PERFORMANCE-BASED
PRACTICAL DESIGN FOR OPERATIONS

USE OF NARROW LANES AND NARROW SHOULDERS ON FREEWAYS:

A Primer on Experiences, Current Practice, and Implementation Considerations

U.S. Department of Transportation
Federal Highway Administration

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16. Abstract

Congested freeways are often located in urban areas with constrained environments and/or rights-of-way where significant widening of the roadway is not practical due to adjacent developments and land use, physical constraints, along with limited availability of funding. Among the strategies for increasing freeway capacity in such constrained environments – and thereby reducing congestion and improving operations – is to add a travel lane within the existing roadway footprint by reducing the widths of the existing lanes and/or shoulders. The additional lane may be utilized by all traffic at all times, as a special use or managed lane that is open only to specific types of vehicles or movements (e.g., High Occupancy Toll (HOT) lane, exit only lane), or only during selected times of the day and/or when congestion warrants opening the lane (e.g., temporary shoulder use). Narrow lanes and shoulders may be applied to add capacity on the freeway mainline and in interchange areas including ramps.

This primer provides information to policy makers, transportation agency managers, designers and operators on the use of narrow lanes and narrow shoulders to improve capacity within an existing roadway footprint. Much of the information contained in the primer is presented in the broader context of both Performance Based Planning and Programming (PBPP) and Performance – Based Practical Design (PBPD). Primer contents include case studies on the use of narrow lanes, issues and approaches for analyzing the operational and safety impacts of narrow lanes and narrow shoulders, and the role of transportation systems management and operations (TSMO) in support of narrow lanes operations.

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Foreword

The Federal Highway Administration (FHWA) Office of Operations is pleased to present this publication titled "Use of Narrow Lanes and Narrow Shoulders on Freeways: A Primer on Experiences, Current Practice, and Implementation Considerations" (Narrow Lanes Primer).

Freeways in major urban areas are increasingly burdened by growing traffic volumes, and widening projects are increasingly challenging due to physical and fiscal constraints. Performance-Based Practical Design (PBPD) solutions – linked with Operations strategies – offer a means of reducing freeway congestion in a manner that is achievable in today's resource constrained environment. PBPD modifies the traditional "top down, standards first" approach to a "design up" approach where engineering judgement is used to build up a roadway from existing conditions to a state where project and system objectives can be cost-effectively achieved.

In urban settings where those physical or fiscal constraints prevent adding full-width lanes with full shoulders, applying PBPD approaches to provide additional capacity by adding lanes that are slightly narrower than standard or reducing shoulders below standard width are sometimes viable options. The slight reduction in efficiency from narrower individual lanes or shoulders can be more than offset by the capacity gain of an additional lane. Operations strategies - including enhanced incident management and Active Traffic Management (ATM) strategies such as dynamic speed limits, dynamic lane assignment, and traveler information - can be coupled with the narrow lane and shoulder treatments to further improve operational and safety performance.

Early applications of narrow lanes and narrow shoulders in the 1970s and 1980s typically added general purpose lanes. More recent applications of narrow lane and narrow shoulder use have enabled the implementation of managed lanes or part-time shoulder use within the existing footprint of a freeway. Some applications have also narrowed lanes or shoulders for short distances to eliminate bottlenecks.

The primer includes case studies of narrow lanes and narrow shoulders and provides insights on the operational, safety, and travel time reliability effects of implementing narrow lanes and narrow shoulders. This is one of two primers developed to highlight the linkage between PBPD and Transportation Systems Management and Operations (TSMO). The other primer focuses on Complete Streets. The FHWA Office of Operations is supporting these Primers through related technical assistance. If you have any comments on this material or seek further assistance, please contact Jim Hunt jim.hunt@dot.gov or Greg Jones GregM.Jones@dot.gov from the FHWA Office of Operations.

Robert Arnold
Director Office of Transportation Management
Office of Operations, FHWA

Conversion Factors

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

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

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

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List of Acronyms and Symbols

AADT	Average Annual Daily Traffic
CMF	Crash Modification Factors
CMP	Congestion Management Process (Federal guidelines) or Congestion Management Program (locally or regionally adopted)
DOT	Department of Transportation
FFS	Free Flow Speed
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
MPO	Metropolitan Planning Organization
MTP	Metropolitan Transportation Plan
NHS	National Highway System
NPMRDS	National Performance Management Research Data Set
PCE	Performance Car Equivalent
PDO	Property Damage Only Crashes
PeMS	(California's) Performance Measurement System
PBPD	Performance-Based Practical Design
PBPP	Performance-Based Planning and Programming
PTI	Planning Time Index
SHRP 2	The Second Strategic Highway Research Program
SOV	Single Occupant Vehicle
SPF	Safety Performance Functions
TIP	Transportation Improvement Program
TMA	Transportation Management Area
TMC	Transportation Management Center
TSMO	Transportation System Management and Operations
TTI	Travel Time Index
V/C	Volume to Capacity Ratio
VHD	Vehicle Hours of Delay
VHT	Vehicle Hours Traveled
VMT	Vehicle Miles Traveled

Source: Kittelson & Associates, Inc.

Chapter 1 Overview

This primer is designed for policy makers, transportation agency managers, designers and operators working to find solutions to today's transportation and mobility challenges. The purpose is to provide information on the use of narrow lanes and narrow shoulders to improve capacity within an existing roadway footprint, and to give the reader a starting point for exploring narrow lanes and shoulders as a potential solution.

Much of the information in this primer is presented in the broader context of **Performance – Based Practical Design (PBPD)**. Per the Federal Highway Administration (FHWA) website (Reference 12):

PBPD is a decision making approach that helps agencies better manage transportation investments and serve system-level needs and performance priorities with limited resources. PBPD uses appropriate performance-analysis tools, considers both short and long term project and system goals while addressing project purpose and need.

The PBPD approach encourages designers and decision makers to exercise engineering judgment in identifying and analyzing alternatives - including narrow lanes - to deliver cost-effective operational improvements that meet both project and system objectives.

Topics covered in the primer include the following:

- Examples of narrow lane / narrow shoulder applications – **Chapter 1**
- Examining potential narrow lane / narrow shoulder solutions in the context of PBPD; and the role of Transportation Systems Management and Operations (TSMO) in supporting narrow lane applications – **Chapter 2**
- Case studies of the use of narrow lanes – **Chapter 3**
- Issues and approaches for analyzing the operational and safety impacts of narrow lanes and narrow shoulders – **Chapter 4**

Congested freeways are often located in urban areas with constrained environments and/or rights-of-way where significant widening of the roadway is not practical due to the adjacent development and land use, physical constraints, along with limited available funding. Among the strategies for increasing freeway capacity in such constrained environments – and thereby reducing congestion and improving operations – is to add a travel lane within the existing roadway footprint by reducing the widths of the existing lanes and/or shoulder. The additional lane may be utilized by all traffic at all times, as a special use or managed lane that is open only to specific types of vehicles or movements (e.g., High Occupancy Toll (HOT) lane, exit only lane), or only during selected times of the day and/or when congestion warrants opening the lane (e.g., temporary shoulder use).

This concept of adding a travel lane within the existing roadway footprint (by narrowing existing lanes and/or shoulders) to increase capacity at a relative low cost is not a new concept. As noted in a 1978 research document (1):

> *"When the congestion becomes so extensive and repetitive, measures to increase capacity or reduce demand should be undertaken. However, sufficient funds to make major changes to urban freeways may not be available, and in some instances, space may be so limited as to rule out normal expansions in roadway width. One approach that many transportation agencies are considering is the downscoping of design standards to achieve greater capacity at lower cost. The usual method to accomplish this is to reduce lane widths and to reduce or eliminate the roadway shoulders and create an additional lane for travel."*

Potential scenarios for implementing narrow lanes[1] include the following (with example lane configurations and widths resulting from the implementation of narrow lanes shown in **Figure 1)**:

- Adding a general purpose lane to increase capacity and reduce recurring congestion. This can be for an extended section of roadway, or for a relatively short area as part of bottleneck reduction or to maintain lane continuity[2]. Examples of this approach are listed in **Table 1**.

- Adding a managed lane, such a High Occupancy Vehicle (HOV) or HOT lane. Examples of this approach are listed in **Table 2**.

Source: Kittelson & Associates, Inc.

- Adding a lane in and/or within the vicinity of an interchange, to provide additional capacity on a ramp, an auxiliary lane between closely-spaced interchanges, or additional capacity beyond the interchange to prevent traffic from backing up into the interchange area. Examples of this approach are listed in **Table 3**.

A related application that can involve narrow lanes and narrow shoulders is to open either the left or right shoulder – as is, or perhaps widened (with a corresponding narrowing of general purpose lanes) – to traffic during selected times of the day or when congestion warrants. The shoulder may be open to all vehicles, only light-duty vehicles, or buses only. By definition, during times of shoulder use, there is no shoulder available for vehicle refuge. Additional information on part time shoulder use, including several locations where this strategy has been implemented, is provided in Reference 6 ("Use of Freeway Shoulders for Travel - Guide for Planning, Evaluating, and Designing Part-Time Shoulder Use as a Traffic Management Strategy; Publication No. FHWA-HOP-15-023).

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[1] The additional lane and associated capacity may operate at all times or part time (e.g., peak periods).

[2] Per the 3rd Edition of the AASHTO Highway Safety Design and Operations Guide, lane continuity allows a driver to remain in the through movement without changing lanes. Lack of lane continuity is usually the result of a change in the number of lanes, such as dropping a left lane at an exit without the use of an auxiliary lane.

Table 1. Examples: Narrowing Lanes to Add a General Purpose Lane.

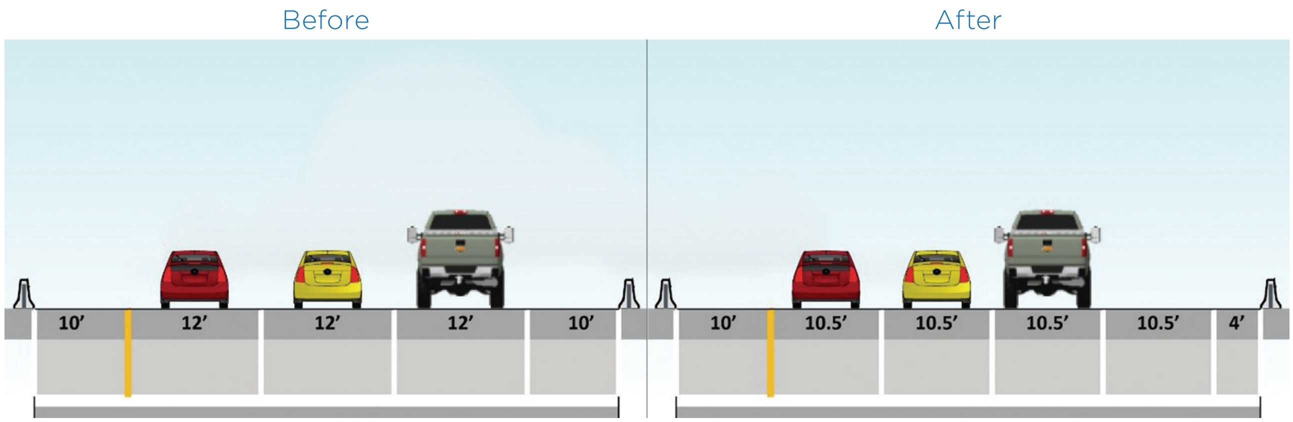
Location	Route(s) and Length	Date	Cross-Sections	Reference(s)
Houston, Texas	US 59 (Southwest Freeway) Approx. 3.1 miles (both directions)	1976	4 lanes converted to 5 lanes 3 lanes converted to 4 lanes (Refer to Figure 1)	1 (Additional information provided in Appendix A)
Honolulu, Hawaii	H1 Approx. 3.5 miles (both directions)	2014	3 lanes converted to 4 lanes (11.5 -12 ft. lanes re-striped to 10 ft. with reduced shoulder widths)	2
Northern Virginia	I-395 (Approx. 1.5 miles NB; 2.5 miles SB)	1989	3 lanes converted to 4 lanes (12 foot lanes re-striped to 11 ft., with reduced shoulder widths (2 ft. or less inside; 4 to 10 ft. outside)	3
Milwaukee, Wisconsin	I-94 Less than 1-mile (both directions)	2015 Planning	4 lanes to be narrowed from 12 ft. to 11 ft., with narrow shoulders, due to R.O.W constraints, as part of a reconstruction project	6 (Refer to case study herein)

Table 2. Examples: Narrowing Lanes to Add a Managed Lane.

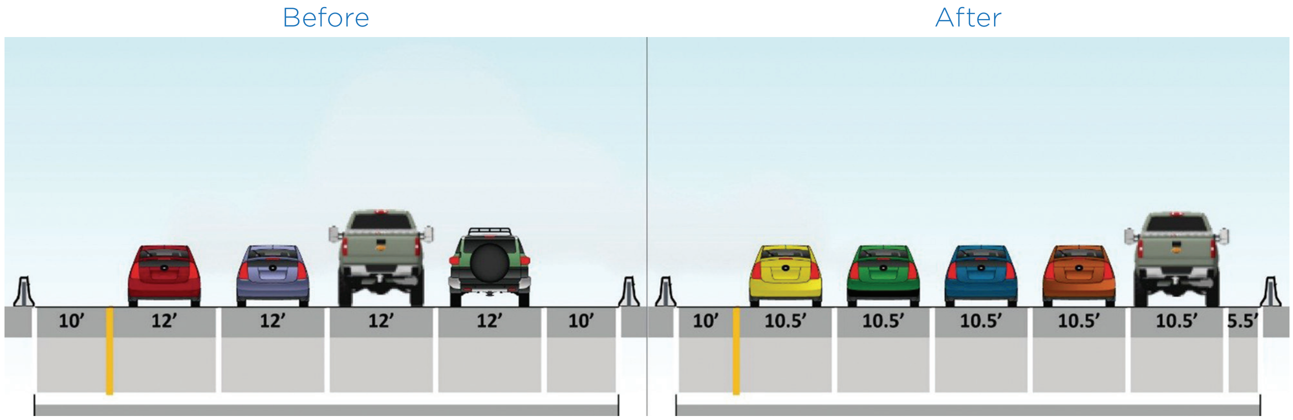
Location	Route(s) and Length	Date	Cross-Sections	Reference(s)
Los Angeles, California	Multiple routes Approximately 49 miles	1993	5 lanes converted to 6 lanes 4 lanes converted to 5 lanes Additional lane used as HOV in nearly all cases (Refer to Figure 1)	1, 3, 4, 5, 16 (Additional information provided in Appendix A)
Miami – Dade, Florida	I-95 and SR 826	Initial segment in 2008 Ongoing	4 general purposed lanes + HOV lane converted to 4 lanes + 2HOT lanes (Refer to Figure 1)	9 (Refer to case study herein)

Table 3. Examples: Narrowing Lanes to Add a Lane in the Vicinity of an Interchange.

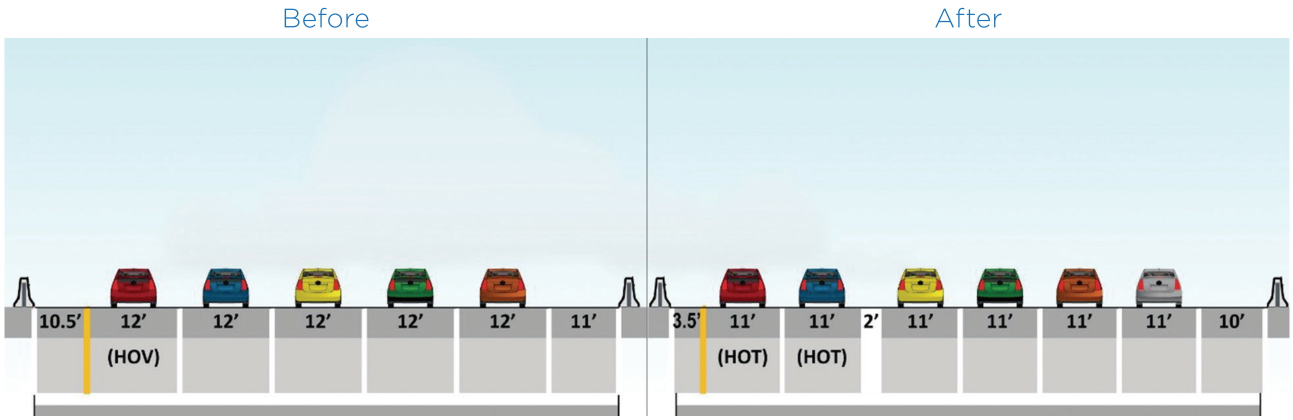
Location	Route(s) and Length	Date	Cross-Sections	Reference(s)
Los Angeles, California	NB SR 110 connector to NB I-5	2010	Connector ramp re-striped to provide two lanes, the second lane being the shoulder for part time use. Signage installed on SR 110 to allow through and exit movements from a lane when connector ramp shoulder open to traffic.	7 (Refer to case study herein)
Everett, Washington	US 2 from the I-5 / US 2 Interchange EB to SR-204 (Approx. 1.6 miles)	2009	2 general purpose lanes narrowed from 12 ft. to 11 ft., inside shoulder narrowed from 4 ft. to 2 ft., and outside shoulder widened from 10 ft. to 14 ft. (all via re-striping). Shoulder opened to traffic during PM peak to prevent exiting traffic (from I-5 to US 2) from backing onto I-5, and to reduce crashes in the interchange. (Refer to Figure 1)	10 (Refer to case study herein)



Note: Three general purpose lanes converted to four general purpose lanes US 59 – Houston, Texas (Reference 1).

