SAFETY ANALYSIS NEEDS ASSESSMENT FOR TRANSPORTATION SYSTEMS MANAGEMENT AND OPERATIONS

FHWA Safety Program

U.S. Department of Transportation
Federal Highway Administration

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Quality Assurance Statement

TECHNICAL DOCUMENTATION PAGE

1. Report No. FHWA-SA-19-041	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Safety Analysis Needs Assessment for Transportation Systems Management and Operations		5. Report Date October 2019 6. Performing Organization Code
7.Author(s) R.J. Porter, Michael Dunn, Ian Hamilton, Jeff Gooch, and Vikash Gayah		8. Performing Organization Report No.
9. Performing Organization Name and Address Vanasse Hangen Brustlin, Inc (VHB) 8300 Boone Blvd., Ste. 700 Vienna, VA 22182-2626		10. Work Unit No. 11. Contract or Grant No. DTFH61-16-D-00005 (VHB)
12. Sponsoring Agency Name and Address Federal Highway Administration Office of Safety 1200 New Jersey Ave., SE Washington, DC 20590		13. Type of Report and Period Final Report, July 2017 – October 2019 14. Sponsoring Agency Code FHWA
15. Supplementary Notes The contract manager for this report was Jerry Roche, Federal Highway Administration Office of Safety.		

16. Abstract

This report documents a safety analysis needs assessment for Transportation Systems Management and Operations (TSMO). It includes the following key content: syntheses of strategy-specific safety performance knowledge and capabilities (Chapter 2), a synthesis of research on interrelationships between measures of traffic operational performance and safety performance (Chapter 3), a synthesis of research relating weather and weather-related road conditions to safety performance (Chapter 4), a synthesis of research, tools, and challenges in estimating safety performance effects of TSMO that result from changes in travel choices and traffic demand patterns (Chapter 5), and TSMO-related safety performance analysis gaps, limitations, and needs (Chapter 6). The literature contains various types of safety performance evaluations for some TSMO strategies. However, there are only a limited number of published safety performance evaluations that are robust enough to inform future evaluations and/or the development of quantitative safety performance predictions. There is a need for safety and operations staff from local, State, and Federal agencies, as well as researchers and other stakeholders, to engage in regular dialog on safety performance evaluation needs and priorities specific to TSMO strategies. The needs assessment also identified five categories of methodological needs for analyzing the safety performance of TSMO: 1) "sub-annual" safety data collection and analysis, 2) safety performance effects beyond the site level, 3) safety performance effects of operational conditions, 4) study design and statistical analysis, and 5) mechanistic approaches to safety performance analysis of TSMO. The report concludes with recommended next steps in continuing to advance safety performance analysis capabilities of TSMO. Readers of this report will gain an increased understanding of existing knowledge, analysis methods, and research needs in the context of quantifying the safety performance effects of TSMO.

17. Key Words:	18. Distribution Statement No restrictions.		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 220	22. Price

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

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

AADT	annual average daily traffic
AASHTO	American Association of State Highway and Transportation Officials
ASCT	Adaptive Signal Control Technology
ATDM	Active Transportation and Demand Management
AVL	automated vehicle location
AWIS	Automated Work Zone Information System
AWS	advance warning signal
B/C	benefit-cost
BRT	bus rapid transit
CMF	crash modification factor
CVS	coefficient of variation of speed
DCM	Data Capture and Management
DIC	Deviance Information Criterion
DOT	Department of Transportation
DRAC	deceleration rate to avoid a crash
DRCOG	Denver Regional Council of Governments
DTA	dynamic traffic assignment
EB	empirical Bayes
EDC	Every Day Counts
EMS	emergency management services
EOQ	end-of-queue
EOQWS	end-of-queue warning system

FAA	Federal Aviation Administration
FARS	Fatal Accident Reporting System
FAST	Fixing America's Surface Transportation
FAST	fixed automated spray technology
FHWA	Federal Highway Administration
FI	Fatal and injury crashes (includes KABC crashes on the KABCO scale)
HCM	*Highway Capacity Manual*
HOT	high-occupancy toll
HOV	high-occupancy vehicle
HSM	*Highway Safety Manual*
ICWS	intersection conflict warning systems
iMiT	Incident Management Integration Tool
ITRD	International Transport Research Documentation
ITS	intelligent transportation systems
ITS JPO	Intelligent Transportation Systems Joint Program Office
KA	fatal and suspected serious injury crashes (KA on the KABCO scale)
KABCO	all possible severity levels of a crash determined by the highest injury severity for any person involved in the crash: K = fatal A = suspected serious injury B = suspected minor injury C = Possible injury O = No apparent injury
LOS	level of service
LUCS	lane use control signals
MAP-21	Moving Ahead for Progress in the 21st Century

MARS	multivariate adaptive regression splines
MLPNN	multilayer perceptron neural networks
MnDOT	Minnesota Department of Transportation
MoDOT	Missouri Department of Transportation
MPC	model predictive control
MPO	Metropolitan Planning Organization
MV	multiple-vehicle
NB	negative binomial
NCHRP	National Cooperative Highway Research Program
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
PDO	property damage only
PET	post-encroachment time
PRS	portable rumble strip
PTSU	part-time shoulder use
RSAPv3	Roadside Safety Analysis Program version 3
RTM	regression to the mean
RWIS	Road Weather Information System
Safety PM Final Rule	National Performance Management Measures: Highway Safety Improvement Program Final Rule
SCATS	Sydney Coordinated Adaptive Traffic System
SPF	safety performance function
SSAM	Surrogate Safety Assessment Model
SV	single-vehicle

