis. While it does not provide the exact same operational results as the individual segment methodologies during undersaturated time periods, the oversaturated approach does adequately approximate the method to the extent that it will not demonstrably affect the results of the experiment.

The second consideration is that the default 15-minute time step provides an analysis resolution that is too coarse to capture the necessary responsiveness of a D-PTSU system. However, as mentioned previously, the oversaturated approach actually updates operational conditions at a 15-second resolution before being aggregated to 15-minute results for consistency. By overriding the HCM's default 15-minute aggregation of results and replacing it with a reduced increment, such as a one-minute resolution, this issue can be circumvented in a straightforward manner without any true modifications to the methodology.

Bypassing the 15-minute aggregation of results does not require changing any underlying methodological assumptions or modifying any specific computational steps. Rather, it is accomplished by changing a single global variable of the methodology as defined in chapter 25 of the HCM: S – the number of computational time steps in an analysis period.

Reducing this from the default value of 60 (corresponding to a 15-minute analysis period) to a value of 4 effectively sets the length of an analysis period of the methodology to one minute. This required modification to the aggregation procedure as well as corresponding updates to the interface, which were made directly within the open-source FREEVAL engine to support the computational details needed for this project and the effective modeling of D-PTSU.

APPENDIX D. GENERALIZED THRESHOLDS FOR OPENING SHOULDER

The tables in this appendix present the number of minutes until capacity is reached on a freeway. When this duration begins to approach the duration of the sweep time, an operator should consider opening a shoulder. More specific information on these tables follows.

These tables were developed in this project to provide simple, off-the-shelf decision parameter values for agencies operating D-PTSU, particularly newer agencies without established practices and experience. They were developed using methods I and III as described in chapter 4. A user begins by identifying the capacity of the bottleneck being relieved with PTSU, and chooses the appropriate table. Identifying the capacity of a bottleneck is discussed in chapter 4. Once the appropriate table is selected, a user chooses the current volume per lane from the left column and the change in volume in the past five minutes from the top portion of the table. Both volume values are presented in terms of vehicles per hour, and the current volume could be measured over a shorter period of time (say the previous 15 or 30 minutes) to be more reflective of current traffic conditions. Once the two volume values are selected, the number in the body of the table indicates the minutes until capacity is reached. In this appendix, times of less than 20 minutes are red and times of 20-30 minutes are green. This example illustrates a facility with 20-minute sweep time. An operator should consider initiating shoulder-opening activities if the table returns a green or red number. A red number indicates the freeway will reach capacity before the shoulder is opened.

The methods described in chapter 4 are ultimately the most reliable for forming decisions of when to open and close the shoulder, but it is recognized that use of these tables is less resource-intensive.

Table 13. Minutes until Capacity is reached when per lane capacity is 2,100 veh/h/ln.

Bottleneck Per Lane Capacity	Minutes until Capacity Is Reached									
	Increase in Hourly Volume Rate In Past 5 Minutes									
2,100	10	20	30	40	50	60	70	80	90	100
Current Volume (veh/h/ln)										
0	210	105	70	53	42	35	*30	*27	*24	*21
100	200	100	67	50	40	34	*29	*25	*23	*20
200	190	95	64	48	38	32	*28	*24	*22	*†19
300	180	90	60	45	36	30	*26	*23	*20	*†18
400	170	85	57	43	34	*29	*25	*22	*†19	*†17
500	160	80	54	40	32	*27	*23	*20	*†18	*†16
600	150	75	50	38	*30	*25	*22	*†19	*†17	*†15
700	140	70	47	35	*28	*24	*20	*†18	*†16	*†14
800	130	65	44	33	*26	*22	*†19	*†17	*†15	*†13
900	120	60	40	*30	*24	*20	*†18	*†15	*†14	*†12
1,000	110	55	37	*28	*22	*†19	*†16	*†14	*†13	*†11
1,100	100	50	34	*25	*20	*†17	*†15	*†13	*†12	*†10
1,200	90	45	*30	*23	*†18	*†15	*†13	*†12	*†10	*†9
1,300	80	40	*27	*20	*†16	*†14	*†12	*†10	*†9	*†8
1,400	70	35	*24	*†18	*†14	*†12	*†10	*†9	*†8	*†7
1,500	60	*30	*20	*†15	*†12	*†10	*†9	*†8	*†7	*†6
1,600	50	*25	*†17	*†13	*†10	*†9	*†8	*†7	*†6	*†5
1,700	40	*20	*†14	*†10	*†8	*†7	*†6	*†5	*†5	*†4
1,800	*30	*†15	*†10	*†8	*†6	*†5	*†5	*†4	*†4	*†3
1,900	*20	*†10	*†7	*†5	*†4	*†4	*†3	*†3	*†3	*†2
2,000	*†10	*†5	*†4	*†3	*†2	*†2	*†2	*†2	*†2	*†1
2,100	*†0	*†0	*†0	*†0	*†0	*†0	*†0	*†0	*†0	*†0
2,200	--	--	--	--	--	--	--	--	--	--