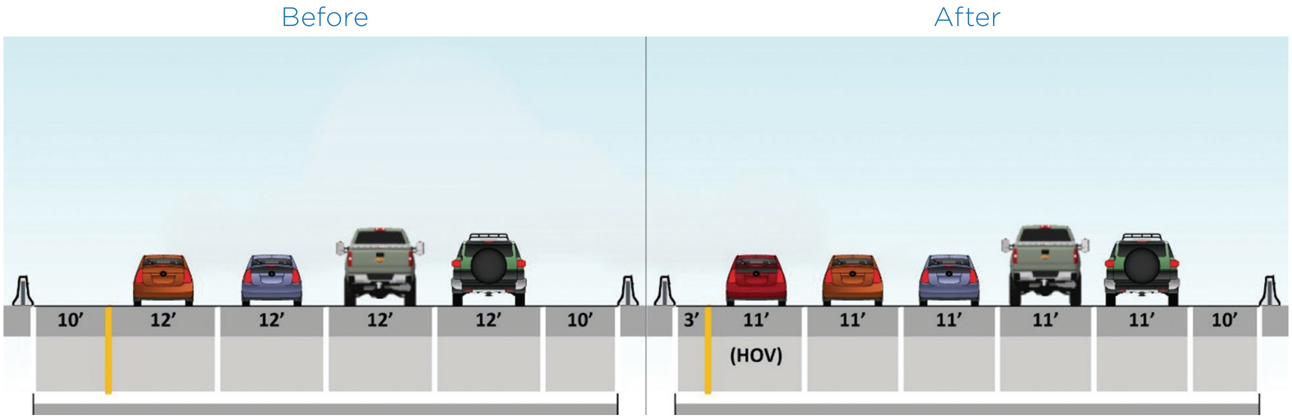


Note: Four general purpose lanes converted to five general purpose lanes US 59 – Houston, Texas (Reference 1).

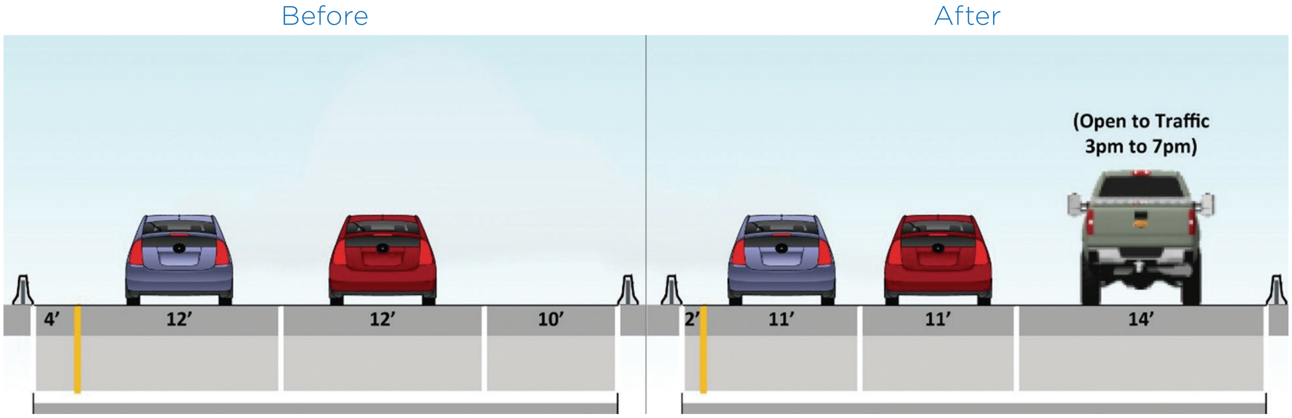


Note: Four general purpose lanes and one High Occupancy Vehicle lane converted to four general purpose lanes and two High Occupancy Toll lanes Miami, Florida Typical (Reference 5).

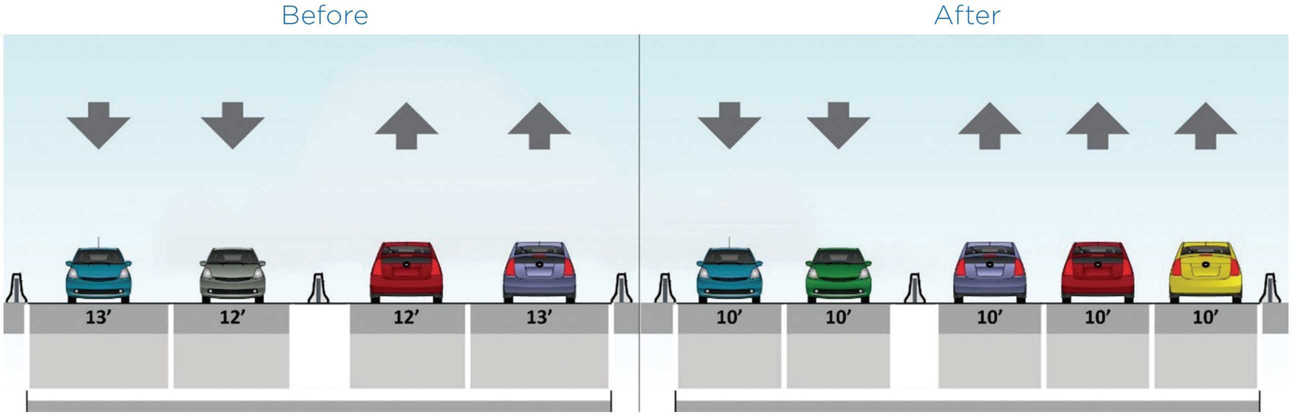
Figure 1. Diagrams. Example Narrow Lanes and Shoulder Configurations.



Note: Four general purpose lanes converted to four general purpose lanes and an High Occupancy Vehicle lane Los Angeles, California Typical (Reference 5).

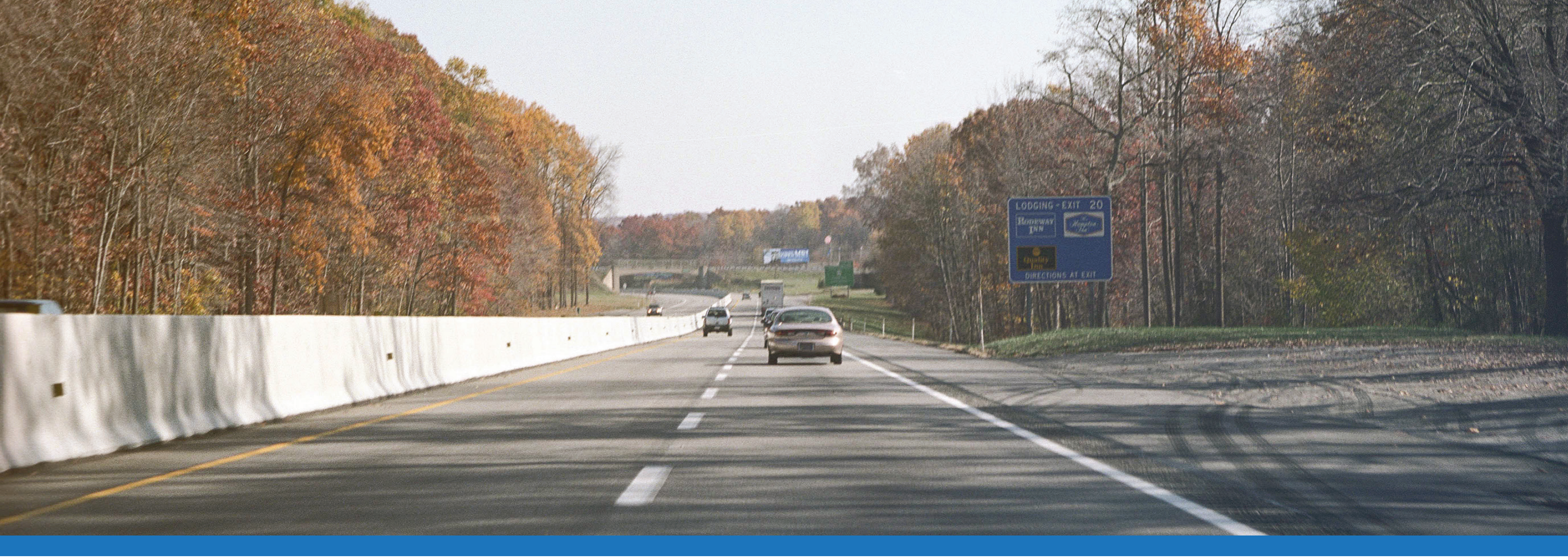


Note: Re-striping of general purpose lanes and inside shoulder to accommodate part time use of the outside shoulder Washington State US 2 (Reference 10).



Note: Four lanes total (two lanes in each direction) converted to five lanes total Inner Ring Expressway, Shanghai, China (Reference 11).

Figure 1. Diagrams. Example Narrow Lanes and Shoulder Configurations. (continuation)



Source: Kittelson & Associates, Inc.

Chapter 2 Performance Based Practical Design and the Role of Operations

PERFORMANCE-BASED PRACTICAL DESIGN

Performance-Based Practical Design (PBPD) modifies the traditional "top down, standards first" approach to a "design up" approach where designers and decision makers exercise engineering judgment to build up the roadway and operational improvements from existing conditions to meet both project **and** system objectives. PBPD uses appropriate analysis tools – such as those discussed in **Chapter 4** – to evaluate the performance impacts of planning and design decisions in relation to the cost of providing various geometric elements and operational features.

PBPD should not be viewed as a stand-alone set of activities. Rather, it is an integral part of a broader process known as "Performance-Based Planning and Programming." The Federal Highway Administration (FHWA) publication "Performance Based Planning and Programming Guidebook" (Reference 25) describes the application of performance management principles within the planning and programming processes of transportation agencies and regional entities (e.g., Metropolitan Planning Organization (MPOs)) to achieve desired performance outcomes for the multimodal transportation system. **Figure 2** shows the Performance-Based Planning and Programming (PBPP) process, indicating where PBPD concepts and activities may be applied. As shown in **Figure 2**, PBPD-related activities can be applied to the preliminary engineering and design activities, with any cost savings going to support additional projects as part of the regional programming process.

PBPD concepts can also be used during planning activities to help identify strategies and analyze alternatives.

Figure 3 identifies and summarizes the various PBPD concepts and potential activities, starting with "baseline conditions" including design policies and guidelines, current and projected issues and needs, and stakeholder concerns; and then moving into analysis such as developing alternatives, analyzing these alternatives in terms of improved performance and costs, coupled with trade-offs and engineering judgment. The results of these PBPD-related activities and concepts (i.e., "Moving Forward") is the selection of the optimal concepts and strategies for design, the identification of any design exceptions, and the documentation of the decisions. The optimal design concepts, along with any associated cost savings, are fed back into the PBPP framework.

As collectively shown in **Figures 2** and **3**, with PBPD designers apply a "design up" approach by using existing conditions as the baseline and engineer solutions that meet the project purpose based on explicitly defined transportation performance needs as derived from system and regional goals and objectives. This approach differs from a more conventional approach of setting project design criteria based solely on values listed in design specifications or standards for a set of given conditions. Designers then evaluate the solutions against the tradeoffs based on an objective analysis of performance data. Some of the tradeoffs considered include the estimated costs for each potential solution, coupled with due consideration of agency polices, legal requirements, stakeholder sensitivities, and any other potential constraints.

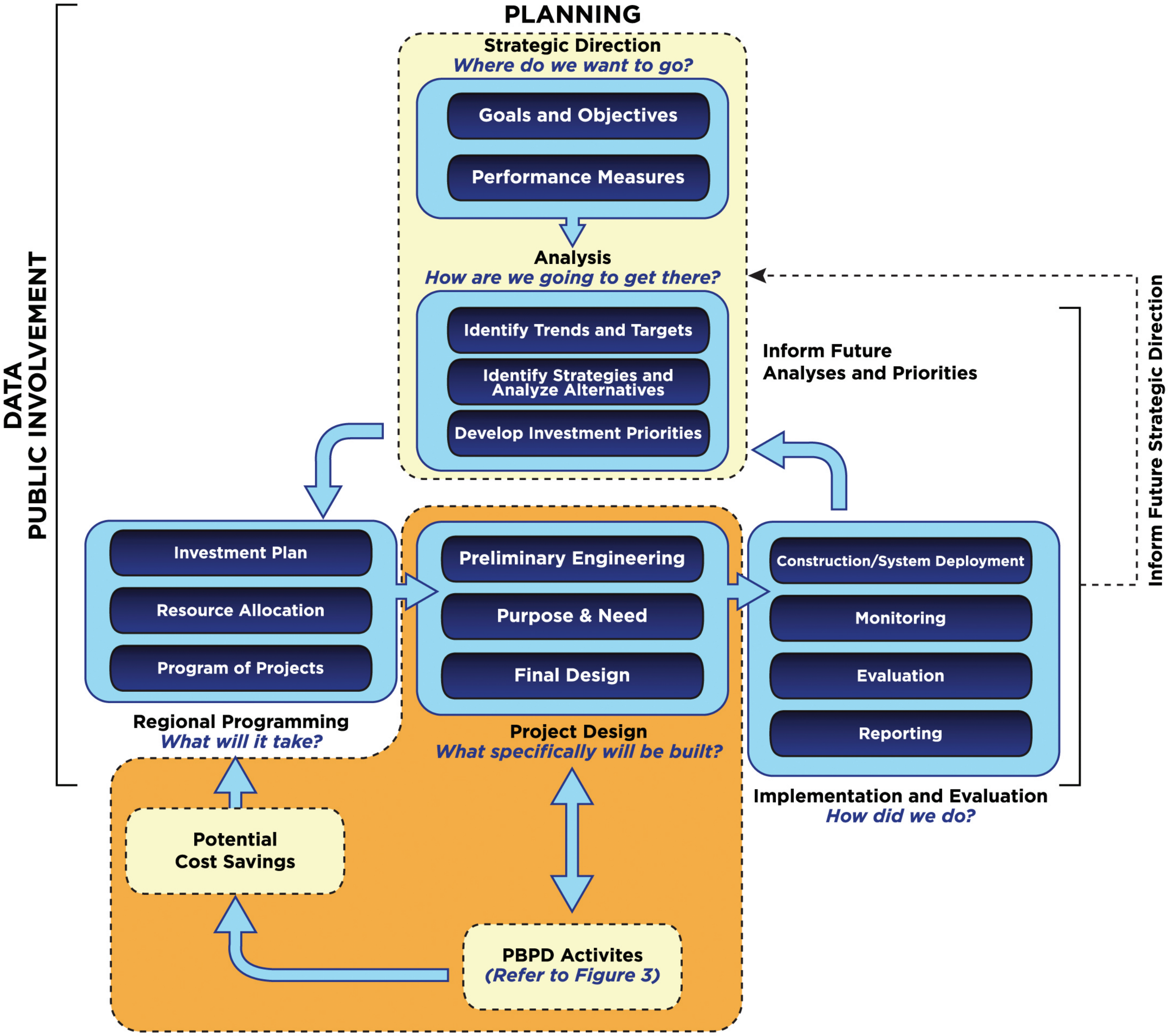


Figure 2. Diagram. Framework for Performance-Based Planning and Programming.

Note: Performance-Based Practical Design shown in orange.