TCRP	Transit Cooperative Research Program
TIM	traffic incident management
TkSP	truck signal priority
TLR	truck lane restriction
TPF	Transportation Pooled Fund
TRB	Transportation Research Board
TRID	Transport Research International Database
TSMO	Transportation Systems Management and Operations
TSP	transit signal priority
TTC	time to collision
USDOT	United States Department of Transportation
VAMS	Value Added Meteorological Services
V/C	volume-to-capacity
VMT	vehicle miles traveled
VEWF	Vehicle Entering When Flashing
VSL	variable speed limits
V2I	vehicle-to-infrastructure
V2V	vehicle-to-vehicle
WRT	with respect to
WxDE	Weather Data Environment

EXECUTIVE SUMMARY

Moving Ahead for Progress in the 21st Century (MAP-21) defines Transportation Systems Management and Operations (TSMO) as an "integrated set of 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" (MAP-21 §1103 (a) (30) (A)). TSMO offers agencies a wide range of potential strategies for addressing system- and project-level performance needs with cost-effective, tailored strategies. State and local agencies are increasingly recognizing TSMO as a core business area in support of maximizing the performance of their transportation infrastructure and making better use of resources. Some regions in the United States have found it useful to develop TSMO plans to define a common vision for TSMO in the region, develop performance objectives to guide the selection of TSMO strategies, and identify performance measures that enable the region to track progress towards their objectives. TSMO plans also identify potential projects, services, and implementation policies to reach the objectives.

Performance analysis helps agencies make sound decisions on which TSMO policies, services, and projects to pursue as part of performance-based planning and programming. A performance analysis of a TSMO strategy might quantify, for example, how the strategy would be expected to affect measures of travel time, travel time reliability, pollutants/air quality, and the number and severity of traffic crashes. The agency could monetize these expected effects and determine an overall benefit-cost ratio for the investment.

The ability for agencies to quantify the effects of TSMO strategies on the number and severity of traffic crashes is limited when compared to similar abilities for operational performance measures. This report presents a safety performance analysis needs assessment for TSMO. The purpose of this needs assessment was to characterize the current state of safety performance analysis practice, knowledge, and skills with respect to specific TSMO strategies and broader TSMO program areas, and then to identify gaps and associated research needs. Readers of this report will gain an increased understanding of existing knowledge, analysis methods, and research needs in the context of quantifying the safety performance effects of TSMO. This information will be valuable to staff at various Federal, State, and local transportation agencies, as well as universities and other organizations that are involved in safety performance research and working to advance performance-based practices in planning, design, operations, and maintenance.

The objective of a safety performance analysis of a TSMO strategy (or combination of strategies) is to determine how implementing the strategy (or combination of strategies) will affect, or has affected, safety performance. The number, severity, and types of crashes characterize the safety performance of a highway segment, intersection, facility, corridor, subarea, or network. While safety and TSMO have always had visible interrelationships, there is incompatibility between many existing safety performance analysis tools and the characteristics of TSMO. For example, few TSMO strategies have robust crash modification factors (CMFs) and the American Association of State Highway and Transportation Officials (AASHTO) *Highway Safety Manual* (*HSM*) analysis methods do not currently incorporate daily, hourly, or sub-hourly variations in traffic characteristics and the road environment that are key factors in fully assessing the safety performance impacts of TSMO.

The needs assessment characterized the current state of TSMO-related safety performance analysis practice, knowledge, and skills through four sets of activities:

1) Syntheses of TSMO strategy-specific safety performance evaluations and analysis capabilities (Chapter 2).
2) A synthesis of research on interrelationships between measures of traffic operational performance and safety performance (Chapter 3).
3) A synthesis of research relating weather and weather-related road conditions to safety performance (Chapter 4).
4) A synthesis of research, tools, and challenges in estimating safety performance effects of TSMO that result from changes in travel choices and traffic demand patterns (Chapter 5).

The syntheses of strategy-specific safety performance evaluations and analysis capabilities addresses 15 strategies or sets of strategies:

1) Managed lanes
2) Part-time shoulder use
3) Reversible lanes
4) Dynamic lane use control
5) Dynamic junction control
6) Ramp metering
7) Variable speed limits
8) Traffic signal coordination
9) Adaptive signal control technology
10) Transit signal priority
11) Truck signal priority
12) Queue jump lanes
13) Safety warning applications
14) Work zone management and temporary traffic control applications
15) Traffic incident management

The strategy-specific syntheses show that the literature contains various types of safety performance evaluations for some TSMO strategies. However, there are only a limited number of published safety performance evaluations that may be robust enough to inform future evaluations or the development of quantitative safety performance predictions. There is a need for safety and operations staff from local, State, and Federal agencies, as well as researchers and other stakeholders, to engage in regular dialogue on safety performance evaluation needs and priorities specific to TSMO strategies. TRB activities, AASHTO meetings, and pooled-fund efforts are logical forums for such communications. The report presents an overview of potential near-term needs for consideration by these groups that cover HOV/HOT lanes, part-time shoulder use, bus facilities and preferential treatments, traffic signal technology and timing practices, ramp metering, variable speed limits, dynamic lane assignment, and strategy combinations.

The syntheses of strategy-specific safety performance knowledge and capabilities documented in Chapter 2, as well as the syntheses of crosscutting topics contained in Chapters 3, 4, and 5, also resulted in insights on methodological (i.e., study design and analysis) issues and related lessons learned. These issues and lessons learned led to a set of methodological safety performance analysis needs for TSMO, which fell into five categories:

1) “Sub-annual” safety data collection and analysis.
2) Safety performance effects beyond the site level.
3) Safety performance effects of traffic operational conditions.
4) Study design and statistical analysis.
5) Mechanistic approaches to safety performance analysis of TSMO.