veh/h/ln = vehicles per hour per lane.
-- = not applicable.
* Operator should consider initiating shoulder-opening activities.
† The freeway will reach capacity before the shoulder is opened.

Table 14. Minutes until Capacity is reached when per lane capacity is 2,000 veh/h/ln.

Bottleneck Per Lane Capacity	Minutes until Capacity Is Reached									
	Increase in Hourly Volume Rate In Past 5 Minutes									
2,000	10	20	30	40	50	60	70	80	90	100
Current Volume (veh/h/ln)										
0	200	100	67	50	40	34	*29	*25	*23	*20
100	190	95	64	48	38	32	*28	*24	*22	*†19
200	180	90	60	45	36	30	*26	*23	*20	*†18
300	170	85	57	43	34	*29	*25	*22	*†19	*†17
400	160	80	54	40	32	*27	*23	*20	*†18	*†16
500	150	75	50	38	*30	*25	*22	*†19	*†17	*†15
600	140	70	47	35	*28	*24	*20	*†18	*†16	*†14
700	130	65	44	33	*26	*22	*†19	*†17	*†15	*†13
800	120	60	40	*30	*24	*20	*†18	*†15	*†14	*†12
900	110	55	37	*28	*22	*†19	*†16	*†14	*†13	*†11
1,000	100	50	34	*25	*20	*†17	*†15	*†13	*†12	*†10
1,100	90	45	*30	*23	*†18	*†15	*†13	*†12	*†10	*†9
1,200	80	40	*27	*20	*†16	*†14	*†12	*†10	*†9	*†8
1,300	70	35	*24	*†18	*†14	*†12	*†10	*†9	*†8	*†7
1,400	60	*30	*20	*†15	*†12	*†10	*†9	*†8	*†7	*†6
1,500	50	*25	*†17	*†13	*†10	*†9	*†8	*†7	*†6	*†5
1,600	40	*20	*†14	*†10	*†8	*†7	*†6	*†5	*†5	*†4
1,700	30	*†15	*†10	*†8	*†6	*†5	*†5	*†4	*†4	*†3
1,800	*	*†10	*†7	*†5	*†4	*†4	*†3	*†3	*†3	*†2
1,900	*†10	*†5	*†4	*†3	*†2	*†2	*†2	*†2	*†2	*†1
2,000	*†0	*†0	*†0	*†0	*†0	*†0	*†0	*†0	*†0	*†0
2,100	--	--	--	--	--	--	--	--	--	--
2,200	--	--	--	--	--	--	--	--	--	--

veh/h/ln = vehicles per hour per lane.
-- = not applicable.
* Operator should consider initiating shoulder-opening activities.
† The freeway will reach capacity before the shoulder is opened.

Table 15. Minutes until Capacity is reached when per lane capacity is 1,900 veh/h/ln.