(Source: Adapted from Federal Highway Administration document number HEP-13-041, Reference 25)

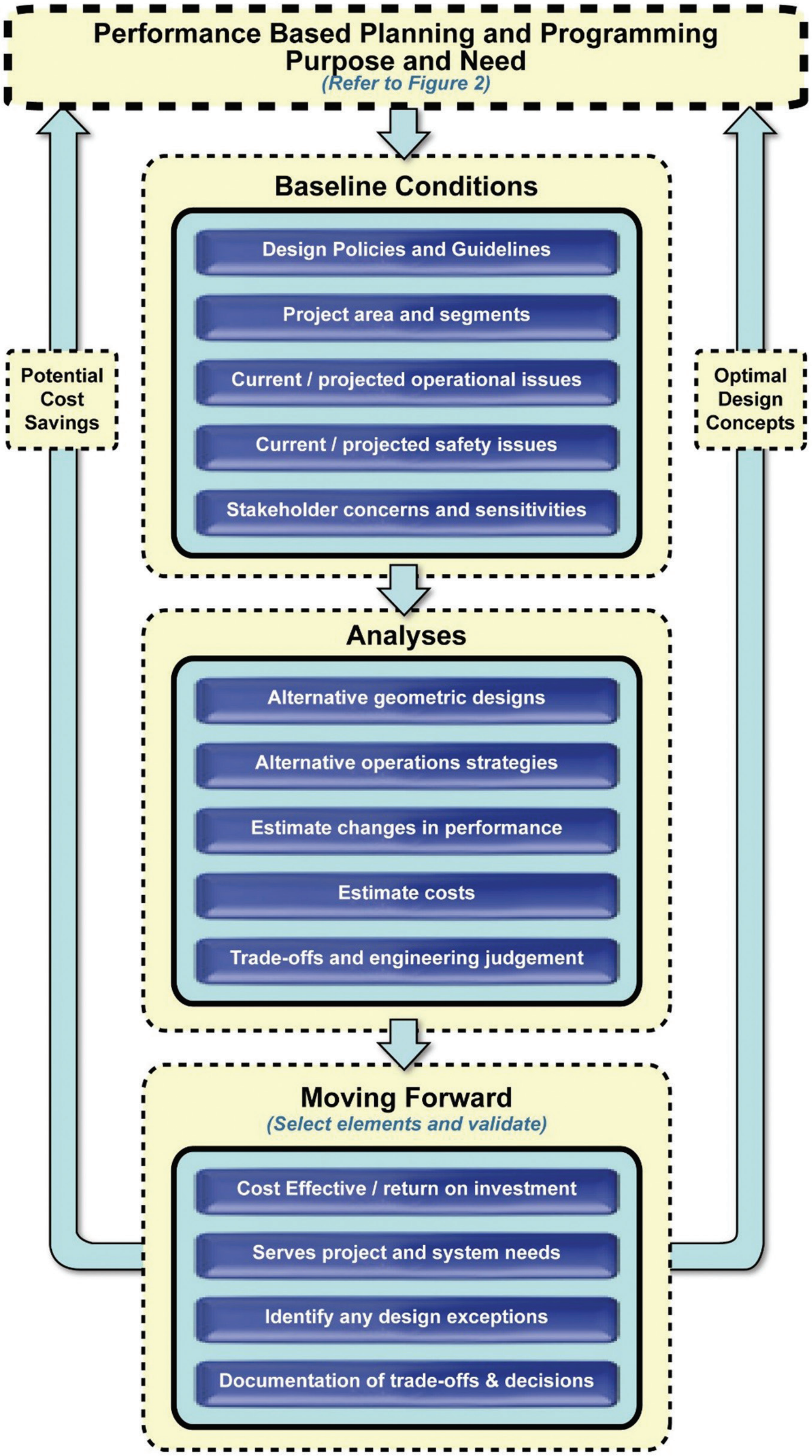


Figure 3. Diagram. Concepts and Activities Associated with Performance-Based Practical Design.

(Figure is based on several Federal Highway Administration documents and presentations on the subject of Performance-Based Practical Design)

A basic tenet of PBPD involves making project decisions that directly serve performance needs while considering whether the same investment of money would yield a greater return on investment if applied to other system needs and/or priorities. It is important to document the design decisions and present them to decision makers showing the benefits relative to the no-build option. These PBPD design and decision-making analyses can easily be transferred to design exception forms for review, approval and record-keeping.

By implementing a PBPD approach, agencies may reduce or eliminate project elements that are determined to be non-essential, resulting in lower cost and improved value by taking advantage of existing design flexibility. Agencies may also use the associated cost saving to deliver a greater number of projects that yield a greater performance return on investment than otherwise possible under existing project development and design approaches.

Relationship Between PBPD and Context Sensitive Solutions

Context-sensitive solutions (CSS) seek a transportation solution that addresses the needs of all road users and the functions of the facility within the context of its setting, considering land use, users, the environment, and other factors. CSS is a collaborative, interdisciplinary approach that includes the viewpoints of all stakeholders in the development of a shared vision of project goals, and uses a defined decision-making process. CSS and PBPD rely on flexibility to achieve results that meet the project purpose and need. PBPD compliments CSS by providing performance information that supports decision-making.

Design Criteria and Design Exceptions

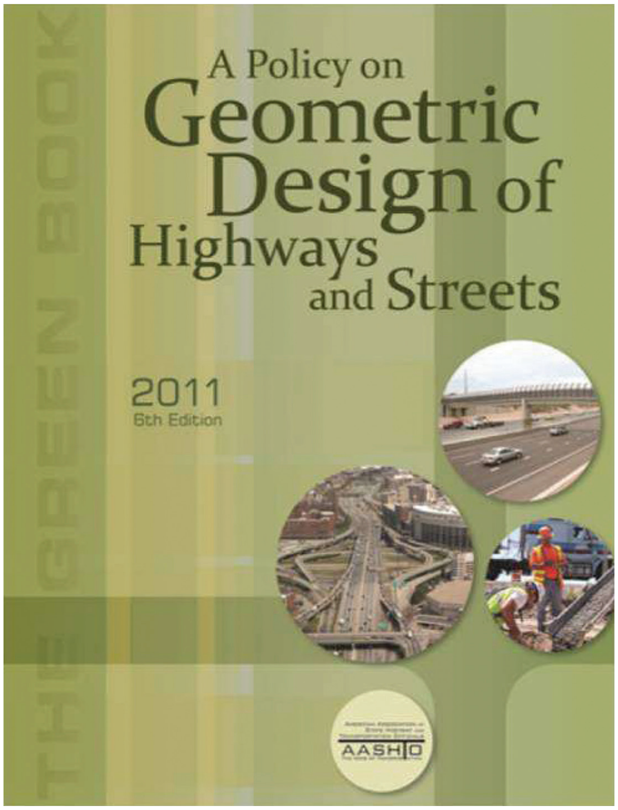
As previously noted, PBPD moves away from the more conventional “top down, standards first” approach to more of a performance and value-based “design up” approach. Designers that focus on the relationships between design dimensions and performance may become less obligated to meet one or more of the design guidelines, such as those found in the AASHTO Green Book (“A Policy on Geometric Design of Highways and Streets”). Design criteria and standards offer many benefits, including promoting consistency, establishing a design “norm, and promoting efficiency in design development. However, “standard” does not necessarily mean “best”, nor are standards intended to be a substitute for engineering judgment and context-specific considerations. PBPD provides planners and designers with the flexibility to make the optimum design decisions.

A **design exception** is a documented decision to design a highway element or a segment of highway to design criteria that do not meet minimum values or ranges established for that highway or project. Federal regulations (Reference 13) state that *“Approval …may be given on a project basis to designs which do not conform to the minimum criteria as set forth in the standards, policies, and standard specifications.”* A design exception is <u>NOT</u> an indication of failure or a “flawed” design; rather it is a necessary and legitimate process to allow professional and engineering judgment in the design process, providing a useful “tool” for employing practicality and flexibility in design decisions in a design-up approach such as PBPD.

As noted in the FHWA document “Mitigation Strategies for Design Exceptions” (Reference 14) there are a broad range of reasons why design exceptions may be considered and found to be necessary. Some of these include the following:

- Impacts to the natural environment
- Social or right-of-way impacts
- Preservation of historic or cultural resources
- Sensitivity to context and community values
- Construction or right-of-way costs

Widening the roadway footprint, including the possibility of additional right-of-way, will certainly impact the last bullet, and may impact one or more of the other bullets. Adding a lane by narrowing the existing lanes **within the existing roadway footprint** can help reduce or even eliminate the concerns noted above in the bulleted list that so often apply to projects that end up widening the roadway.



Even the Cover of the “Green Book” is Flexible

A final notice published in the Federal Register on May 5, 2016 completed FHWA’s effort to update the policy regarding controlling criteria for design, applicable to projects on the National Highway System. FHWA reduced the number of controlling criteria from 13 to 10 for Interstate highways, other freeways, and roadways with design speed ≥ 50 mph, and now applies only 2 of those criteria to low speed roadways (non-freeways with design speed <50 mph). FHWA also clarified when design exceptions are needed and the documentation that is expected to support such requests.

FHWA has adopted new policies to modify highway design standards that encourage greater flexibility in order to achieve a design that best suits the desires of the community, while satisfying the purpose for the project and needs of its users. As an example, FHWA published revisions to current federal policy that will help reduce cost and speed up the design of local roads and streets. In 1985, thirteen design criteria were prioritized because of their perceived impact on operations and safety. Under the new policy, ten criteria will be prioritized for high speed roadways, and only two criteria will be emphasized for lower-speed roads such as rural roads that become main streets through smaller towns and cities. This will provide state and local engineers to develop flexible design solutions that meet local travel needs and goals.

Chapter 8 of the *Green Book* recommends shoulder widths for freeways shown in Table 4. Additionally, the AASHTO policy on design standards for the Interstate highway system requires a 10 ft. paved right (outside) shoulder. Shoulder widths less than the values shown in Table 4 will also require a design exception under the existing and proposed FHWA policy on Controlling Criteria.

Moving the inside travel lane closer to the roadway edge – including part time use of the shoulder as a travel lane – may also impact the horizontal alignment (to be renamed as “horizontal curve radius” under the proposed FHWA policy on Controlling Criteria) and sight distance as shown in Figure 4, and may therefore also require a design exception.

Controlling Criteria for Design Exceptions, 2016

1. Design Speed*
2. Lane Width
3. Shoulder Width
4. Horizontal Curve Radius
5. Superelevation
6. Maximum Grade
7. Stopping Sight Distance
8. Cross Slope
9. Vertical Clearance
10. Design Loading Structural Capacity*

* Design Speed and Design Loading Structural Capacity apply to all roads on the National Highway System

Table 4. Recommended Shoulder Widths for Freeways.

Side of Roadway	DDHV for truck traffic (veh/hr)	Total numbers of freeway lanes	Recommended shoulder width (ft)
Right Shoulder	≤ 250	All	10
Right Shoulder	> 250	All	12
Left Shoulder	≤ 250	Less than 6	4
Left Shoulder	≤ 250	6 or more	10
Left Shoulder	> 250	All	12

(Source: NCHRP Report 783: Evaluation of the 13 Controlling Criteria for Geometric Design; adapted from Chapter 8 of the AASHTO Green Book)

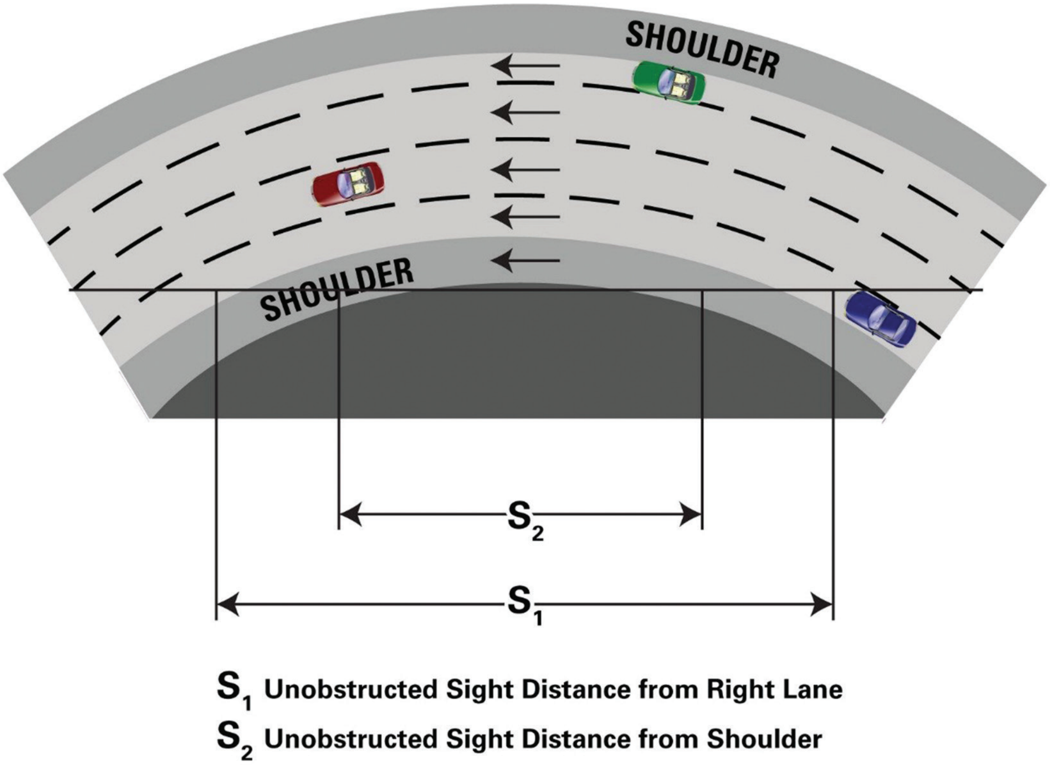


Figure 4. Diagram. Potential Impact on Sight Distance From Moving the Left-Most Travel Lane To the Inside.

TRANSPORTATION SYSTEMS MANAGEMENT AND OPERATIONS

Transportation Systems Management and Operations (TSMO)—also often referred to simply as "operations"—is defined as:

"Integrated strategies to optimize the performance of existing infrastructure through the implementation of multimodal and intermodal, cross-jurisdictional systems, services, and projects designed to preserve capacity and improve security, safety, and reliability of the transportation system."

Intelligent Transportation System (ITS) technologies – be they devices for monitoring traffic flow on the roadways, hardware and software at Transportation Management Centers (TMCs), and/or "Connected Vehicle" applications – are crucial to the success of these operations strategies. ITS represents the *"enabling technology for operations."*

TSMO strategies—coupled with the supporting ITS technology—are a most important aspect of delivering transportation services to customers. Experience has shown that aggressive applications of these operations strategies can, in effect, "take back" much of the capacity lost due to congestion and disruptions. Operations strategies also enhance safety, promote reduced emissions, and increase system reliability.

Perhaps most importantly, actively managing the transportation network can improve travelers' experiences, providing them with real-time information and choices throughout the trip chain—from origin to destination—leading to network performance optimization and increased efficiency. TSMO strategies are relatively low cost (compared with adding capacity), much quicker to implement (two to three years), and offer substantial benefits (with very positive benefit-cost ratios).

FHWA recommends an "objectives-driven, performance-based approach" for including "operational and management strategies to improve the performance of existing transportation facilities" in the planning process. This objectives-driven, performance-based approach to planning for operations within a metropolitan area—conducted in collaboration among planners, transportation providers, operators, and other stakeholders—is shown in **Figure 5**.

The activities shown in **Figure 5** parallel the PBPP and PBPD concepts identified in previous **Figures 2** and **3**, including the development of potential strategies based on goals, objectives, and needs; and then evaluating and subsequently selecting strategies in terms of performance and cost. Moreover, low-cost, rapidly deployable, and flexible treatments – as provided by many TSMO strategies – all fall under the collective umbrella of PBPP and PBPD. **Table 5** provides a list of TSMO strategies that may be used in conjunction with narrow lanes and/or shoulders as part of the PBPD process.

Figure 5. Flowchart. An Objectives-Driven, Performance-Based Approach.
(Adapted from Federal Highway Administration, Reference 25)

Table 5: Transportation System Management and Operations Strategies Typically Used On Freeways and the Potential Relationships to Performance-Based Practical Design.

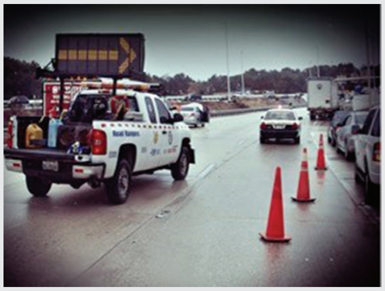
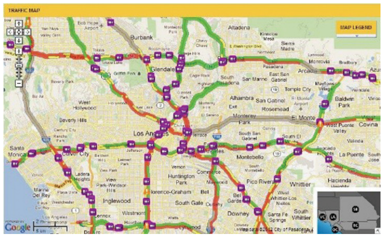
TSMO Strategy	Description	Potential Use and Value in Narrow Lanes/Shoulders
Incident Management  (Source: Florida DOT)	The systematic, planned, and coordinated use of human, institutional, electrical, mechanical, and technical resources to reduce the duration and impact of incidents, and improve the safety of motorists, crash victims, and incident responders.	Used to address safety and reliability concerns of narrow lanes or the loss of the shoulder as a vehicle refuge.
Ramp Management  (Source: Florida DOT)	The application of control devices, such as traffic signals, signing, and gates to regulate the number of vehicles entering or leaving the freeway, or to smooth out the rate at which vehicles enter and exit the freeway.	Metering the traffic that enters the freeway from on-ramps can help prevent flow breakdown on the mainline, and improve safety in merge and weaving areas that may be impacted by the use of narrow lanes and/or shoulders.
Managed Lanes (HOV,HOT)  (Source: Minnesota DOT)	Highway facilities or a set of lanes where operational strategies are proactively implemented and actively managed to optimize traffic flow and vehicular and person throughput. These strategies typically involve pricing, vehicle eligibility, and access control.	Used to improve travel time and reliability for vehicles carrying the most passengers or those willing to pay an additional fee for using the lane. The use of narrow lanes and shoulders may provide the opportunity to add or expand such lanes.
Traveler Information (511, apps on Smartphones, DMS)  (Source: Minnesota DOT)	A combination of strategies for enabling better traveler decision making throughout the trip chain – before, during, and near the end of a trip.	Allows drivers to adjust their route, time of travel, or mode, thus lessening demand on key facilities at peak times. DMS can also alert motorists that queues, significant slowdowns, or blocked lanes are ahead – as may result from narrow lanes or shoulders – thus reducing rear-end crashes and improving safety.