SUB-ANNUAL SAFETY DATA COLLECTION AND ANALYSIS

A significant number of TSMO strategies operate (or have the potential to operate) dynamically, based on changing traffic or environmental conditions. Most safety performance evaluations of TSMO strategies in the literature ignored these operational aspects, instead analyzing annual crash frequencies (i.e., crash frequencies across all days, all times) and using an annual average number of vehicles as a measure of exposure (i.e., numbers of vehicles across all days, all times).

There is a need to distinguish between the following measures of crash frequency and exposure as part of safety performance evaluations of TSMO:

- Average crash frequency (all days, all times) and actual or average number of vehicles (all days, all times): most relevant to TSMO features and strategies that operate permanently (“on” 24/7).
- Average crash frequency (during specific statically defined days or times, such as daytime, weekday, weekday peak-period) and actual or average number of vehicles (during the same specific statically defined days or times, such as annual weekday volume, annual weekday peak-period volume): most relevant to TSMO features and strategies that operate on a set time-of-day schedule.

- Average crash frequency (during dynamically defined days or times) and actual or average number of vehicles (during dynamically defined days or times, such as during certain operational conditions or weather conditions): most relevant to TSMO features and strategies that operate dynamically.

SAFETY PERFORMANCE EFFECTS BEYOND THE SITE LEVEL

This methodological need deals with capturing safety performance effects of TSMO strategies beyond a site level to get a more complete picture of their total effects. Many of the TSMO strategies reviewed in Chapter 2 are expected to affect performance beyond an individual segment, intersection, or interchange. The needs assessment identified at least four different mechanisms by which this occurs:

1. Application of the strategy itself extends beyond an individual intersection or segment and therefore has an effect on performance at that level (e.g., arterial signal coordination, part-time shoulder use, and managed lanes).
2. The location of crashes changes following the removal of a bottleneck.
3. The spatial boundary at which safety performance is affected by non-recurring congestion resulting from an incident as well as the spatial boundary at which safety performance is affected by incident management strategies changes with the characteristics of each incident.
4. Some TSMO strategies are expected to effect performance at a corridor, area, or system level because of their influence on traveler behavior (e.g., where, when, and how people make trips).

SAFETY PERFORMANCE EFFECTS OF TRAFFIC OPERATIONAL CONDITIONS

TSMO strategies affect traffic operational and safety performance. The safety performance effects of TSMO strategies will depend on the traffic operational conditions with a strategy in place and what would have been the traffic operational conditions without the strategy. There is a need to develop methodologies and tools that incorporate traffic operational conditions into the safety performance analysis of TSMO. Depending on the strategy, examples of addressing this methodological need include:

- Incorporating macroscopic measures of traffic operations throughout the year into an analysis of average annual crash frequency. This might include, for example, effects of annual average hourly flow, density, and V/C ratio during a defined hour on average annual crash frequency during that same hour (e.g., midnight – 1 a.m., 1 a.m. – 2 a.m., 2 a.m. – 3 a.m.).
- Incorporating macroscopic measures of traffic operations during defined time intervals into an analysis of crash frequency or crash probability during those time periods and future time periods. This might include, for example, effects of average volume, average

> speed, standard deviation of volume, and standard deviation of speed on crash probability during the next 5, 10, 15, 20, 25, and 30 minutes from the time of the macroscopic traffic operations measurement.

Quantifying relationships between traffic operations and safety performance would also inform how to operate TSMO strategies from a safety performance perspective. This could include, for example, the most desirable operational conditions from a safety performance perspective under which to dynamically open (or close) a shoulder as a travel lane. This could also lead to methods to achieve desirable operational conditions from a safety performance perspective using dynamic lane assignment by increasing or decreasing the number of open travel lanes during different times of day.

Linking operational measures to safety performance is also related to the use of alternative measures of safety (i.e., safety surrogates). Numerous studies used surrogate safety measures to assess TSMO strategies. However, only a small portion attempted to validate the link between surrogate measures and the occurrence and/or severity of crashes.

STUDY DESIGN AND STATISTICAL ANALYSIS

A significant portion of published safety research on TSMO used naïve before-after or with-without study designs and analyzed measures such as observed crash rates and observed crash frequencies. Methodological issues with these study designs and performance measures are well documented, including in the *Highway Safety Manual*, and they are continuing to be phased out as options for defensible safety analysis and evaluation. Study design and statistical analysis approaches within safety performance analysis research and practice continue to advance. Such advancements should be incorporated into future safety performance analyses of TSMO.

MECHANISTIC APPROACHES TO SAFETY PERFORMANCE ANALYSIS OF TSMO

This needs assessment did not identify any studies in the literature that used mechanistic approaches to analyze the safety performance of TSMO. The literature does, however, contain examples of such approaches in contexts that show potential for future application to TSMO. There is a need to advance research on the use and validation of mechanistic approaches to quantify the safety performance effects of TSMO.

Continuing to advance both strategy-specific knowledge and analysis capabilities related to safety performance of TSMO will provide agencies with new information for considering TSMO solutions for addressing system- and project-level needs within a performance-based decision-making framework.

CHAPTER 1— OVERVIEW

This report documents the results of a safety analysis needs assessment for Transportation Systems Management and Operations (TSMO). Conducting a needs assessment generally includes two types of activities:

1. Characterizing the current state of practice, knowledge, and skills for the topic of interest.
2. Identifying gaps in the existing body of knowledge and corresponding needs, which then provide the foundation for future research activities and advancements in practice.

Readers of this report will gain an increased understanding of existing knowledge, analysis methods, and research needs in the context of quantifying the safety performance effects of TSMO. The primary intended audiences are those involved in developing transportation safety-related research needs and priorities. This audience spans staff at Federal, State, and local transportation agencies, private industry, and universities who develop research needs and priorities for their specific entities as well as for organizations and groups who fund shared research priorities, such as the American Association of State Highway and Transportation Officials (AASHTO) and the Transportation Pooled Fund (TPF) Program. This report will also be of interest to practitioners looking for a single reference that identifies and synthesizes safety information relevant to specific TSMO strategies (e.g., variable speed limits, adaptive signal control) as well as broader TSMO program areas (e.g., incident management, traffic management, demand management).