Bottleneck Per Lane Capacity	Minutes until Capacity Is Reached									
	Increase in Hourly Volume Rate In Past 5 Minutes									
1,900	10	20	30	40	50	60	70	80	90	100
Current Volume (veh/h/ln)										
0	190	95	64	48	38	32	*28	*24	*22	*†19
100	180	90	60	45	36	30	*26	*23	*20	*†18
200	170	85	57	43	34	*29	*25	*22	*†19	*†17
300	160	80	54	40	32	*27	*23	*20	*†18	*†16
400	150	75	50	38	*30	*25	*22	*†19	*†17	*†15
500	140	70	47	35	*28	*24	*20	*†18	*†16	*†14
600	130	65	44	33	*26	*22	*†19	*†17	*†15	*†13
700	120	60	40	*30	*24	*20	*†18	*†15	*†14	*†12
800	110	55	37	*28	*22	*†19	*†16	*†14	*†13	*†11
900	100	50	34	*25	*20	*†17	*†15	*†13	*†12	*†10
1,000	90	45	*30	*23	*†18	*†15	*†13	*†12	*†10	*†9
1,100	80	40	*27	*20	*†16	*†14	*†12	*†10	*†9	*†8
1,200	70	35	*24	*†18	*†14	*†12	*†10	*†9	*†8	*†7
1,300	60	*30	*20	*†15	*†12	*†10	*†9	*†8	*†7	*†6
1,400	50	*25	*†17	*†13	*†10	*†9	*†8	*†7	*†6	*†5
1,500	40	*20	*†14	*†10	*†8	*†7	*†6	*†5	*†5	*†4
1,600	30	*†15	*†10	*†8	*†6	*†5	*†5	*†4	*†4	*†3
1,700	*	*†10	*†7	*†5	*†4	*†4	*†3	*†3	*†3	*†2
1,800	*†10	*†5	*†4	*†3	*†2	*†2	*†2	*†2	*†2	*†1
1,900	*†0	*†0	*†0	*†0	*†0	*†0	*†0	*†0	*†0	*†0
2,000	--	--	--	--	--	--	--	--	--	--
2,100	--	--	--	--	--	--	--	--	--	--
2,200	--	--	--	--	--	--	--	--	--	--

veh/h/ln = vehicles per hour per lane.
-- = not applicable.
* Operator should consider initiating shoulder-opening activities.
† The freeway will reach capacity before the shoulder is opened.

Table 16. Minutes until Capacity is reached when per lane capacity is 1,800 veh/h/ln.

Bottleneck Per Lane Capacity	Minutes until Capacity Is Reached									
	Increase in Hourly Volume Rate In Past 5 Minutes									
1,800	10	20	30	40	50	60	70	80	90	100
Current Volume (veh/h/ln)										
0	180	90	60	45	36	30	*26	*23	*20	*†18
100	170	85	57	43	34	*29	*25	*22	*†19	*†17
200	160	80	54	40	32	*27	*23	*20	*†18	*†16
300	150	75	50	38	*30	*25	*22	*†19	*†17	*†15
400	140	70	47	35	*28	*24	*20	*†18	*†16	*†14
500	130	65	44	33	*26	*22	*†19	*†17	*†15	*†13
600	120	60	40	*30	*24	*20	*†18	*†15	*†14	*†12
700	110	55	37	*28	*22	*†19	*†16	*†14	*†13	*†11
800	100	50	34	*25	*20	*†17	*†15	*†13	*†12	*†10
900	90	45	*30	*23	*†18	*†15	*†13	*†12	*†10	*†9
1,000	80	40	*27	*20	*†16	*†14	*†12	*†10	*†9	*†8
1,100	70	35	*24	*†18	*†14	*†12	*†10	*†9	*†8	*†7
1,200	60	*30	*20	*†15	*†12	*†10	*†9	*†8	*†7	*†6
1,300	50	*25	*†17	*†13	*†10	*†9	*†8	*†7	*†6	*†5
1,400	40	*20	*†14	*†10	*†8	*†7	*†6	*†5	*†5	*†4
1,500	30	*†15	*†10	*†8	*†6	*†5	*†5	*†4	*†4	*†3
1,600	*	*†10	*†7	*†5	*†4	*†4	*†3	*†3	*†3	*†2
1,700	*†10	*†5	*†4	*†3	*†2	*†2	*†2	*†2	*†2	*†1
1,800	*†0	*†0	*†0	*†0	*†0	*†0	*†0	*†0	*†0	*†0
1,900	--	--	--	--	--	--	--	--	--	--
2,000	--	--	--	--	--	--	--	--	--	--
2,100	--	--	--	--	--	--	--	--	--	--
2,200	--	--	--	--	--	--	--	--	--	--

veh/h/ln = vehicles per hour per lane.
-- = not applicable.
* Operator should consider initiating shoulder-opening activities.
† The freeway will reach capacity before the shoulder is opened.