Table 5: Transportation System Management and Operations Strategies Typically Used On Freeways and the Potential Relationships to Performance-Based Practical Design. (continuation)

TSMO Strategy	Description	Potential Use and Value in Narrow Lanes/Shoulders
Dynamic Speed Limits  **(Source: Washington State DOT)**	Adjusts speed limit (or advisory) displays based on real-time traffic, roadway, and/or weather conditions. They can be applied to an entire roadway segment or individual lanes. This "smoothing" process helps minimize the differences between the lowest and highest vehicle speeds.	Used to reduce speeds in advance of congestion, or perhaps in advance of segments with narrow lanes, limited shoulder widths, or reduced sight distance (e.g., requiring a reduced design speed as part of the design exception process). Is often used in conjunction with part time shoulder use, dynamic lane assignment. (Refer to Figure 6)
Dynamic Lane Assignment  **(Source: Washington State DOT)**	Dynamically closing or opening individual traffic lanes as warranted and providing advance warning of the closure(s), typically through lane control signs, to safely merge traffic into adjoining lanes.	Used to open and close a part time lane (e.g., part time shoulder use), or to close lane(s) upstream of a crash or disabled vehicle (e.g., with no shoulder for refuge). One or more lanes may also be closed to allow emergency vehicles to reach the crash scene quicker, particularly if there are narrow shoulders. This strategy is often used in conjunction with dynamic speed limits.
Dynamic Junction Control  **(Source: Caltrans)**	Dynamically allocating lane access on mainline and ramp lanes in interchange areas. This may consist of assigning lanes dynamically either for through movements, shared through-exit movements, or exit-only.	Used to better allocate available capacity at interchange areas and reduce the amount of weaving and merging. Is typically used with some sort of dynamic lane assignment. May be deployed to identify if the ramp shoulder is open to traffic and which mainline lanes can access the ramp; or may be deployed to promote safe merging operations during use of the mainline shoulder.

Incorporating the consideration of TSMO strategies into the PBPD concepts and activities, designers and decision makers can expand the variety of options available to them, including perhaps the ability to postpone or reduce the need for conventional capacity improvements. Additionally, TSMO strategies may also help mitigate some of the safety and reliability impacts of PBPD solutions that result in less than full standard geometric design decisions, thereby providing solutions and support for any design exceptions. For example, dynamic speed limits and dynamic lane assignment strategies may be used in this context as shown in **Figure 6**.

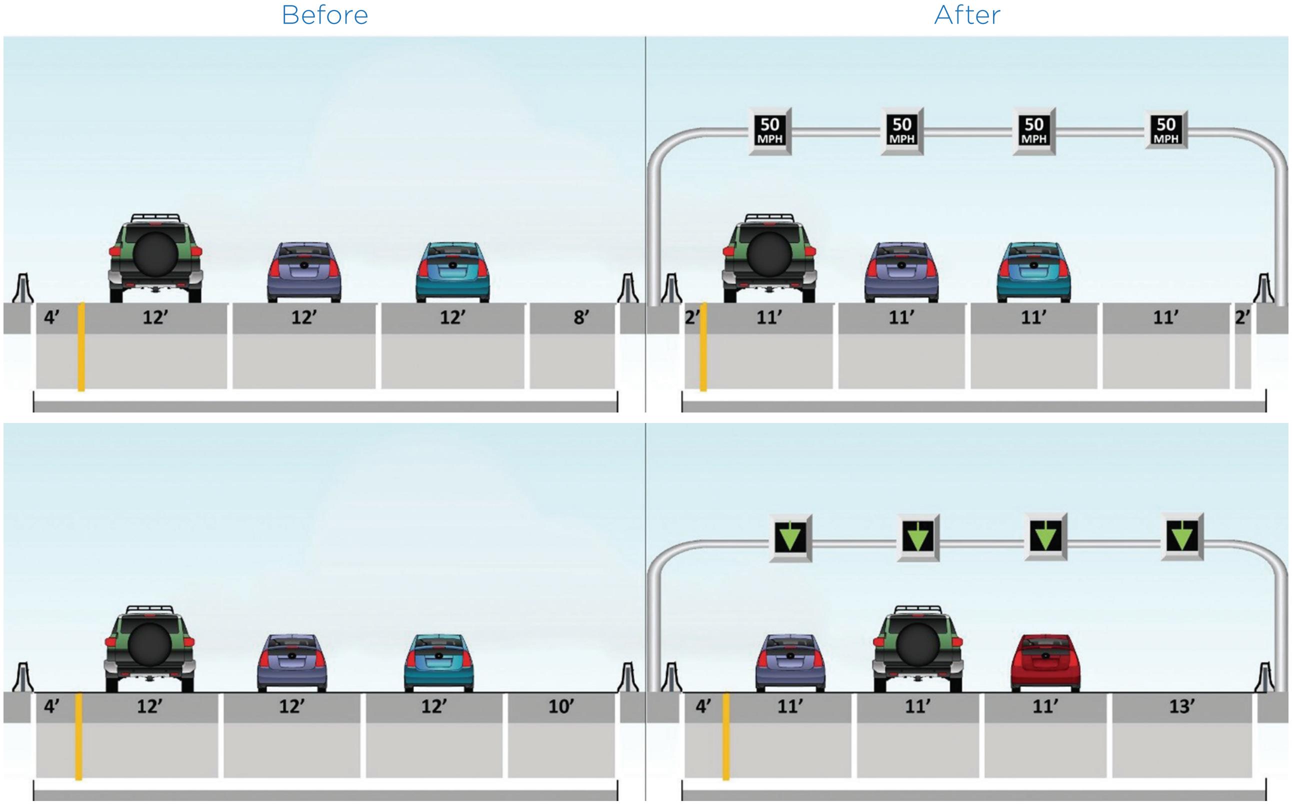


Figure 6. Diagram. Example of Dynamic Speed Limits and Dynamic Lane Assessment in Support of Narrow Lanes and Shoulders.

In summary, PBPD and TSMO – along with Context Sensitive Solutions and value engineering – are very complimentary as shown in **Figure 7**. Their respective approaches have much in common, and they all strive for the same goal – namely, providing a well-performing transportation system using the most cost-effective improvements.

The FHWA website for PBPD (Reference 12) identifies notable attributes for PBPD as listed below. The phrase "and TSMO" can be added immediately after "PBPD" in this list and still ring very true.

- PBPD (and TSMO) focuses on performance improvements that benefit both project and system needs.
- Agencies make sound decisions based upon performance analysis.
- By scrutinizing each element of a project's scope relative to value, need, and urgency, a PBPD (and TSMO) approach seeks a greater return on infrastructure investments.
- PBPD (and TSMO) strengthens the emphasis on planning-level corridor or system performance needs and objectives when planning, scoping and developing individual projects.
- PBPD (and TSMO) can be implemented within the Federal-aid Highway Program regulatory environment utilizing existing flexibility. PBPD does not eliminate, modify, or compromise existing design standards or regulatory requirements.

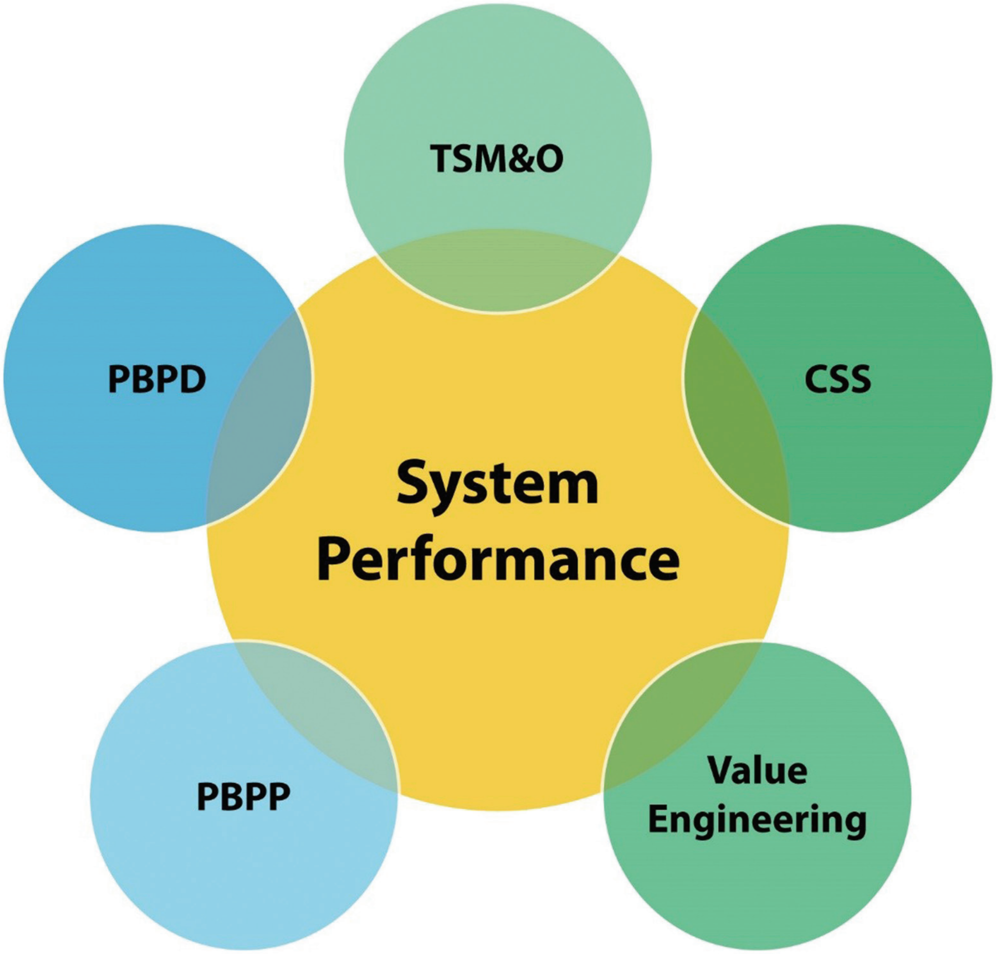


Figure 7. Diagram. Overlapping Relationship between Performance-Based Practical Design, Performance-Based Planning and Programming, Transportation System Management and Operations, Context Sensitive Solutions, and Value Engineering.

Source: Kittelson & Associates, Inc.

Chapter 3 Case Studies of Narrow Lanes and Narrow Shoulders

Significant widening of a freeway in an urban area is often impracticable due to the adjacent development and land use and physical constraints, often coupled with funding constraints. An additional lane may nevertheless be provided within the existing roadway footprint by reducing the widths of the existing lanes and/or shoulder, or using the shoulder as a part time travel lane. The use of narrow lanes to provide additional capacity and improve operations within the existing roadway footprint is not new. Brief case studies of this approach are provided below.

NARROW LANES AS PART OF FREEWAY MODERNIZATION ALONG I-94 IN MILWAUKEE, WISCONSIN

This Case Study illustrates how a Performance-Based Practical Design (PBPD) approach can be used to analyze and make trade-offs during the design of major freeway reconstruction in a constrained urban area – specifically, the reconstruction of I-94, the East-West freeway, in Milwaukee, WI, and the ultimate recommendation to incorporate narrow lanes and shoulders along a segment of the project.

The I-94 East-West corridor study area is located in central Milwaukee County between the downtown Milwaukee Marquette Interchange and the Zoo Interchange. This portion of the I-94 East-West Freeway corridor is comprised of six lanes, three in each direction. It plays a key role in moving commuters, tourists, freight and other movements to major sites around and beyond the Southeast region of the state. As the corridor is nearing the end of its useful life, WisDOT initiated analyses to determine how the corridor should be rebuilt to ensure that it serves the economy of Southeastern Wisconsin for decades to come. The option of merely rebuilding the six-lane freeway was eliminated early in the process based on a DOT analysis showing the need for eight lanes to reduce congestion and accommodate future traffic growth.

One segment, less than a mile in length, passes between a number of cemeteries as shown in **Figure 8**. As part of the screening process, two preferred alternatives were identified and scoped to avoid direct impacts to the adjacent cemeteries.

- **At-Grade Alternative:** The At-grade alternative would reconstruct I-94 to eight travel lanes (four in each direction) at essentially the same elevation as the existing freeway. To avoid encroachment on the cemeteries, the reconstructed freeway mainline would include narrowing the lanes and converting the outside shoulder to a permanent fourth lane in each direction. As a result, the freeway would have less than 12-foot driving lanes between the adjacent cemeteries. Eastbound and westbound traffic would travel in 11-foot lanes for roughly 30 feet in each direction, with the lanes transitioning from 12 feet to 11 feet (and back to 12 feet) for several hundred feet east and west of the 11-foot-lane segment. The shoulder widths would vary in this segment as the available right-of-way varies (with the shoulders being as narrow as two feet). East and west of the cemeteries, the freeway would have standard 12-foot lanes and full shoulders. Active Traffic Management (ATM) tools – such as advance warning signs alerting drivers to the narrow lanes and narrow shoulders, and dynamic lane assignment and dynamic speed limits to warn drivers of closed lanes and reduced speeds in the narrow segment – are being considered to make the narrow lane/narrow shoulder segment operate as safe as possible.

- **Double Deck Alternative:** The Double Deck alternative would reconstruct I-94 to eight travel lanes (four in each direction). A Double Deck (with one set of freeway lanes elevated over the other) would be constructed in the area between the cemeteries to avoid any direct impacts. All I-94 lanes would be 12-feet-wide under this alternative. The shoulder widths would vary slightly in this segment because insufficient right-of-way is available near the cemeteries to provide full shoulder width. East and west of the cemeteries, the freeway would have full shoulders in both directions.

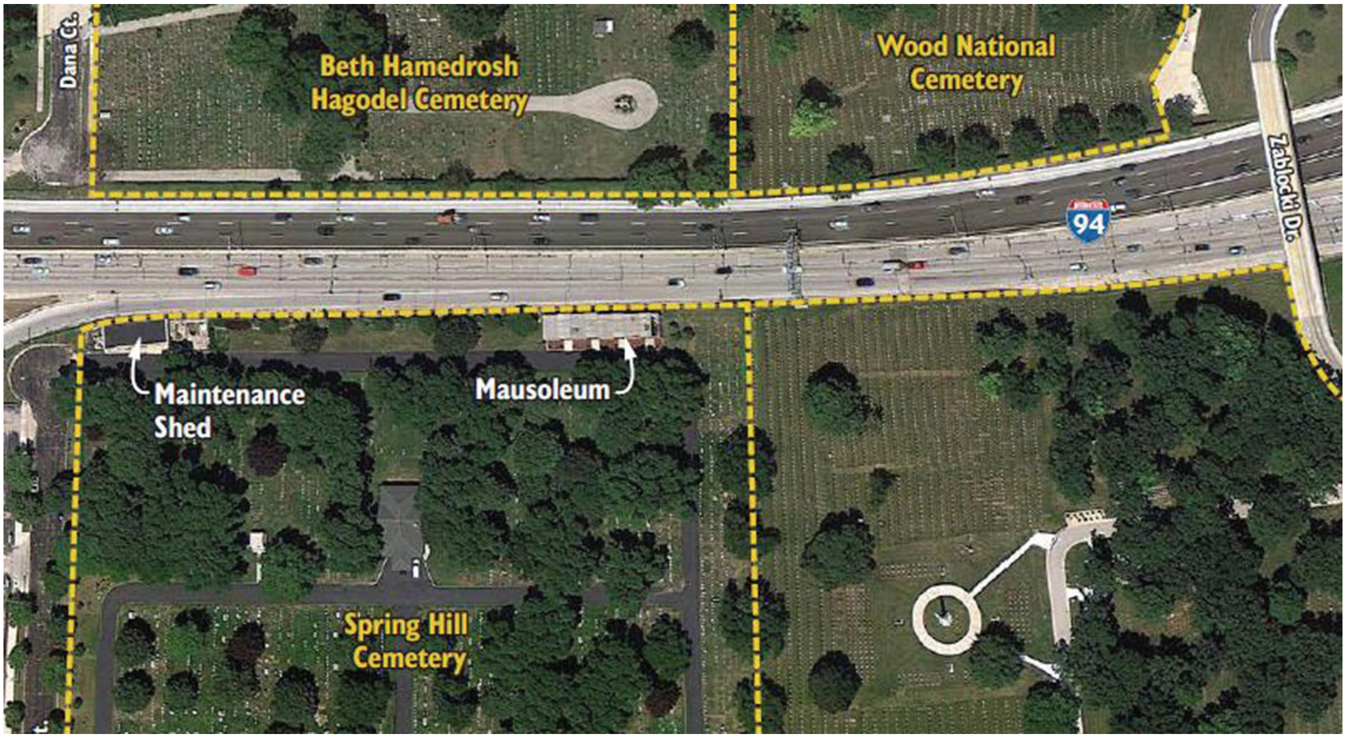


Figure 8. Picture. Milwaukee, Wisconsin Case Study Project Area.

(Source: Wisconsin Department of Transportation)

Analyses were conducted for the various scenarios for the design year 2040 conditions using the proposed geometric alternatives and projected traffic data. The results of the analyses relative to the system needs and objectives are summarized below.

- **Safety:** Based on a crash prediction analysis to measure the number of annual crashes, and addressing the freeway and nearby arterial streets, the double deck alternative would have fewer total crashes than the at-grade alternative (with narrow lanes and shoulders) over the 20-year analysis period. Nevertheless, the at-grade alternative would have 23 percent fewer crashes than the replace in kind alternative over the 20-year period, thereby addressing improved safety and reduced crashes on I-94.

- **Traffic Volumes and Operations:** Another goal of the I-94 project is to accommodate existing and future traffic demand at an acceptable Level of Service (LOS). The at-grade and double deck alternatives would provide LOS C or D in the A.M. and P.M. peak periods in 2040, thereby satisfying this operational goal.