The remainder of this introductory chapter provides overviews of TSMO and safety performance analysis approaches. It also includes background information on the reliability of safety effectiveness evaluations, statistical significance, and “correlation versus causation” that will help readers put the findings of previous research in context. Chapters 2 through 5 synthesize safety analysis information relevant to specific TSMO strategies and broader TSMO program areas. This information includes:

- Syntheses of strategy-specific safety performance knowledge and capabilities (Chapter 2).
- A synthesis of research on interrelationships between measures of traffic operational performance and safety performance (Chapter 3).
- A synthesis of research relating weather and weather-related road conditions to safety performance (Chapter 4).
- A synthesis of research, tools, and challenges in estimating safety performance effects of TSMO that result from changes in travel choices and traffic demand patterns (Chapter 5).

Building on the findings of Chapter 2 through Chapter 5, Chapter 6 describes safety performance analysis gaps/limitations and needs. Chapter 7 provides a summary of the report along with key conclusions and recommendations.

TRANSPORTATION SYSTEMS MANAGEMENT AND OPERATIONS (TSMO)

Moving Ahead for Progress in the 21st Century (MAP-21) defines TSMO as an "integrated set of 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" (MAP-21 §1103 (a) (30) (A)). The scope of TSMO strategies spans intelligent transportation systems (ITS), traffic operations and management, travel demand management, planning, and policy development. TSMO is undertaken from a systems perspective, which means that related TSMO strategies are coordinated with each other and across multiple jurisdictions, agencies, and modes. TSMO includes both efforts to operate the multimodal transportation system and activities to manage travel demand.(1)

A single universally-accepted typology for the range of possible strategies that fall under the broad umbrella of TSMO does not currently exist. In addition, the growth of emerging mobility services (e.g. Shared Use Mobility) and new data sources for systems management and traveler information lead to new and continually-evolving TSMO applications. The Federal Highway Administration (FHWA) Office of Operations provides several resources with suggestions for how these TSMO strategies might be categorized.(2,3,4) This report adopts a framework from a recently completed FHWA Office of Operations task order on incorporating travel time reliability into transportation systems management. The framework, shown in figure 1, organizes TSMO strategies into three overarching categories: 1) incident/event management, 2) traffic management, and 3) demand management. Within each of these broader categories are more specific tactical program areas (e.g., road weather management, active traffic management, parking management). Each tactical program area then contains a list of specific actions in the form of implementing individual TSMO strategies to contribute to achieving a performance objective (e.g., implement variable speed limits, adopt ramp metering, deploy managed lanes). Within this framework, specific TSMO strategies can be implemented in different contexts. For instance, implementing variable speed limits supports six different tactical program areas: road weather management, traffic incident & emergency transportation operations, work zone management, planned special event management, freeway management, and active traffic management. Strategies can also be implemented in combination (e.g., part-time shoulder use and dynamic lane use controls) in support of one or more tactical program areas.

MANAGEMENT STRATEGIES ▶ TACTICAL PROGRAM AREAS ▶ TACTICS/FUNCTIONS

1 INCIDENT/EVENT MANAGEMENT ADDRESS INCIDENTS AND EVENTS

Road Weather Management

- Create weather-related traffic operational response plans
- Implement variable speed limits
- Detect road weather conditions and disseminate weather and warning information to travelers through dynamic message signs and other information dissemination systems. Warn drivers of ice, snow, high winds, low visibility and flooded roads.
- Provide emergency truck parking facilities and emergency parking information
- Implement vehicle restrictions along roadways during inclement weather

Traffic Incident & Emergency Transportation Operations

- Establish traffic incident management (TIM) teams
- Conduct after action reviews
- Stage tow trucks in critical areas
- Provide roadway safety service patrols
- Integrate computer-aided dispatch (CAD) into transportation management centers (TIMCs)
- Pre-establish towing service agreements
- Co-locate dispatch units
- Develop shared quick clearance goals
- Pre-plan detour routes
- Implement hard shoulder running
- Deploy adaptive ramp metering
- Provide variable speed limits
- Implement dynamic lane use controls
- Deploy network surveillance with cameras or detectors
- Implement incident traffic signal timing plans
- Enact supporting legislation (e.g., driver removal laws, authority removal laws, move over laws)
- Integrate TMC with law enforcement dispatch center/emergency operations center

Work Zone Management

- Coordinate maintenance and construction activities
- Implement queue length detection
- Deploy network surveillance with cameras or detectors
- Implement variable speed limits
- Support dynamic lane merging
- Implement dynamic lane use controls
- Deploy temporary ramp metering
- Implement dynamic warning systems (e.g., queues, congestion, over-dimension vehicles, and work zone intrusions)

Planned Special Event Management

- Activate special event signal timing plans
- Deploy adaptive ramp metering
- Implement variable speed limits
- Use hard shoulder running
- Support reversible lanes
- Implement dynamic lane use controls
- Establish dynamic pricing
- Deploy network surveillance with cameras or detectors
- Activate dynamic transit fare reduction
- Implement dynamic wayfinding
- Conduct after action reviews

2 TRAFFIC MANAGEMENT MANAGE MOVEMENT OF PEOPLE AND GOODS DURING TYPICAL CONDITIONS

Freeway Management

- Implement network surveillance with cameras or detectors
- Deploy high occupancy vehicle/toll lanes
- Implement adaptive ramp metering
- Deploy hard shoulder running
- Implement variable speed limits
- Deploy dynamic lane use control
- Construct physical operations improvements such as overpass widening, curve corrections, or auxiliary lanes