Table 17. Minutes until Capacity is reached when per lane capacity is 1,700 veh/h/ln.

Bottleneck Per Lane Capacity	Minutes until Capacity Is Reached									
	Increase in Hourly Volume Rate In Past 5 Minutes									
1,700	10	20	30	40	50	60	70	80	90	100
Current Volume (veh/h/ln)										
0	170	85	57	43	34	*29	*25	*22	*†19	*†17
100	160	80	54	40	32	*27	*23	*20	*†18	*†16
200	150	75	50	38	*30	*25	*22	*†19	*†17	*†15
300	140	70	47	35	*28	*24	*20	*†18	*†16	*†14
400	130	65	44	33	*26	*22	*†19	*†17	*†15	*†13
500	120	60	40	*30	*24	*20	*†18	*†15	*†14	*†12
600	110	55	37	*28	*22	*†19	*†16	*†14	*†13	*†11
700	100	50	34	*25	*20	*†17	*†15	*†13	*†12	*†10
800	90	45	*30	*23	*†18	*†15	*†13	*†12	*†10	*†9
900	80	40	*27	*20	*†16	*†14	*†12	*†10	*†9	*†8
1,000	70	35	*24	*†18	*†14	*†12	*†10	*†9	*†8	*†7
1,100	60	*30	*20	*†15	*†12	*†10	*†9	*†8	*†7	*†6
1,200	50	*25	*†17	*†13	*†10	*†9	*†8	*†7	*†6	*†5
1,300	40	*20	*†14	*†10	*†8	*†7	*†6	*†5	*†5	*†4
1,400	30	*†15	*†10	*†8	*†6	*†5	*†5	*†4	*†4	*†3
1,500	*	*†10	*†7	*†5	*†4	*†4	*†3	*†3	*†3	*†2
1,600	*†10	*†5	*†4	*†3	*†2	*†2	*†2	*†2	*†2	*†1
1,700	*†0	*†0	*†0	*†0	*†0	*†0	*†0	*†0	*†0	*†0
1,800	--	--	--	--	--	--	--	--	--	--
1,900	--	--	--	--	--	--	--	--	--	--
2,000	--	--	--	--	--	--	--	--	--	--
2,100	--	--	--	--	--	--	--	--	--	--
2,200	--	--	--	--	--	--	--	--	--	--

veh/h/ln = vehicles per hour per lane.
-- = not applicable.
* Operator should consider initiating shoulder-opening activities.
† The freeway will reach capacity before the shoulder is opened.

Table 18. Minutes until Capacity is reached when per lane capacity is 1,600 veh/h/ln.

Bottleneck Per Lane Capacity	Minutes until Capacity Is Reached									
	Increase in Hourly Volume Rate In Past 5 Minutes									
1,600	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
Current Volume (veh/h/ln)										
0	160	80	54	40	32	*27	*23	*20	*†18	*†16
100	150	75	50	38	*30	*25	*22	*†19	*†17	*†15
200	140	70	47	35	*28	*24	*20	*†18	*†16	*†14
300	130	65	44	33	*26	*22	*†19	*†17	*†15	*†13
400	120	60	40	*30	*24	*20	*†18	*†15	*†14	*†12
500	110	55	37	*28	*22	*†19	*†16	*†14	*†13	*†11
600	100	50	34	*25	*20	*†17	*†15	*†13	*†12	*†10
700	90	45	*30	*23	*†18	*†15	*†13	*†12	*†10	*†9
800	80	40	*27	*20	*†16	*†14	*†12	*†10	*†9	*†8
900	70	35	*24	*†18	*†14	*†12	*†10	*†9	*†8	*†7
1,000	60	*30	*20	*†15	*†12	*†10	*†9	*†8	*†7	*†6
1,100	50	*25	*†17	*†13	*†10	*†9	*†8	*†7	*†6	*†5
1,200	40	*20	*†14	*†10	*†8	*†7	*†6	*†5	*†5	*†4
1,300	30	*†15	*†10	*†8	*†6	*†5	*†5	*†4	*†4	*†3
1,400	*	*†10	*†7	*†5	*†4	*†4	*†3	*†3	*†3	*†2
1,500	*†10	*†5	*†4	*†3	*†2	*†2	*†2	*†2	*†2	*†1
1,600	*†0	*†0	*†0	*†0	*†0	*†0	*†0	*†0	*†0	*†0
1,700	--	--	--	--	--	--	--	--	--	--
1,800	--	--	--	--	--	--	--	--	--	--
1,900	--	--	--	--	--	--	--	--	--	--
2,000	--	--	--	--	--	--	--	--	--	--
2,100	--	--	--	--	--	--	--	--	--	--
2,200	--	--	--	--	--	--	--	--	--	--