- **Cost:** The total costs for the at-grade alternative are significantly less compared to the double deck alternative (i.e., $125 million as compared to $295 to $345 million, in 2014 dollars), and the at-grade alternative satisfies the project need and purpose.

WisDOT has identified the at-grade alternative, with narrow lanes, as the preferred alternative [3] . As noted in the WisDOT press release:

"The alternative selected provides the community with the best balance when all critical factors are evaluated together. We are recommending an approach which addresses the problems of crumbling infrastructure, congestion, and integration with the local street network. The at-grade alternative is the least expensive to construct and have lower potential for community and cultural resources impacts."

The 11-foot travel lanes and narrow shoulders through the cemetery area (with the At-Grade alternative) do not meet WisDOT and AASHTO criteria for the approximately 2,000-foot distance between the cemeteries and require design exceptions.

The At-Grade Alternative also requires a design exception for inadequate sight distance in the cemetery area (that is, the slight curve on I-94 through the cemeteries, combined with the 2 foot shoulders, would cause the concrete median barrier to reduce sight distance). These design exceptions do not reach a level that makes proceeding with the project in light of the stated purpose and need unreasonable, nor do they result in unacceptable safety or operational problems. Moreover, potential safety concerns with the designs could be mitigated to some extent by the inclusion of Transportation System Management and Operations (TSMO) strategies such as ATM.

In summary, this example illustrates how the use of narrow lanes and shoulders – identified and analyzed using a PBPD approach – can result in a feasible and cost-effective solution for upgrading an older urban freeway.

NARROW LANES TO ACCOMMODATE ADDITIONAL MANAGED LANE ALONG I-95 IN MIAMI - DADE, FLORIDA

I-95 from I-395 in Downtown Miami to I-595 in Broward County was comprised of four general purpose lanes and a single High Occupancy Vehicle (HOV) lane, with the separation of the HOV and general purpose lanes via striping only. The HOV lanes had an occupancy requirement of 2+ during peak hours (7-9 AM and 4-6 PM). The HOV and general purpose lanes on I-95 were operating at LOS F during peak periods. Additionally, the violation rates on the HOV lane were very high, exceeding 30 percent in many segments.

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[3] As of the writing of this Primer, the preferred alternative is still going through the final environmental impact statement process.

Florida DOT implemented a conversion of the facility – shown in **Figure 9** – as follows:

- Existing HOV lane converted to a High Occupancy Toll (HOT) lane
- A second HOT lane was added by re-striping the entire facility with narrower lanes and shoulders. No new pavement was added. (Refer to diagrams in previous **Figure 1**)
- The separation of the HOT lanes and the general purpose lanes is via delineators spaced 10 feet apart within a one-two foot painted buffer.
- The occupancy limit was raised to three+

A carpool registration component of I-95 Express was developed due to the right of way constraints that prohibited a dedicated declaration lane (for occupancy verification).

The ability to leverage Florida Turnpike Enterprises electronic violation enforcement system also provided the Department with the opportunity to reduce the scope of Florida Highway Patrol (FHP) enforcement in the lanes.

Current users of the HOT lane are three+ registered carpools and buses for free; with SunPass users allowed to use the lanes and pay a toll rate which is variable in relationship to the lane usage.

The converted I-95 Express lanes have improved overall traffic conditions along the project corridor since its inception as shown in **Table 6**.

In summary, this example illustrates how the use of narrow lanes and shoulders within an existing roadway footprint can help increase the capacity of managed lanes and improve the operation of both the managed lanes and general purpose lanes.

Figure 9. Photo. I-95 Express Lanes in Miami-Dade, Florida.

(Source: Google Maps / Street View)

Table 6. Average Travel Speeds Before and After I-95 Conversion.

	Am Peak - Southbound		PM Peak - Northbound	
	Before (2008 HOV Study)	After (12 months – FY 2009-2010)	Before (2008 HOV Study)	After (12 months – FY 2009-2010)
General Purpose Lanes	15 mph	51 mph	15 mph	41 mph
HOV lane (Before) / Express Lanes (After)	20 mph	64 mph	18 mph	56 mph

NARROW LANES TO ACCOMMODATE PART TIME SHOULDER USE ON US 2 IN WASHINGTON STATE

This site is located on the US-2 eastbound Trestle between the I-5 and SR-204 interchanges (MP 0.66 to MP 2.22). This segment was re-striped from a configuration consisting of 4' left shoulder, two 12' general purpose lanes and a 10' right shoulder; to a 2' left shoulder, two 11' general purpose lanes, and a 14 foot auxiliary lane/shoulder on the right, as shown in previous **Figure 1**. A photograph of the current configuration is shown in **Figure 10**.

The primary purposes for WSDOT to develop this static shoulder use were to reduce collisions in the I-5 / US-2 interchange and to keep traffic on the ramp from I-95 NB to US-2 from backing up onto the mainline of I-5 NB. The shoulder was first opened to traffic on April 6, 2009. The shoulder use operates in the PM peak period from 3:00 PM to 7:00 PM Monday through Friday. The shoulder is not open to traffic during all other time periods.

The average speeds on the I-5 NB connector to US-2 EB have improved from 10 MPH to 37 MPH during the PM period of heaviest traffic.

Figure 10. Photo. Shoulder Use Along US 2 in Washington State.

(Source: Washington State Department of Transportation)

The capacity in the narrower general purpose lanes along US 2 is approximately 2,000 vphpl and the corresponding speed is approximately 50 mph. The capacity on the shoulder is approximately 1,400 vphpl and the corresponding speed is approximately 40 mph. When considered in terms of crash rates, since the shoulder was opened to traffic in the eastbound direction of US-2, the rate of crashes in terms of crashes per million vehicle miles traveled (crashes/MVMT) has decreased overall as shown in **Figure 11**.

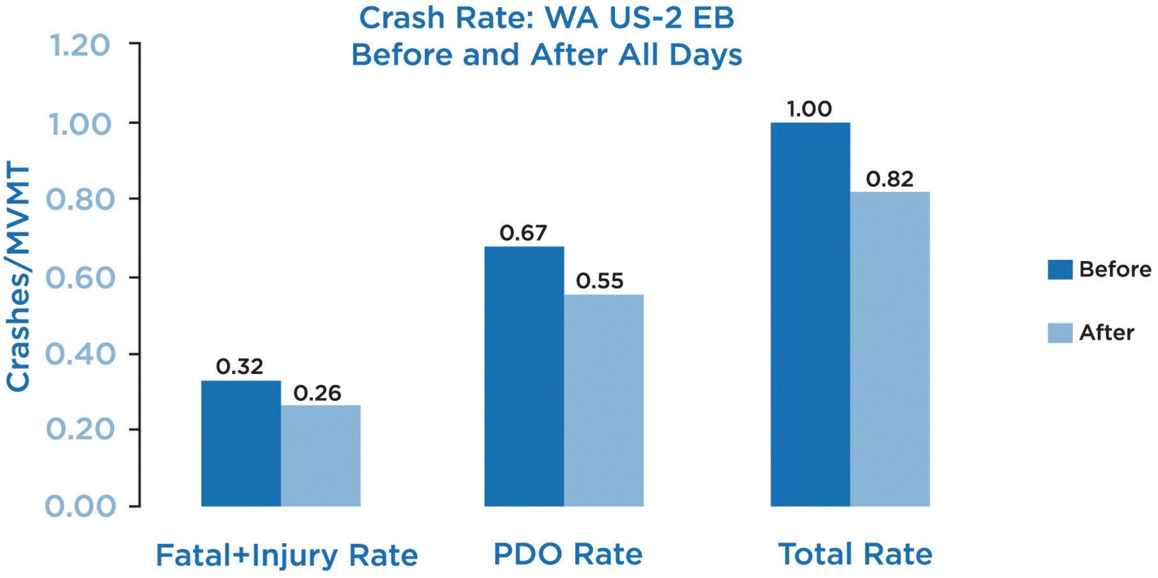

Figure 11. Graph. Change in Crash Rate On US-2 in Washington State.

(Source: Washington State Department of Transportation)

A significant finding from the analysis of the new lane configuration is that incident clearance times on US-2 during the PM peak (when shoulder use is allowed) are significantly longer than the PM peak clearance times before shoulder use was allowed – from approximately 20 minutes to 28 minutes for all incident types combined. This is an important consideration whenever shoulders are narrowed or when a full width shoulder is used by traffic. As previously noted, (TSMO) strategies such as enhanced incident management and dynamic lane assignment may help mitigate such concerns.

In summary, this example illustrates how by narrowing travel lanes and one shoulder can help convert the other shoulder into a part-time travel lane, thereby improving operation of the facility, including reducing back-ups at an interchange. The reduction in congestion can also improve safety.

JUNCTION CONTROL IN LOS ANGELES, CALIFORNIA

Junction control is an Active Traffic Management (ATM) strategy that dynamically allocates lane access on mainline and ramp lanes in interchange areas where high traffic volumes are present, and the relative demand on the mainline and ramps change throughout the day. For off-ramp locations, this may consist of assigning lanes dynamically either for through movements, shared through-exit movements, or exit-only. For on-ramp locations, this may involve a dynamic lane reduction on the mainline upstream of a high-volume entrance ramp and/or providing an additional lane for the on ramp. Volumes on the mainline lanes and ramps are continuously monitored, and lane access is dynamically changed based on the real-time and anticipated conditions. Implementing junction control may involve narrowing lanes, and/or part time use of the ramp and/or mainline shoulder thereby resulting in a narrow or no shoulder during junction control operation.

A junction control system was installed in Los Angeles at the northbound State Route 110 connector to northbound I-5. The system required re-striping of the SR-110 mainline and the off ramp to provide a second ramp lane and an optional turn from the second mainline lane. The mainline and ramp lanes were not narrowed; but during junction control operation, there is minimal shoulder on the ramp. The project also included the installation of blank out signs allowing the lane adjacent to the exit-only lane to also be used as an exit lane (in addition to remaining a through lane) during peak periods. The new ramp configuration and signage are shown in Figure 12.

Following implementation of this junction control system, the average ramp delay reduced from greater than 20 minutes to under five minutes, and the number of crashes decreased 30 percent from the previous year prior to installation as queued vehicles now are stopped towards the end of the slower moving ramp versus being stopped on the mainline of SR-110.

In summary, this example illustrates how converting an off-ramp shoulder into a part time travel lane, and using Intelligent Transportation Systems (ITS) technologies to designate the appropriate freeway lane for both through and exit movements, can increase the capacity of an interchange during peak periods, thereby reducing ramp delay and improving safety.

Figure 12. Photo. Ramp Configuration and Mainline Signage for Junction Control in Los Angeles, California.

(Source: Caltrans)

Source: Kittelson & Associates, Inc.

Chapter 4 Analyzing the Effects of Narrow Lane and Shoulder Width

As previously discussed, Performance-Based Practical Design (PBPD) and Performance-Based Planning and Programming (PBPP), plus the "objectives-driven, performance- based approach" to planning for operations, are all very compatible and consistent with one another. They also contain the term "performance-based;" and one of the key activities in all three approaches is to analyze and evaluate the resulting performance of various alternatives and strategies and how well they will meet the purpose and need of the project. From the perspective of narrowing lanes and/or shoulder widths to provide additional capacity within the existing footprint of an urban freeway, the operational and safety effects are perhaps the most critical aspect of this evaluation. This chapter provides an overview of some of the tools and analysis methods that can be used to estimate these effects.

OPERATIONAL EFFECTS

By definition, adding a travel lane – whether permanently or part time (as is often the case with shoulder use) – will increase overall roadway capacity, thereby reducing recurring congestion and improving operations. However, with narrower lanes, vehicles are traveling in closer proximity to each other, increasing the likelihood of lower speeds. Evaluations of narrow lane operations from the literature – as summarized in **Table A-1** in the **Appendix** and as described in the case studies from the previous chapter – bear this out. The Level of Service (LOS) is generally improved, but with a slight reduction in average speed.

Adding a lane by narrowing the existing lanes and shoulders generally improves operations and level of service, but with a decrease in average speeds.

Analyzing Operational Impacts

The PBPD approach includes the evaluation of alternative solutions and making tradeoffs and decisions based on an objective analysis of performance data. The most recent version of the *Highway Capacity Manual* (HCM – Reference 18) includes information that can be used to estimate the operational impacts of additional, but narrow, lanes. For example, **Table 7** shows the relationship between freeway lane widths, lateral clearances, and the resulting capacity and Free Flow Speed (FFS). As shown in this Table, a reduction in lane widths to less than 12' will result in a reduction in free-flow speed. This reduction in free-flow speed does reduce throughput of an individual lane; but the additional lane more than offsets this loss in "per lane" throughput and capacity.

Adjustments should also be made to estimated FFS and lane capacity for lateral clearances if the width of the right side shoulder is reduced to accommodate an additional general purpose lane, or if the shoulder itself is used as a travel lane during parts of the day. Lateral clearance is measured from the right edge of the travel lane to the edge of the paved shoulder. As shown in **Table 8**, if the right-side lateral clearance is greater than or equal to 6 ft., no reduction in free-flow speed is made. The amount of free-flow speed reduction increases as the right-side lateral clearance decreases. The HCM assumes that left-side lateral clearance is greater than or equal to 2 ft. for all cases.

Table 7. Highway Capacity Manual Adjustment to Free-Flow Speed for Lane Width. (2010 Highway Capacity manual; Exhibit 11-8) (Free-Flow Speed values are based on freeway speeds ranging from 55 mph to 75 mph)

Average Lane Width (ft.)	Reduction in FFS, f_{LW} (mi/h)
≥12	0.0
≥11–12	1.9
≥10–11	6.6

Table 8. Highway Capacity Manual Reductions in Free-Flow Speed for Right-Side Lateral Clearance on Freeways. (2010 Highway Capacity Manual Exhibit 11-9)

Right-Side Lateral Clearance (ft)	Lanes in One Direction			
	2	3	4	≥5
≥6	0.0	0.0	0.0	0.0
5	0.6	0.4	0.2	0.1
4	1.2	0.8	0.4	0.2
3	1.8	1.2	0.6	0.3
2	2.4	1.6	0.8	0.4
1	3.0	2.0	1.0	0.5
0	3.6	2.4	1.2	0.6

Adding a lane within an existing roadway footprint will typically involve both the narrowing of the travel lanes and a reduction in shoulder width (and the associated right side lateral clearance). For example, consider a scenario where a directional roadway is converted from three 12 ft. lanes and a 10 ft. right shoulder to four 10.5 ft. lanes with a 4' shoulder as shown in **Figure 13**.

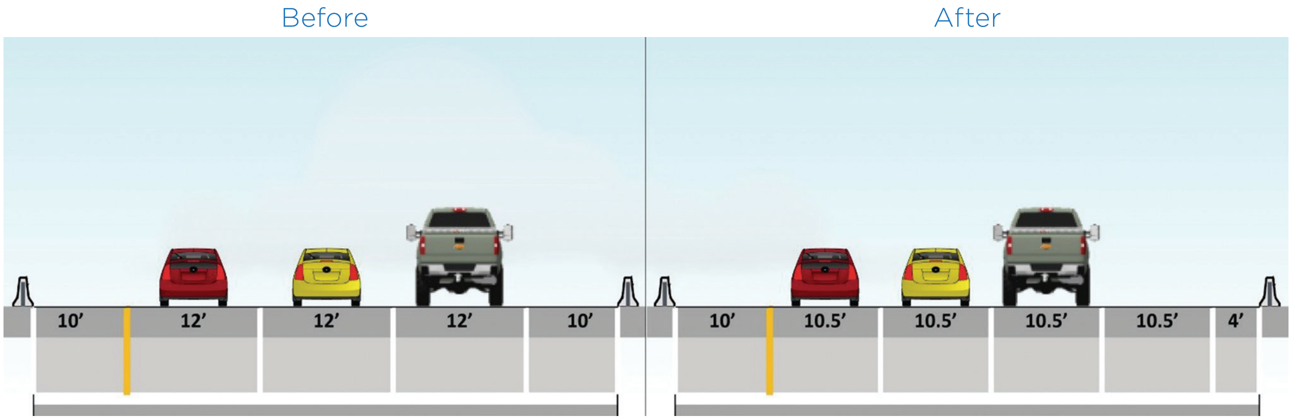

Figure 13. Diagram. Example Conversion from three Lanes to four Lanes.

Per the information in **Tables 7** and **8**, this example narrow lane conversion will reduce the free flow speed by an estimated 7.0 mph (6.6 mph from **Table 7** plus 0.4 mph from **Table 8**). Using the maximum service flow rates from HCM Exhibit 11-17 (recreated in **Table 9** below), and assuming a 10 mph reduction in FFS from 65 to 55 MPH (somewhat larger than the 7.4 mph value from **Tables 7** and **8**) and a target LOS D, the per-lane capacity will be reduced 6.4 percent from 2030 pc/hr to 1900 pc/hr (as highlighted in blue). However, converting this directional roadway from three lanes to four narrower lanes increases the total estimated directional throughput from 6090 pc/hr (2,030 X three lanes) to 7600 pc/hr (1,900 X four lanes) – nearly a 25 percent increase.

Table 9. Highway Capacity Manual Exhibit 11-17 (Maximum Service Flow Rates for Basic Freeway Segments).