Active Traffic Management

- Adopt adaptive ramp metering
- Implement adaptive signal control
- Deploy dynamic lane reversal
- Implement dynamic lane use control
- Deploy dynamic merge control
- Implement hard shoulder running
- Use variable speed limits
- Deploy queue length detection
- Provide transit signal priority
- Implement dynamic warning signs (e.g., queue, road weather conditions)

Integrated Corridor Management

- Implement network surveillance with cameras or detectors
- Conduct access management/driveway access controls
- Implement adaptive ramp metering
- Deploy adaptive signal control
- Deploy transit signal priority
- Install queue jumping lanes
- Provide traveler information on alternative modes
- Deploy emergency vehicle preemption

Freight Management

- Implement roadside truck electronic screening/clearance
- Deploy truck signal priority
- Deploy truck parking management systems
- Install truck climbing lanes
- Implement freight loading zone policies (e.g., delivery times, designated zones, electronic parking payment systems)

Arterial Management

- Install queue jumping lanes
- Deploy transit signal priority
- Support emergency vehicle preemption
- Implement network surveillance with cameras or detectors
- Implement access management/driveway access controls
- Establish a TMC
- Deploy enhanced traffic signal operations (e.g., re-timing, adaptive detection, better detection)
- Implement transit only lanes
- Implement truck traffic signal priority
- Design for complete streets
- Add capacity for critical movements
- Reduce travel speeds (e.g., speed limit reductions)
- Provide automated enforcement
- Conduct operations asset management
- Provide enhanced bicycle and pedestrian crossings

3 DEMAND MANAGEMENT AVOID TRIPS OR CHANGE TRIP MODE, TIME, OR ROUTE

Congestion Pricing

- Implement dynamic pricing - variable pricing by lane, segment, time of day, or day of week
- Establish dynamic transit fare reductions
- Deploy managed lanes - high occupancy vehicle lanes, high occupancy toll lanes

Parking Management

- Deploy dynamically priced parking
- Implement dynamic parking wayfinding, reservations, capacity
- Deploy dynamic overflow transit parking
- Implement electronic payment systems
- Implement shared-use parking
- Provide incentives to use underutilized parking facilities

Public Transportation and Ridesharing Management

- Implement dynamic ridesharing
- Implement transit signal priority
- Use queue jump lanes at signalized intersections
- Deploy electronic fare collection and integration
- Implement transit surveillance and security

Source: FHWA

Figure 1. Graphic. Framework for organizing TSMO strategies.

TSMO offers agencies a wide range of potential strategies for addressing network and project-level performance needs with cost-effective, tailored strategies. State and local agencies are increasingly recognizing TSMO as a core business area in support of maximizing the performance of their existing transportation infrastructure and making better use of resources. Some regions in the United States have found it useful to develop TSMO plans to define a common vision for TSMO in the region, develop performance objectives to guide the selection of TSMO strategies, and identify performance measures that will enable a region to track progress towards their objectives.(5) TSMO plans also identify potential TSMO projects, services, and implementation policies to reach the objectives. Building on these concepts, some State Departments of Transportation (DOTs) have expressed goals to shift the development of their Statewide Transportation Improvement Program to first funding TSMO solutions to address project needs when possible prior to funding road widening projects or other significant changes to the highway infrastructure. Increasingly, interest in TSMO strategies and their performance effects is spanning multiple business units within DOTs, including those units involved in the management and analysis of safety performance.

SAFETY PERFORMANCE ANALYSIS

The number, severity, and type of crashes define the safety performance of a highway segment, intersection, facility, corridor, subarea, or network. As a step towards achieving safety performance-based planning, programming, project implementation, operations, and maintenance, FHWA published the National Performance Management Measures: Highway Safety Improvement Program Final Rule (Safety PM Final Rule) in the Federal Register on March 15, 2016, with an effective date of April 14, 2016. The Safety PM Final Rule requires States and Metropolitan Planning Organizations (MPOs) to set annual safety performance targets for the following measures:

- Number of fatalities.
- Rate of fatalities per 100 million vehicle miles traveled (VMT).
- Number of serious injuries.
- Rate of serious injuries per 100 million VMT.
- Number of non-motorized fatalities and number of non-motorized serious injuries combined.

The Safety PM Final Rule emphasizes fatalities and serious injuries in defining safety performance. While the number of less severe crashes are often a part of a safety performance analysis and could provide some hints about the potential of future fatal and serious injury crashes to occur, a larger portion of their immediate costs to society is derived from their effects on property, travel time reliability, delay, and traffic management resources (e.g., traffic incident management and response). As much as possible, reference to safety performance effects of TSMO must clearly distinguish the types and severities of crashes that are affected.

The amount of information available to quantify the safety performance effects of policies, programs, and project-level decisions has grown substantially over the last decade. AASHTO published the First Edition of the *Highway Safety Manual* (*HSM*) in 2010. Development of the Second Edition is underway. The *HSM* includes methods for quantifying safety performance to facilitate performance-based decision-making during planning, programming, project implementation, operations, and maintenance. Various stakeholder groups, including AASHTO, FHWA, State DOTs, and Transportation Research Board (TRB) standing technical committees, have cooperated in efforts to institutionalize the *HSM* and its associated analytical tools to support data-driven decisions, inform trade-off decisions, advance knowledge on factors influencing safety performance, and ultimately reduce fatalities and serious injuries.

The objective of a safety performance analysis of a TSMO strategy (or combination of strategies) is to determine how implementing the strategy (or combination of strategies) will affect, or has affected, safety performance. There are three general sets of approaches for analyzing effects on safety performance:

1. Approaches based on analysis of crash data.
2. Approaches based on alternative (i.e., surrogate) measures of safety.
3. Approaches based on simulating crash occurrence and severity.