veh/h/ln = vehicles per hour per lane.
-- = not applicable.
* Operator should consider initiating shoulder-opening activities.
† The freeway will reach capacity before the shoulder is opened.

Table 19. Minutes until Capacity is reached when per lane capacity is 1,500 veh/h/ln.

Bottleneck Per Lane Capacity	Minutes until Capacity Is Reached									
	Increase in Hourly Volume Rate In Past 5 Minutes									
1,500	10	20	30	40	50	60	70	80	90	100
Current Volume (veh/h/ln)										
0	150	75	50	38	*30	*25	*22	*†19	*†17	*†15
100	140	70	47	35	*28	*24	*20	*†18	*†16	*†14
200	130	65	44	33	*26	*22	*†19	*†17	*†15	*†13
300	120	60	40	*30	*24	*20	*†18	*†15	*†14	*†12
400	110	55	37	*28	*22	*†19	*†16	*†14	*†13	*†11
500	100	50	34	*25	*20	*†17	*†15	*†13	*†12	*†10
600	90	45	*30	*23	*†18	*†15	*†13	*†12	*†10	*†9
700	80	40	*27	*20	*†16	*†14	*†12	*†10	*†9	*†8
800	70	35	*24	*†18	*†14	*†12	*†10	*†9	*†8	*†7
900	60	*30	*20	*†15	*†12	*†10	*†9	*†8	*†7	*†6
1,000	50	*25	*†17	*†13	*†10	*†9	*†8	*†7	*†6	*†5
1,100	40	*20	*†14	*†10	*†8	*†7	*†6	*†5	*†5	*†4
1,200	30	*†15	*†10	*†8	*†6	*†5	*†5	*†4	*†4	*†3
1,300	*	*†10	*†7	*†5	*†4	*†4	*†3	*†3	*†3	*†2
1,400	*†10	*†5	*†4	*†3	*†2	*†2	*†2	*†2	*†2	*†1
1,500	*†0	*†0	*†0	*†0	*†0	*†0	*†0	*†0	*†0	*†0
1,600	--	--	--	--	--	--	--	--	--	--
1,700	--	--	--	--	--	--	--	--	--	--
1,800	--	--	--	--	--	--	--	--	--	--
1,900	--	--	--	--	--	--	--	--	--	--
2,000	--	--	--	--	--	--	--	--	--	--
2,100	--	--	--	--	--	--	--	--	--	--
2,200	--	--	--	--	--	--	--	--	--	--

veh/h/ln = vehicles per hour per lane.
-- = not applicable.
* Operator should consider initiating shoulder-opening activities.
† The freeway will reach capacity before the shoulder is opened.

APPENDIX E. ADDITIONAL RESOURCES

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ACKNOWLEDGMENTS

Figure 21: The original chart was developed by Richard Dowling, Alexander Skabardonis, and David Reinke and is the copyright property of the *Transportation Research Record*. The overlay showing the tan congested speed band was added for this research project.

Figure 24: The original chart was developed by Richard Dowling, Alexander Skabardonis, and David Reinke and is the copyright property of the *Transportation Research Record*. The overlay showing the green and tan quadrants, including blue lines, percentages, arrows, and text within the chart area, were added for this research project.

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November 2019

FHWA-HOP-19-029