FFS (mph)	Target Level of Service				
	A	B	C	D	E
75	820	1310	1750	2110	2400
70	770	1250	1690	2080	2400
65	710	1170	1630	2030	2350
60	660	1808	1560	2010	2300
55	600	990	1430	1900	2250
Note: All values rounded to nearest 10 pc/hr/ln					

It is critical to remember that when using tools such as the HCM, the baseline values and the adjustment factors – such as those shown in **Tables 8** and **9** – are statistical estimates or expected values. Moreover, it is important to remember that while the HCM can give close approximations to changes in FFS, the speed-flow curves have not been calibrated with real data for different (i.e., narrower) lane widths, and their true impact on driver behavior and the resulting capacity cannot be known for sure. As such, the HCM and other analytical tools should not be viewed as 100 percent accurate prognosticators of future conditions. The actual impact of narrow lanes may be expected to vary around the estimated values, dependent on a variety of factors. Decisions supported by the results of these analytical tools involve some degree of uncertainty, and engineering judgment is required as part of the overall PBPD process.

Impact of Trucks on Narrow Lanes Operations

One such area of uncertainty involves the operational impacts of trucks on narrow lanes operations. As discussed in NCFRP Report 31 - Incorporating Truck Analysis into the *Highway Capacity Manual* (Reference 22), most HCM chapters – including freeway – convert heavy vehicles [4] to equivalent Passenger Car Equivalent (PCE) units [5] (passenger cars per hour per lane) and add them to the passenger car volumes to obtain the total equivalent passenger car volume that is used in the HCM methodologies. The HCM analysis then estimates the capacity, density, speed, delay, and LOS for the equivalent passenger car stream. Truck speeds and delays are not isolated from the values predicted using the equivalent passenger car stream performance.

The NCFRP Report evaluates the 2010 HCM from two perspectives: its ability to predict the specific performance of trucks, and its ability to model the effects of trucks on the traffic stream. Regarding the ability of the HCM to model the effects of trucks on the traffic stream NCFRP report states the following:

- The HCM truck classification scheme is extremely simplistic, not reflecting the spectrum of truck performance capabilities in the U.S. fleet.
- The HCM PCEs are too simplistic since they do not reflect the variation in the truck fleet or the influence of truck proportion or grades on urban street PCEs.
- The HCM PCE look-up tables stop at 25 percent trucks (as a percentage of total traffic flow) even though there are many facilities in the United States where trucks routinely exceed 25 percent and can exceed 50 percent of the average daily traffic flow.
- The HCM approach is independent of significant variables like the truck type and weight-to-horsepower ratio.

Thus, while narrow lanes are addressed in the HCM, their impact on truck operations is not addressed other than incorporating an increase in PCE's, which in turn may result in a further decrease in LOS and speeds that may not be reflected in the narrow lanes analyses.

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[4] A heavy vehicle is defined in the HCM as "A vehicle with more than four wheels touching the pavement during normal operation." Three heavy vehicle types are defined: transit buses, recreational vehicles (RVs), and trucks. These three types are grouped in the HCM under the broader category of heavy vehicles.

[5] These adjustment factors vary with the percent of grade, length of grade, and the proportion of heavy vehicles in the traffic stream – from the lowest value are 1.5 PCE per heavy vehicle for grades less than 2 percent for all listed percentages of trucks and buses (1 to 25 percent), to the highest value of 7.0 PCE per heavy vehicle for an upgrade greater than 6 percent stretching for over a mile in length and 2 percent trucks. As the number of trucks increases for this steep grade, the PCE value decreases to a value of 4.0 for 25 percent trucks (The equivalents decrease as the number of heavy vehicles increases, because these vehicles tend to form platoons and have operating characteristics that are more uniform as a group than those of passenger cars)

SAFETY

The consideration of safety is arguably the primary issue involved in a PBPD-based analysis and subsequent decision to include narrow lanes and/or shoulders in a roadway design (and to subsequently approve a design exception). Evaluations of the safety of narrow lanes from the literature – as summarized in **Table A-2** in the **Appendix** and as described in the case studies from the previous chapter – show mixed results; although there appears to be a general tendency for the frequency (or number) of crashes to increase with a narrowing of lanes and shoulders (although not always); while the crash rate (e.g., number of crashes per million vehicle-miles) often decreases (again, with exceptions). It may be that even with an increase in the number of crashes, the additional throughput provided by the extra lane results in an even greater increase in the denominator of vehicle-miles of travel, resulting in a decreased crash rate [6] . There are undoubtedly several other factors that can impact crash frequency and rates associated with narrow lanes – such as volumes, speeds, the resulting decrease in congestion and improved traffic flow, the length of the narrow lane segment, horizontal and vertical curves, percentage of heavy vehicles in the traffic stream – which may explain the variations in results between different studies of the safety impacts of narrow lanes. Additionally, comparing studies and findings in terms of their statistical significance is difficult due to the different approaches used for statistical analysis.

As was the case with the operational analyses, the designer should address the entire network and system as part of the PBPD process, making sure that implementing narrow lanes to improve throughput in one segment doesn't increase congestion in a downstream segment potentially resulting in an increased number of crashes in that segment.

When reviewing and comparing safety studies of narrow lanes, it is important to note which specific measures were used in the study:

- **Crash frequency** (i.e., the number of crashes during a specific period of time).
- **Crash rate** (i.e., number of crashes per some amount of vehicle-miles of travel.)

Analyzing Safety Impacts

In performing a safety analysis of alternative lane and shoulder configurations and widths (as part of the PBPD process), it is important to understand the relationship of safety to design criteria and standards, along with the concepts of nominal and substantive safety as shown in **Figure 14** and discussed below.

Nominal Safety

The concept of nominal safety is a consideration of whether a roadway, design alternative, or design element meets minimum design criteria. According to this concept, a highway or proposed design is considered to have nominal safety if its design features (such as lane width, shoulder width, lateral clearance, etc.) meet the minimum values or ranges. The measure of nominal safety is simply a comparison of design element dimensions to the adopted design criteria; an "either – or" scenario where a design feature either meets minimum criteria or it does not. Thus, narrowing one or more lanes of an urban freeway to less than the standard 12 ft. width (per the Green Book) would not meet the concept of nominal safety.

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[6] The additional throughput may be the result of freeing up a bottleneck or other constraint to flow, induced demand, or some combination.

Figure 14. Graph. Nominal and Substantive Safety.

In actuality, the safety effects of incremental differences in a given design dimension can be expected to produce an incremental, not absolute, change in safety. The nominal safety concept is limited in that it does not examine or express the actual or expected safety performance of a highway. This second dimension of safety is critical to making good decisions regarding design exceptions.

Substantive Safety

Substantive safety is defined as the expected, or estimated long-term average, safety performance of a roadway. The concept of substantive safety encompasses methods for estimating the following expected quantitative measures:

- Crash frequency (number of crashes per mile or location over a specified time period).
- Crash type (run-off-road, intersection, pedestrian, etc.).
- Crash severity (fatality, injury, property damage).

Understanding a location's substantive safety and making judgments about whether it meets expectations may involve formal comparisons of its crash profile with aggregate data for facilities with similar characteristics (e.g., traffic volumes, number of current and proposed lanes and widths, location (urban, rural, suburban), inclusion of Transportation System Management and Operations (TSMO) strategies, and terrain); predictive methods such as those presented in the AASHTO Highway Safety Manual (HSM); or some combination.

In evaluating project alternatives from a substantive safety perspective, the practitioner is interested in the future safety performance of a facility and comparing that future performance for alternative geometrics, lane and shoulder widths, operational strategies, etc. Crash history is used to identify and diagnose safety concerns on an existing facility; but it may not be the most accurate approach for estimating long-term average safety performance. The HSM argues for the value of using predictive methods in addition to crash history, to improve accuracy and precision of estimates.

Highway Safety Manual

The HSM (Reference 20) complements design guidelines, such as the AASHTO Green Book, by allowing a more scientifically rigorous methodology to quantify the "safety effects" of various design choices as part of the PBPD process. The 2014 Supplement to the HSM, 1st Edition, provides a structured methodology and specialized procedures to estimate the expected average crash **frequency** for various freeway facilities.

The HSM freeway chapters provide Safety Performance Functions (SPF) for 4- to 10-lane freeway facilities that account for several variables that need to be considered when looking at cross-section alternatives, including the following:

- Average Annual Daily Traffic (AADT),
- Proportion of AADT during high-volume hours,
- Number of through lanes,
- Distance to median barrier,
- Lane width, and
- Shoulder width (left and right).

The HSM also provides Crash Modification Factors (CMS's) for various roadway treatments. These are used to estimate the expected number of crashes after implementing a given treatment. A CMF less than 1.0 – the value that corresponds to a 12-ft. lane width for freeways, a 6-ft. width for inside shoulders, and a 10-ft. width of outside shoulders – indicates that a treatment has the potential to reduce the **number of crashes**. **Figures 15 -17** show the CMF's for lane widths, inside shoulder widths, and outside shoulder widths, respectively. Looking at the CMF alone, narrowing a freeway lane to under 12 ft. and/or narrowing the outside shoulder to less than 10 ft. will result in an increase in the number of crashes (i.e., the associated CMF values are greater than 1.0.)

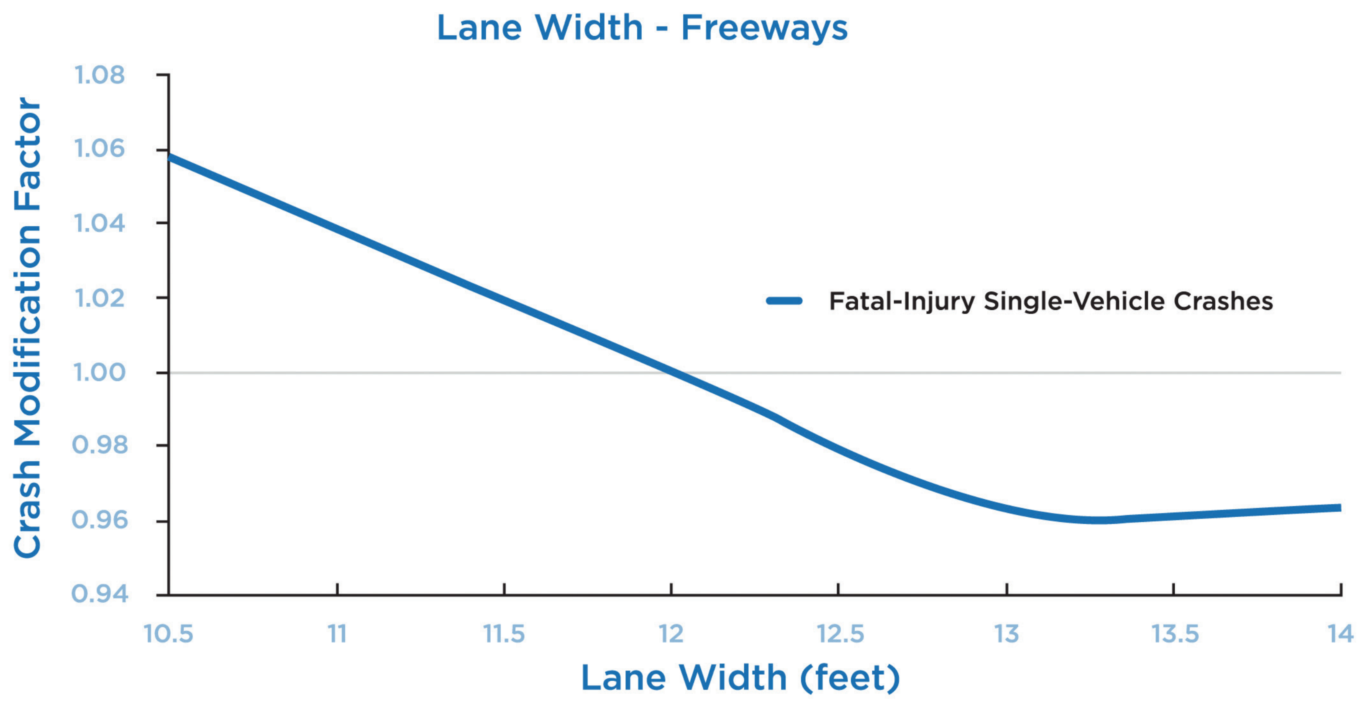

Figure 15. Graph. Crash Modification Factors for Lane Widths.

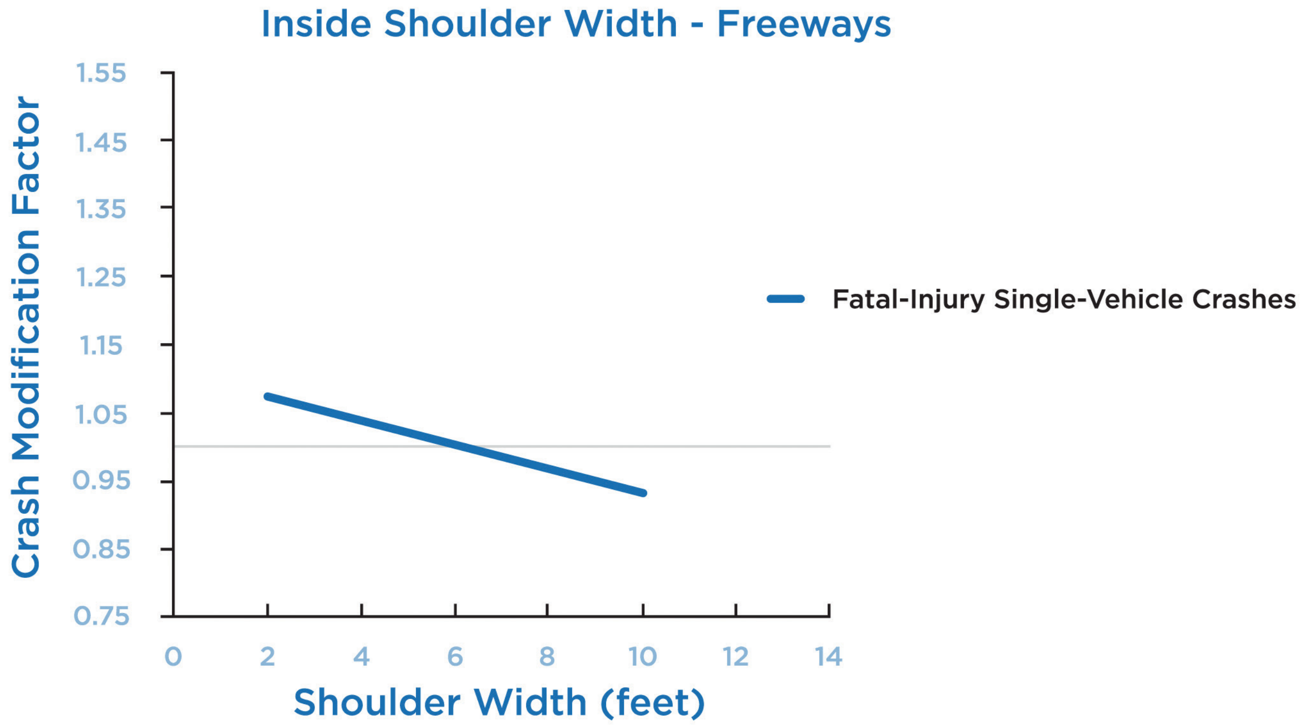

Figure 16. Graph. Crash Modification Factors for Inside Shoulder Widths.

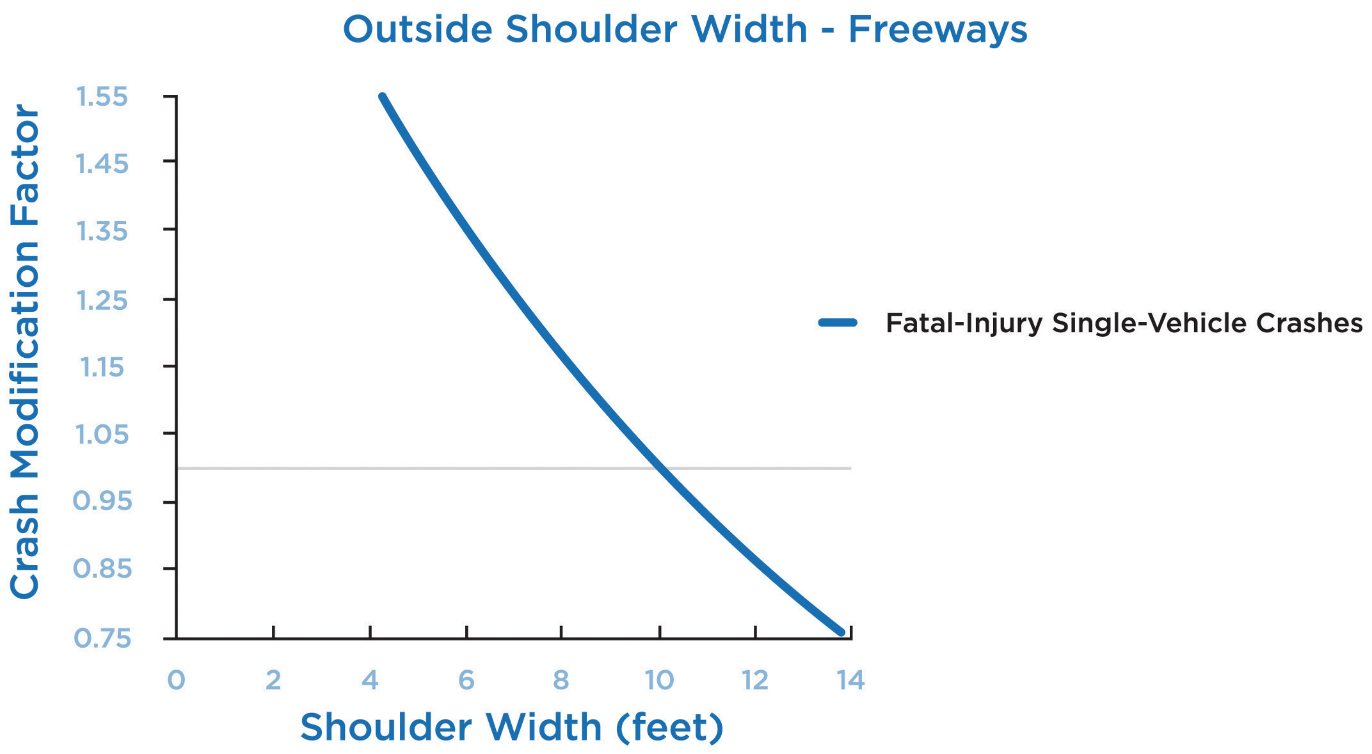

Figure 17. Graph. Crash Modification Factors for Outside Shoulder Widths.