Approaches Based on Analysis of Crash Data

One way to determine how the implementation of a TSMO strategy affects safety performance is to analyze the frequency, type, and severity of crashes at locations (i.e., segments, intersections, facilities, corridors) before and after implementation of the strategy. Alternatively, one can compare the frequency, type, and severity of crashes at locations where the strategy is present to similar types of locations without the strategy. FHWA's *A Guide to Developing Quality Crash Modification Factors* describes how to conduct before-after and cross-sectional studies to determine the safety performance effects of strategies based on an analysis of crash data.(6)

Information derived from before-after and cross-sectional studies can also be used to develop methods to forecast (i.e., predict) the frequency, type, and severity of crashes for existing or new facilities; under current or forecasted traffic conditions; and for different design, operational, or management alternatives.

Most safety performance analysis approaches based on an analysis of crash data, including those in the *HSM*, predict or estimate an average annual crash frequency assuming relatively static conditions over the course of a year. There are significant limitations to these types of approaches when analyzing the safety performance effects of TSMO. These limitations include the following:

- Some TSMO strategies are only operational during certain times of the day and have operational characteristics that vary in real-time as a function of traffic and weather conditions. Most methods based on an analysis of crash data are applied at the annual level and do not incorporate daily, hourly, or sub-hourly variations in the operational environment.
- TSMO strategies that are applied to support the attainment of traffic operational objectives (e.g., improve travel time) have significant direct effects on traffic operational performance metrics, such as speed, flow, and capacity. Most methods based on an analysis of crash data incorporate average traffic volumes – specifically the annual average daily traffic (AADT) – and do not consider safety performance effects of the magnitudes of and variations in speed, flow, capacity, and density changes and interactions.
- Most methods based on an analysis of crash data involve statistical analysis and require an adequate number of locations with the strategies of interest to obtain statistically significant results. Specific types and combinations of road design and TSMO strategies are still, in some cases, relatively rare, making it difficult to quantify the anticipated safety performance of these strategies for defined sets of conditions.
- Some TSMO strategies are intended to influence traveler behavior within a region and across a transportation system, including trip timing, mode choice, route choice, destination, or whether to make the trip. Although becoming more widely used through dynamic traffic assignment methods, data and models to describe these behavior changes as a function of time may not be readily integrable with existing safety performance analysis approaches.

While not as common, there are examples of analyzing crash data at a “sub-annual” level. In some cases, the analysis period is as small as 5 minutes. Such examples include studies that are focused on the relationship between safety performance and traffic metrics in real-time. These studies develop models for predicting the probability of a crash occurring for a given set of traffic conditions. Databases for model development are created by merging crash data, roadway data, and high-resolution traffic operations data acquired from various detection systems.

Approaches Based on Surrogate Measures of Safety

Surrogate measures of safety such as speed, speed variation, traffic control compliance, deceleration rate, and lane change behavior can, in theory, be used to determine how the implementation of a TSMO strategy affects safety performance. The use of surrogate measures to estimate the safety performance effects of different strategies is identified as one possible study approach in FHWA’s *A Guide to Developing Quality Crash Modification Factors*.(6) Tarko et al. pointed out that two conditions must be met before a surrogate measure of safety can be useful in a safety performance application:(9)

1. The surrogate measure should be based on an observable non-crash event that is related to crashes.

2. There should be a practical method for converting the changes or differences in non-crash events into corresponding changes or differences in crash frequency and/or crash severity.

In other words, the key to the application of surrogate measures of safety is the availability of reliable models or procedures to relate crash frequency (by crash type and severity), or changes in crash frequency, to the surrogate measures, or changes in the surrogate measures. Establishing links between surrogate measures and crashes has been a challenging area of research. While the use of surrogate measures and related tools such as FHWA's Surrogate Safety Assessment Model (SSAM) has become increasingly popular in research studies, they have not gained traction and remain unproven in informing programmatic or project-level decision-making in practice. However, there are increasing opportunities for progress with the availability of emerging technologies and new data sources. National Cooperative Highway Research Program (NCHRP) project 17-86, *Estimating Effectiveness of Safety Treatments in the Absence of Crash Data*, is developing a procedural guide for using surrogate measures of safety.

Readers of Chapter 2 (strategy-specific evaluations) should use caution in applying the results that come from studies applying surrogate measures of safety that have not been fully vetted and validated. Chapter 6 of this report includes needs related to the use of surrogate measures of safety in the context of TSMO safety evaluations.

Approaches Based on Simulating Crash Occurrence and Severity

The third and currently least common approach to analyzing safety performance is through simulating crashes based on models and mechanisms that characterize how drivers, vehicles, and the road environment interact. *Transportation Research Circular E-C179: Theory, Explanation, and Prediction in Road Safety* describes this process in three general steps:(11)

1. Identify the relevant mechanisms for the occurrence and severity of a specific crash type.
2. Quantify the causal effects of different driver, vehicle, and road characteristics on each mechanism.
3. Aggregate the frequencies of the mechanisms for the location of interest with defined or assumed driver, vehicle, and road characteristics.

Transportation Research Circular E-C179 notes that a benefit of using such a mechanistic approach is that prior or new knowledge of the underlying mechanisms can guide study design, model development, analysis, and interpretation.