HSM Evaluation of Narrower Lanes and Narrower Shoulders

The HSM freeway crash prediction model can be used to assess the change in crash frequency and severity associated with increasing the number of freeway lanes by reducing lane and shoulder widths. The before and after alternatives listed in **Table 10** were analyzed for before conditions of a 4-lane freeway, 6-lane freeway, and 8-lane freeway (bi-directional in each case) with an increase in the number of lanes (one per direction) by narrowing the current lane widths from 12 ft. to 11 ft. and narrowing the shoulders so as to add the lane within the existing roadway footprint (i.e., no widening). **Figures 18**, **19**, and **20** illustrate the predicted frequency of Fatal and Injury (FI) Crashes and Property Damage Only Crashes (PDO) for each freeway alternative shown in the Table.

Table 10. Inputs for Narrow Lane / Shoulder Alternative.

Variable	Narrow Lane / Shoulder Alternatives					
	4-Lane Freeway		6-Lane Freeway		8-Lane Freeway	
	Before	After	Before	After	Before	After
Number of Lanes (bi-directional)	4	6	6	8	8	10
Lane Width	12	11	12	11	12	11
Right Shoulder Width	10	4*	10	4*	10	4*
Left Shoulder Width	6	3*	6	4*	6	5*

* *These are the narrowest shoulder widths for which the HSM has modification factors*

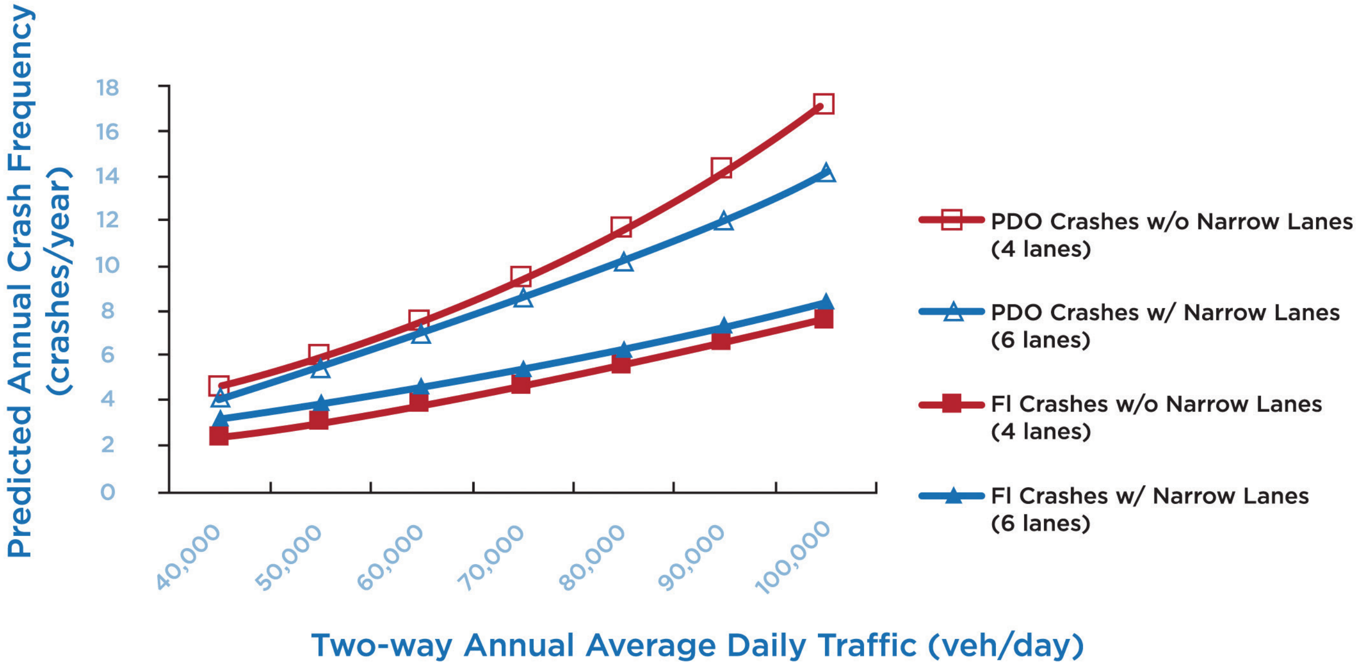

Figure 18. Graph. Predicted Crash Frequency With and Without Narrow Lanes and Narrow Shoulders (Conversion from 4-lane Freeway to 6-lane Freeway).

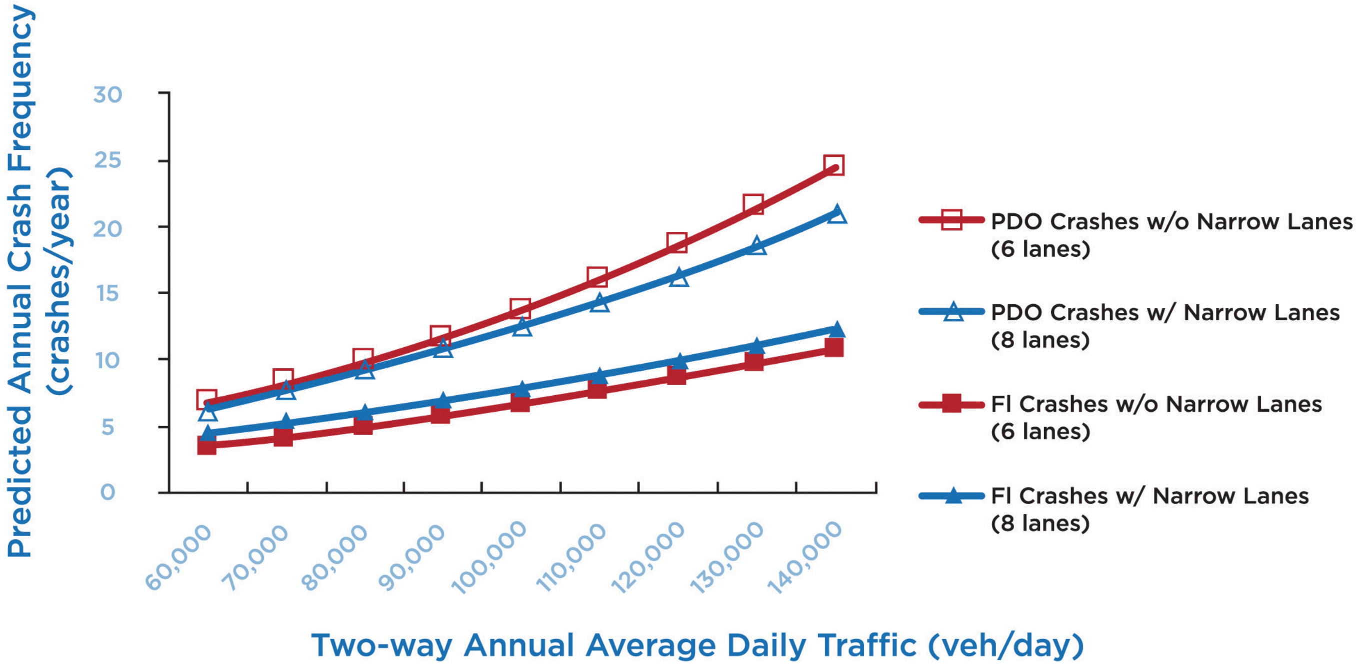

Figure 19. Graph. Predicted Crash Frequency With and Without Narrow Lanes and Narrow Shoulders (Conversion from 6-lane Freeway to 8-lane Freeway).

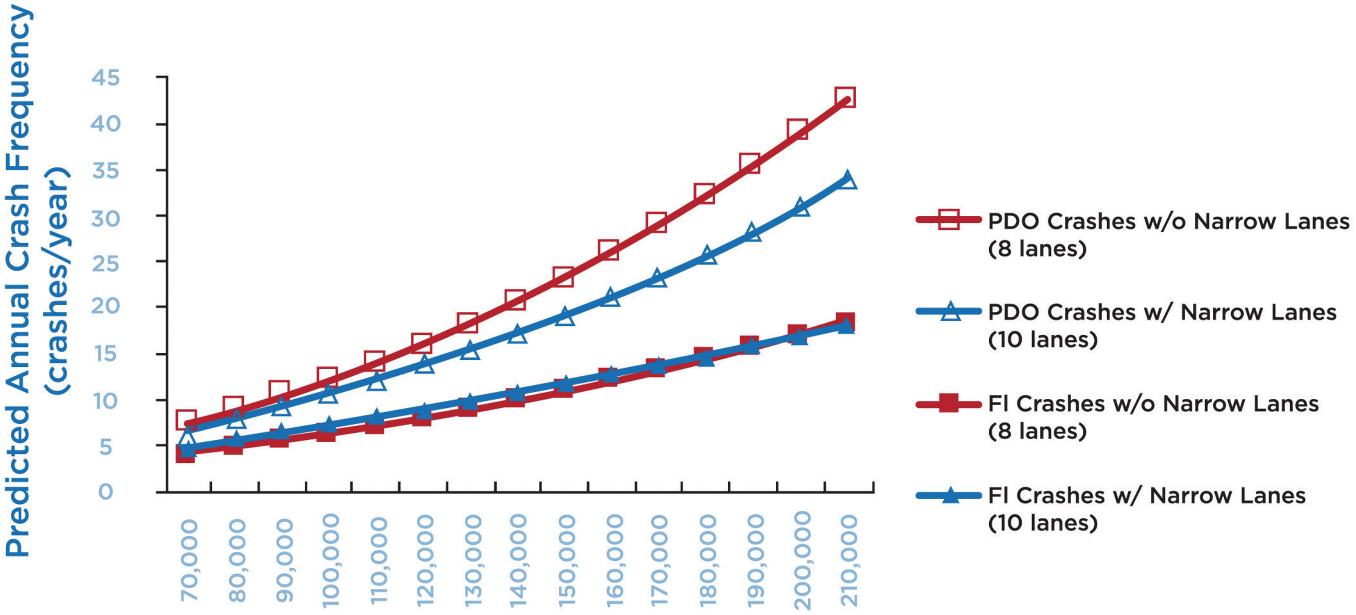

Figure 20. Graph. Predicted Crash Frequency With and Without Narrow Lanes and Narrow Shoulders (Conversion from 8-lane Freeway to 10-lane Freeway).

The HSM freeway crash prediction models estimate that narrowing lanes and shoulder widths to create an additional lane in each direction might have the following influence on crash frequency and severity:

- Reduce the frequency of PDO crashes
- Increase the frequency of FI crashes when converting existing 4- or 6-lane freeways (i.e., two lanes and three lanes in each direction)
- Have little to no effect on the frequency of FI crashes when converting existing 8-lane freeways (i.e., four lanes in each direction)

While Figures 15 and 17 indicate an increase in the number of crashes with a narrowing of travel lanes to less than 12 ft. or a narrowing of the outside shoulder to less than 10 ft., and Figures 18-20 show a slight decrease in PDO crashes (but an increase in injury crashes); there are other considerations in any safety analysis of narrow lanes – specifically, that the increase in the number of lanes (and available capacity) may also reduce congestion, which in turn may improve overall safety.

Figure 21 summarizes the scenarios shown in previous Table 12 and shows the safety effects of adding a lane by narrowing the general purpose lanes to 11 feet and reducing shoulder widths. The point at which each line crosses the 0 percent mark on the y-axis indicates the AADT above which the implementation of narrow lanes and shoulders – with an increase in the number of lanes – would be expected to decrease crash frequency [7]. In general, the greater the average daily traffic – and presumably the greater level of congestion during the "before" condition – the more likely that the safety benefits from reduced congestion (resulting from an additional lane) will outweigh the potential safety issues associated with narrower lanes and shoulders.

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[7] In one respect, Figure 21 does not appear intuitive; that the AADT threshold between an increase to a decreases in crash frequency is greater for the conversion from six to eight lanes (three to four lanes in each direction) than for the eight to ten lane conversion. The HSM is all field-data based, and sometimes the data yields slightly unpredictable results. Another way of looking at this is it reflects the model prediction that an eight- to ten-lane conversion is expected to have a greater reduction in crashes than a six- to eight-lane conversion.

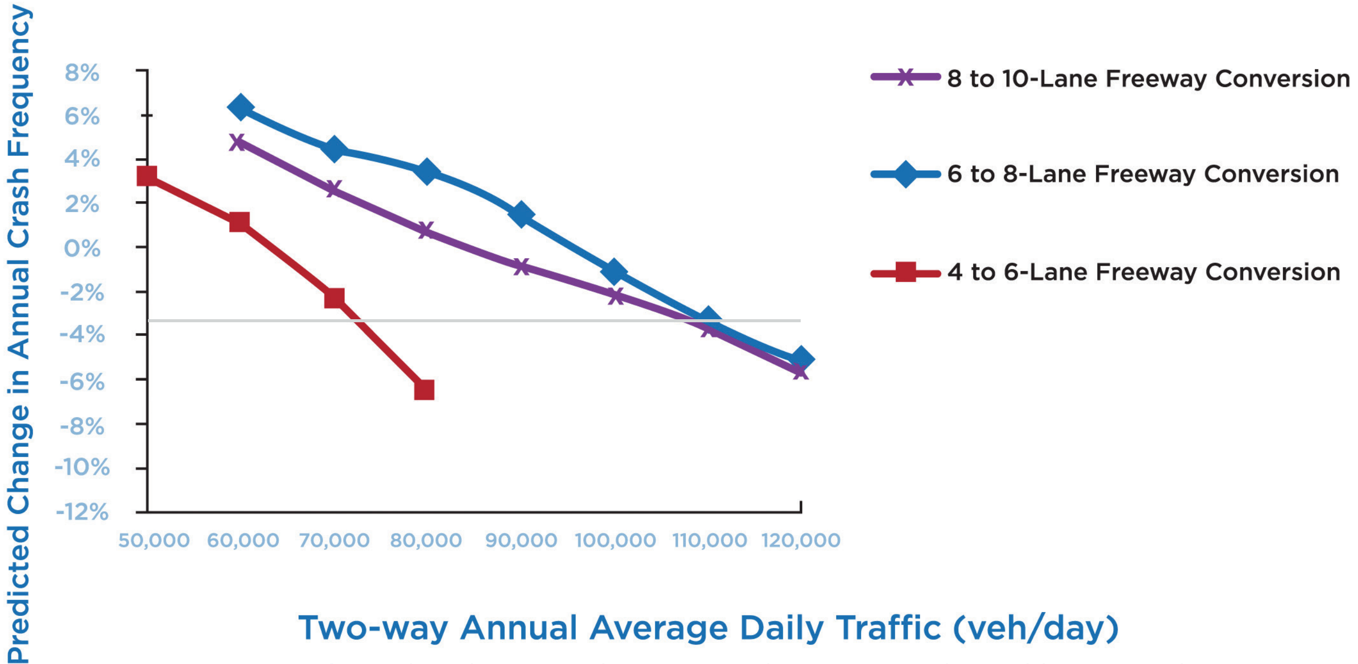

Figure 21. Graph. Predicted Percent Change in Crash Frequency when Adding a Lane by Using the Right Shoulder and Narrowing Lanes.

For the example identified in previous **Figure 13**, adding a fourth lane to a the 3-lane directional roadway (as shown in the line with "diamonds" in **Figure 21** – "6 to 8 Lane Freeway Conversion"), would be predicted to result in a net reduction in the crash frequency if the two-way average annual daily traffic was greater than approximately 95,000 vehicles per day.

Other considerations in performing a safety analysis of narrow lanes include:

- As addressed in an August 2011 article in the Journal of Economic Literature (Reference 23), even if narrower lanes and shoulders increase accident rates by 10 percent, applying standard parameters for costs of accidents, these extra costs may not reverse the advantage of a "narrow" design (in terms of travel time savings and the additional costs associated with widening to maintain 12-foot lanes).
- The predictive methods in the HSM do not include the effect of traffic volume variations throughout the day (other than a factor for the proportion of AADT during peak periods) or the percentages of different vehicle types. Per the HSM, these variables were not necessarily excluded because they have no effect in crash frequency; it may merely mean that the effect is not fully known or has not been quantified at this time.