Two examples of approaches based on simulating crash occurrence and severity through a mechanistic approach include the conditional encroachment-crash-severity approach of the Roadside Safety Analysis Program version 3 (RSAPv3) and Wang et al.'s occurrence-mechanism approach for estimating rear-end crash probability. RSAPv3 uses encroachment models, databases of vehicle trajectories, and models of crashes with roadside hardware and obstacles to predict run-off-road crash occurrence and severity based on characteristics of the roadway and roadside. Wang et al. focused on rear-end crashes at signalized intersections and developed a model to predict their occurrence based on lead vehicle deceleration and following vehicle response time.(12)

This needs assessment will summarize existing knowledge, analysis methods, and research needs for quantifying the safety performance effects of TSMO using "annual" and "sub-annual" analyses of crash data, surrogate measures of safety, and mechanistic approaches to simulate crashes.

The remainder of this chapter includes background information on three topics that will help the reader interpret the study results presented in Chapters 2 through 4: 1) reliability of safety effectiveness evaluations, 2) statistical significance, and 3) correlations vs. causation.

Reliability of Safety Effectiveness Evaluations

The syntheses in Chapter 2 (strategy-specific evaluations), Chapter 3 (interrelationships of traffic operational and safety performance), and Chapter 4 (weather effects on safety performance) will show that a majority of prior TSMO-related safety research is based on analyses of the rate, number, type, and severity of crashes at locations of interest. A significant amount of this prior TSMO-related safety research also used more traditional study design, analysis, and evaluation methods that are more susceptible to bias and may result in less reliable findings. One set of common examples are before-after or with-without analyses of observed numbers of crashes, which are susceptible to regression-to-the-mean (RTM) bias and other biases due to confounding factors that are not addressed in the study design or analysis approach (e.g., temporal trends, inherent differences in sites with and without the treatment).

Crash data are particularly susceptible to RTM bias. The random nature of crash occurrence results in the potential for an unusually high or unusually low number of crashes to occur at a site in any given year. Another set of examples common to the TSMO literature are before-after or with-without analyses of observed crash rates, which assume a linear relationship between the number of crashes and traffic volume. Research studies have repeatedly shown that the relationship between the number of crashes and traffic volume is nonlinear. Comparisons of crash rates can therefore lead to incorrect conclusions on the effects of a TSMO strategy. Observed crash rates are also susceptible to RTM bias.

More reliable methods are those that account for potential bias due to RTM, changes in traffic volume, the nonlinear relationship between number of crashes and traffic volume, and general temporal and other unknown or unobserved effects. One such technique is a before-after study utilizing an Empirical Bayes (EB) approach. The before-after study with EB approach is more robust than a naïve before-after study because it uses what is known about the safety performance of other sites with similar characteristics to the study site (i.e., reference sites) in addition to the crash history of the study site itself.(7) Through the use of reference sites, the EB method addresses bias due to RTM, accounts for changes in traffic volume, and accounts for temporal effects.

Readers of Chapters 2, 3, and 4 should use caution in applying the results that come from studies applying the traditional methods, such as the use of observed number crashes or observed crash rates. The results from these methods that do not properly account for potential sources of bias are less reliable and may result in less effective decisions. The reliability of the results from these traditional methods are even lower if based on only a few study sites and a few years of data. Chapter 6 of this report includes needs related to study design and analysis approaches in the context of TSMO safety evaluations. FHWA's *Reliability of Safety Management Methods: Safety Effectiveness Evaluations* provides additional information on more reliable methods and demonstrates through examples the value of more reliable methods in safety effectiveness evaluation.(7)

Statistical Significance

The content of the needs assessment regularly refers to standard errors, confidence levels, and statistical significance in presenting the results of safety performance evaluations of TSMO strategies. It is important to have some understanding of these concepts to gauge the potential effectiveness of the strategies and compare different TSMO strategies and different evaluation techniques.

The standard error provides a measure of certainty for a given result (e.g., a measure of certainty in the magnitude of an estimated increase or decrease in crash frequency due to the implementation of a TSMO strategy). A small standard error (compared to the magnitude of the estimated increase or decrease) indicates a higher level of certainty in the result. A larger standard error (compared to the magnitude of the estimated increase or decrease) indicates a lower level of certainty in the result.

The standard error can be used by an analyst to calculate the confidence interval, another measure of certainty in an estimate. The confidence interval is a range of values between which the true value of the estimated parameter is expected to fall. The wider this interval is, the less certain the results may be. Additionally, confidence intervals can be wider or narrower given the level of confidence one wants of the true value falling within that range. A 99-percent confidence interval is wider than a 95-percent confidence interval, which is in turn wider than a 90-percent confidence interval. As an example, a 95-percent confidence interval is translated for practical interpretation to indicate that the data shows a 95-percent chance that the true value of the estimated parameter is within that interval.

In a related manner, the confidence level associated with the statistical significance of a result provides an indication that the effect estimated from the sample of data in hand (e.g., an increase or decrease in crash frequency) will be present in other similar samples of data. The following types of statements are found throughout this document when reporting statistical significance and associated confidence levels: "The result was/was not statistically significant at a 95 percent confidence level." Such a statement generally means the following:

1. The result provides an estimate of the effect of a TSMO strategy on the number and/or severity of crashes (e.g., results showed an average crash frequency reduction of 29-percent (standard error of 5-percent)).
2. The study implemented null hypothesis significance testing, where the null hypothesis is that the TSMO strategy has no effect on the safety performance measure in question.
3. The estimated p-value, the estimated probability that the researchers would have observed the effect in their data (or a greater effect) under the null hypothesis is less than or equal to 0.05 (for a 95-percent confidence level), 0.10 (for a 90-percent confidence level), etc.