Impact of Trucks on Narrow Lanes Safety

Trucks are wider than cars. Federal size regulations for commercial motor vehicles stipulate a maximum width of 2.6 meters (102.36 inches, or 8.53 feet), excluding mirrors and other safety devices. Thus, with a 12 foot lane, a truck driving in the center will have approximately 21 inches on either side between the truck and the adjacent lanes (not counting mirrors). If the lanes are narrowed to 11 feet, this clear distance to the adjacent lanes is reduced to 15 inches (and even less between mirrors of trucks in adjacent lanes). Thus, narrower lanes may make it more difficult for the drivers of heavy vehicles (including buses) to position their vehicle completely within their lane. A truck encroaching into an adjacent lane can cause a sideswipe crash. Moreover this is probably a greater concern on tight horizontal curves.

The literature on the subject of narrow lanes, trucks, and safety is somewhat sparse (e.g., as noted above, the HSM does not address the proportion of trucks.) Some highlights from the available literature are noted below:

- The 1995 NCHRP Report 369 ("Use of Shoulders and Narrow Lanes to Increase Freeway Capacity" – Reference 3) studied several altered and unaltered [8] corridor segments, concluding that "truck accident rates are almost always higher on altered sections compared with unaltered". At the same time, looking at the results available in the report, there does not seem to be any correlation between the change in truck accident rate and the percentage of trucks (up to 10 percent trucks, the greatest percentage of truck traffic for the study sites with crash data for trucks).
- As reported Ng and Small (Reference 23), on the New Jersey Turnpike, which has two parallel roadways (both with standard lane widths) of which one is for cars only, accident rates are higher in the lanes that allow trucks.
- A Florida study of the influence of arterial lane width on bus safety (Reference 24) suggests a strong relationship between lane width and bus vehicle safety, noting that the narrower the lane width, the higher the likelihood of having bus sideswipe and mirror crashes. The results indicate that narrow lane widths, especially lane widths of 10 feet and narrower, are overrepresented in the occurrences of bus sideswipe crashes.

Based on this admittedly limited documentation, coupled with the notion discussed above that narrow lanes reduce the margin of error for a heavy vehicle operator in terms of keeping the truck in the lane, an analysis of roadway design alternatives involving narrow lanes should consider the safety impacts of trucks, particularly when the percent of trucks in the traffic flow is greater than five to ten percent.

Considerations in this regard include the length of the segment and the horizontal and vertical alignments throughout the segments. Potential mitigation measures include the use of dynamic speed limits wherein the speed limits are lowered depending on the percentage of truck traffic in the flow, the horizontal and vertical curvature, and weather and visibility conditions. Consideration should also be given to keeping one or two of the lanes – including possibly a shoulder lane, assuming that the shoulder was constructed at full depth and can accommodate trucks – at 12-feet or greater, and restricting trucks to those lanes.

Transportation Systems Management and Operations and Safety

Implementing TSMO strategies (refer to previous **Table 5**) may provide additional safety benefits beyond the changes in crash frequency predicted by the HSM tools, and should be considered as part of the PBPD activities and the associated trade-off analyses. **Table 11** shows the safety benefits resulting from several TSMO applications.

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[8] Unaltered refers to standard 12-foot lane; altered refers to narrowed lanes and shoulders.

Table 11. Examples: Safety Benefits of Transportation System Management and Operations Strategies.

TSMO Strategy	Location	Safety Benefits
Traffic Incident Management (TIM) (Reference 21)	General	• Incident duration reduced 30–50 percent (For example, average total incident duration in New Jersey has declined 48 percent, from 2.75 hours (1995) to 1.44 hours (2008) • Effective TIM reduces the occurrence of secondary crashes. The likelihood of a secondary crash increases by 2.8 percent for each minute the primary incident continues to be a hazard. • Faster detection of and response to highway incidents saves lives.
Ramp Metering (Reference 7)	Portland, Oregon	• 43 percent reduction in peak period crashes
	Seattle, Washington	• 39 percent reduction in crash rate
	Minneapolis, Minnesota	• 24 percent reduction in peak period crashes
Dynamic Speed Limits and Dynamic Lane Assignment (Reference 7)	Seattle, Washington (Seven mile segment of I-5) This corridor was already actively managed via ramp metering and a robust incident management program.	• A before-and-after study showed total crashes decreased 4.1 percent along the ATM segment. (During the same period, the southbound segment of I-5 – without ATM – experienced a 4.4 percent increase in the number of crashes.)
	London, England (M-25 Orbital)	• Injury crashes decreased by 10 percent. • Damage-only crashes decreased by 30 percent.
Dynamic Shoulder Lanes with Dynamic Speed Limits and Dynamic Lane Assignment (Reference 7)	Minneapolis, Minnesota I-35W (with speed advisories (not legal limits) and shoulder used as part time HOT)	Crash reductions in the 6-month post-deployment period were as follows: • 9 percent for fatal plus injury crashes • Greater than 20 percent for property damage only, and for total crashes (when the change in vehicle miles traveled was accounted for)
	General – Results of 2006 FHWA Scanning Tour of Europe	• A decrease in primary incidents of 3 to 30 percent. • A decrease in secondary incidents of 40 to 50 percent.

RELIABILITY

The concept of travel time reliability has been receiving significant attention of late, particularly as part of the Strategic Highway Research Program (SHRP 2). The overall goal of the SHRP 2 Reliability program is to reduce congestion through incident reduction, management, response, and mitigation, thereby significantly improving travel time reliability for many types of person and freight trips on the nation's highways. Per SHRP documentation: "travel time reliability refers to how travel time varies over time and the impacts of this variance on highway users. In other words, for repeated travel or vehicles making similar trips, there is an underlying distribution of travel time for a particular type of trip within a specific time period between two points. Individual travelers respond differently to the factors and uncertainties associated with the travel time.

Considering the example in previous **Figure 13** (three lanes to four narrower lanes), and assuming that this conversion covers a five-mile segment with a peak hour volume of 5500 pce (compared to the aforementioned before capacity of 6090 pce/hr at LOS D), and an average travel speed of 40 mph during the peak hour; using equations identified in Reference 22 [9] , the Travel Time Index (TTI) for this before condition is estimated as 1.4 (indicating that the average peak hour travel time is 6.4 minutes, nearly two minutes greater than the free flow travel time of 4.6 minutes).

Travel Time Index

The ratio of the travel time during the peak period to the time required to make the same trip at free-flow speeds

Following the conversion to four lanes, it is assumed that the peak hour volume increases to 6200 pce (i.e., the result of some induced demand brought about by the additional capacity – now at 7600 pce/hr. – provided by the fourth lane), with the directional roadway now operating at a reduced FFS of 55 MPH (due to the narrower lanes) during the peak period, resulting in a travel time of 5.45 minutes over the 5-mile segment. The new average annual mean travel time for the after condition is calculated as 5.8 minutes (with a TTI_m of 1.067), an improvement over the before condition.

These equations and the associated reliability measures do not take into consideration the possibility of an increase in crashes, thereby causing non-recurring congestion and increased travel times (and less reliability. Moreover, a large reduction in shoulder width – such as occurs in the example (i.e., where the shoulder is reduced from 8 ft. to 2. ft.) – may negatively impact reliability. For example, there may no longer be a safe refuge for emergency stops and broken-down vehicles outside the traveled way, nor space for drivers of errant vehicles to make steering corrections before leaving the roadway. Moreover, without a wide shoulder, response times for emergency service vehicles – which often use the shoulder to bypass slow traffic when responding to a crash scene – may increase, thereby increasing incident-related congestion and reducing reliability. Accordingly, enhanced incident management strategies (e.g., frequent service patrols), dynamic lane assignment allowing the closure of a lane upstream of a crash site, and/or emergency refuge areas should be considered when analyzing the possibility of adding a lane via narrow lane and shoulder widths.

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[9] The average annual mean travel time index (TTI_m) =
1 + FFS * (RDR + IDR), where:
FFS = free flow speed (mi. / hr.)
RDR = recurring delay rate (hr. / min.)
IDR = incident delay rate (hr. / min.)
RDR is calculated using: RDR = 1/S – 1/FFS
IDR is calculated using: IDR = [0.020 – (N – 2) * 0.003] * X12
Where:
S = peak hour average speed
N = number of lanes (between 2 and 4)
X = peak hour volume to capacity ratio

Free flow travel time (in minutes) is calculated as [Length of Segment (mi.) / FFS] * 60 minutes / hr.

Source: Kittelson & Associates, Inc.

Chapter 5 Summary and Conclusions

Implementing narrow lanes and shoulders to add a lane within an existing roadway footprint can be a viable and cost effective approach to reduce congestion. In addition to improving mobility, narrow lanes and shoulders may also be implemented with minimal negative impacts on safety and reliability. Potential scenarios for implementing narrow lanes include the following:

- Adding a general purpose lane to increase capacity and reduce recurring congestion. This can be for an extended section of roadway, or for a relatively short area as part of bottleneck reduction.
- Adding a managed lane, such a High Occupancy Vehicle (HOV) or High Occupancy Toll (HOT) lane.
- Adding a lane in and/or within the vicinity of an interchange, to provide additional capacity on a ramp, an auxiliary lane between closely-spaced interchanges, or additional capacity beyond the interchange to prevent traffic from backing up into the interchange area.

Narrow lanes and shoulders should not be implemented without first conducting a thorough evaluation and analysis of their ability to meet the project purpose and needs, such as provided by a Performance-Based Practical Design (PBPD) approach. Each site and segment must be evaluated individually. Analysis considerations should include:

- Existing conditions (e.g., number of lanes and widths, shoulder widths, horizontal and vertical site distance, lateral clearance, locations and causes of congestion, traffic volumes and mix, lane and balance, current safety issues / types and causes of crashes, pavement joints and seem patterns, distances between upstream and downstream ramps.
- Alternative configurations of narrow lanes and shoulders. In this regard, NCHRP Report 369 (Reference 3) recommends the following priority order for narrowing: narrow to 11 foot lanes, reduction in width of the left shoulder, reduction in width of the right shoulder.
- Length of treatment (to ensure that a bottleneck is not merely relocated to some other location)
- Estimated changes in level of service, capacity and crash frequencies / rates (and other performance measures) using appropriate analysis tools
- Potential Transportation System management and Operations (TSMO) strategies and Intelligent Transportation Systems (ITS) technologies – in advance of and through the implementation area – to improve the operations, reliability, and safety of the narrowed lane / shoulder configuration
- Estimated costs

This information will help in developing and getting approval of any design exceptions.

It is also important to involve emergency response personnel, enforcement personnel, and operations and maintenance staff in the analysis and evaluation. Public information and outreach to educate and alert the driving public of the changes should also be addressed.

Appendix Summary of Impacts Resulting from Narrow Lanes and Shoulders

Table A-1. Summary of Operational Impacts Resulting From Narrow Lanes and Shoulders.

Location	Configuration	Results and Lessons Learned
Houston, Texas US 59 (Reference 1)	3- 12' lanes to 4-10.5' lanes 4- 12' lanes to 5-10.5' lanes Narrowed shoulders (Refer to Figure 1)	• The level of service generally improved, with the major operational benefits realized in the peak periods. • Total delay in one section was not reduced significantly, with the bottleneck merely being shifted. (Thus the need to address the entire "system" as part of the PBPD process, and not just an isolated problem location) • One potential operational problem was that the altered outside lane was composed partly of the right shoulder and partly of the mainline pavement, and each of these pavement materials were a different texture and contract. At one of the entrance ramps, the contrast appeared to guide the entrance ramp traffic out of the rightmost lane.
Texas - Multiple locations in Dallas, Houston, and San Antonio, Texas (Reference 5)	Not a before and after analysis of conversions from wider to narrower lanes; but a comparison of different roadway segments – some with 12' lanes, others with 11' lanes.	• Reduction in speed of about 2.2 mph for 11-ft lanes as compared with 12-ft lanes. • A reduced lane and right-side lateral clearance combination directly corresponds to a reduction in the capacity of the travel lanes.
Multiple locations (Reference 3)	NCHRP study of freeway segments throughout the US where lanes were narrowed to 11' to increase capacity.	• Altered sites (i.e., narrower lanes) exhibited slightly lower speeds for a given volume range and a slightly greater tendency to fall into LOS F conditions. • Field observations indicate that operational impacts of reduced shoulder or lane widths are most notable in the transition area (i.e., the beginning of the altered segment).

Table A-1. Summary of Operational Impacts Resulting From Narrow Lanes and Shoulders. (continuation)

Location	Configuration	Results and Lessons Learned
General (Reference 17)	FHWA evaluation of the operational and safety characteristics of shoulders used as part time travel lanes.	• The functional capacity of most shoulder lanes is approximately one-half to two-thirds that of a normal general-purpose lane, depending on the lane's geometric characteristics. • Speeds in the shoulder lane also tend to be 5 to 10 mi/h (8 to 16 km/h) slower than the adjacent general-purpose lanes. • The limited functional capacity may be due in part to the geometric deficiencies, such as narrow width, close proximity of fixed objects, or lack of continuity associated with the lane, and to the fact that motorists may feel uncomfortable using the shoulder as a temporary travel lane.

Table A-2. Summary of Safety Impacts Resulting From Narrow Lanes and Shoulders.

Location	Configuration	Results and Lessons Learned
Multiple locations (Reference 3)	NCHRP study of freeway segments throughout the US where lanes were narrowed (i.e., "altered") to 11' to increase capacity.	• Truck crash rates are almost always higher on altered sections (i.e., narrower lanes) compared with unaltered (12 ft. lanes). • Crash rates for altered sites were higher in three out of the five corridors studies, two of which used shoulders and narrow lanes on a continuous basis for an extended length (more than a mile). • In two locations where narrow lanes and shoulders were used to relieve specific bottlenecks and improve lane continuity, the result was a "smoothing of traffic with a better balance between supply and demand, and the crash rate decreased slightly. • A difference in lane width (12 to 11 feet) by itself had no significant impact. • Crash rates for altered sites tend to be somewhat higher than unaltered sites. However, if strategies are carefully applied in concert with lane balance and lane continuity concepts, rates for altered sections may be lower than for unaltered.

Table A-2. Summary of Safety Impacts Resulting From Narrow Lanes and Shoulders. (continuation)

Location	Configuration	Results and Lessons Learned
Houston, Texas US 59 (Reference)	3- 12' lanes to 4-10.5' lanes 4- 12' lanes to 5-10.5' lanes Narrowed shoulders (Refer to Figure 1)	• The number of crashes and the crash rates declined in the altered sections during the two years following modification for each of the four time periods studied (24 hour, peak, daytime, nighttime). • The larger reductions in crash frequencies occurred during the peak periods (the same period as the greatest operational benefits). • No significant change in the number or rate of severe accidents. • The upstream segment entering the modified section (with narrow lanes and shoulders) also experienced a reduction in crashes and crash rate – likely attributed to the better operations in the downstream segments where capacity had been increased by the additional lane. • The crash rate in the section downstream from the modified segments experienced a significant increase in the crash rate, with the greatest increase occurring the two peak hours – likely attributed to an increase in demand and flow (from the modified segments) but with no increase in capacity.
Los Angeles, California – Multiple segments (Reference 4, 16)	5 lanes converted to 6 lanes 4 lanes converted to 5 lanes 12' lanes to 11' lanes Additional lane used as HOV in nearly all cases. (Refer to Figure 1)	• The projects converting four lanes to five lanes, on average, resulted in increases of 10 to 11 percent in crash frequency, which was found to be statistically significant. • The five- to six-lane conversion projects resulted in an increase in crash frequency of 3 to 7 percent, not statistically significant. • The use of the added lanes as HOV lanes --- and the associated increase in speed differential between the HOV and general purpose lanes – may be an explanation for the increase crash frequency.

Table A-2. Summary of Safety Impacts Resulting From Narrow Lanes and Shoulders. (continuation)

Location	Configuration	Results and Lessons Learned
Various locations in California, Texas, and Arizona (Reference 19)	Lane widths reduced from 12' to 11' (and sometimes 10.5') to accommodate an additional lane.	• Analyses focused on crash rates (i.e., crashes per million vehicle miles). • Left shoulder removals (all but 2 feet) appear to be safe and effective capacity improvements. On severely congested freeways (ADT greater than 20,000 vehicles per lane per day) left shoulder removals appear to aid safety if congestion levels are removed. • The use of 11-foot lanes as a remedial measure to reduce congestion appears to operate safely.
Texas - Multiple locations in Dallas, Houston, and San Antonio, Texas (Reference 5)	Not a before and after analysis of a conversion to narrower lanes; but a comparison of different roadway segments – some with 12' lanes, others with 11' lanes.	• When comparing freeways with 12 ft. and 11 ft. lanes, there is an increase in the number of fatal and serious injury crashes in the segments with 11ft. lanes, all other roadway characteristics being equal. The increase in crash frequency ranges from 5 percent for 2-lane freeways, up to 12 percent for 5-lane freeways.

References

1 - “The Use of Freeway Shoulders to Increase Capacity;” McCasland, William R; FHWATX-78-210-2; September 1978

2 - http://h1rehab.com/

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