A body of literature exists regarding the use and misuse of statistical significance and p-values in various fields, related particularly to the ability (or inability) to independently reproduce research findings. Hauer demonstrated the misapplication of hypothesis testing in road safety literature using three case studies.(13) The American Statistical Association (ASA) released a "Statement on Statistical Significance and P-Values" with six principles underlying their proper use and interpretation:(14)

1. "P-values can indicate how incompatible the data are with a specified statistical model.
2. P-values do not measure the probability that the studied hypothesis is true, or the probability that the data were produced by random chance alone.
3. Scientific conclusions and business or policy decisions should not be based only on whether a p-value passes a specific threshold.
4. Proper inference requires full reporting and transparency.
5. A p-value does not measure the size of an effect, or the importance of a result.
6. By itself, a p-value does not provide a good measure of evidence regarding a model or hypothesis."

The road safety community continues to advance approaches and research protocols that advance reliable study design, statistical analysis, and reporting practices. For the purposes of the syntheses of specific TSMO strategies in Chapter 2, the following information is provided for key results if it could be determined from the papers:

- The estimate of the "effect" of the TSMO strategy on the number, type, and/or severity of crashes along with the standard error of the estimate.
- Whether the result was statistically significant at a 95 percent confidence level.
- If the finding was not statistically significant at a 95 percent confidence level:
    - The level of statistical significance if the confidence level is greater than or equal to 80 percent (i.e., 90, 80).
    - A statement that the finding is not statistically significant if the confidence level is less than 80 percent.

Correlation versus Causation

The syntheses in Chapter 2 through Chapter 4 present the findings of research that generally sought to determine what change in safety performance (if any) was caused by some treatment (e.g., TSMO strategy, weather condition, traffic condition). The question of determining cause-and-effect in an observational study, which is the primary study type for safety performance research, is a broad, complex, and active area of research. Most readers may be familiar with a more commonly used phrase that "correlation does not imply causation," meaning that two events occurring together does not always mean there is a cause-and-effect relationship. As one hypothetical example, a sample of freeway facilities may experience fewer crashes when part-time shoulder use is operational. This outcome, however, does not automatically mean that part-time shoulder use is the cause of fewer crashes during the time periods it is operational. There could be other factors that are reducing the numbers of crashes that tend to be present at the same time part-time shoulder use is operational, and that are not accounted for in the study design (e.g., a certain vehicle mix, driver familiarity and mix, fewer entering and exiting vehicles).

The syntheses in Chapter 2 through Chapter 4 do not directly address the assumption of causation for each set of findings. The discussions and summaries in these chapters do, however, touch on study characteristics that influence the chances that results are evidence of a cause-and-effect relationship. These characteristics include strength of the study design and analysis approach, strength of the association, and consistency of findings across multiple, well-designed studies.

CHAPTER 2 — SAFETY PERFORMANCE OF SPECIFIC TSMO STRATEGIES: CURRENT STATE OF PRACTICE, KNOWLEDGE, AND SKILLS

This chapter contains syntheses of TSMO strategy-specific safety performance evaluations and analysis capabilities. The syntheses are intended to serve multiple purposes. They characterize the current state of safety performance information for individual TSMO strategies, setting the stage for the identification of strategy-specific needs within a performance-based decision-making framework. They also provide a quick reference for practitioners interested in what safety performance research exists for specific strategies. A significant number of references in these syntheses are from research-oriented/academic journals that are often not readily available to the practitioner community. Summaries contained in this document attempt to make the key findings of these studies more readily accessible to readers. Such information and their source studies could be used to inform TSMO-related safety performance questions until TSMO gaps in more widely referenced resources, such as the *HSM* and FHWA Crash Modification Factors (CMF) Clearinghouse, are addressed.

The next section of this chapter describes the process used by the project team to systematically search for and identify relevant resources. This is then followed by syntheses for 15 individual TSMO strategies (see table 1). Each synthesis contains two parts: 1) a general description of the strategy and 2) a summary of safety evaluations.

Table 1. TSMO strategies covered in Chapter 2.

TSMO Strategy	Page Number
Managed Lanes	22
Part-Time Shoulder Use	40
Reversible Lanes	47
Dynamic Lane Use Control	48
Dynamic Junction Control	49
Ramp Metering	51
Variable Speed Limits	56
Traffic Signal Coordination	63
Adaptive Signal Control Technology	69
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Queue Jump Lanes	77
Safety Warning Applications	79
Work Zone Management and Temporary Traffic Control Applications	90
Traffic Incident Management Strategies	96

IDENTIFICATION OF SAFETY RESOURCES

To foster thoroughness and consistency, the project team established a systematic process to identify resources relevant to safety performance analyses of individual TSMO strategies. The project team used four primary search engines and databases: the ITS Benefits Database, the Transport Research International Database (TRID), the CMF Clearinghouse, and Google Scholar. Since TRID and Google Scholar contain information on a wide variety of topics not limited to safety, they were queried using the name of the strategy in question as well as the keywords "safety" and "crash."

The ITS Benefits Database was developed by the Intelligent Transportation Systems Joint Program Office (ITS JPO) of the United States Department of Transportation (USDOT). Its major objectives are to collect and present findings from evaluations of ITS deployments, specifically with respect to ITS effects on safety, mobility, efficiency, productivity, energy, environmental effects, and customer satisfaction.(15) Each result from a search presents a headline, such as the following result of a search for "variable speed limit" and "safety": "Variable Speed Limits (VSL) cut crash rates by more than half during low visibility on I-77 in

Virginia."(16) Each result also includes a concise summary of the context for the stated benefit and sometimes includes a link to the original source of the information.

The TRID database was released in 2011 as a partnership between TRB and the International Transport Research Documentation (ITRD) database.(17) It is maintained by TRB with sponsorship by State DOTs, various USDOT administrations, and other parties. It contains nearly 1.2 million references to books, technical reports, conference proceedings, and peer-reviewed journal articles related to transportation research.(18)

The FHWA CMF Clearinghouse is a central repository for CMFs. A CMF is an estimate of the change in crashes that is expected to occur following the implementation of a chosen countermeasure or strategy.(19) For example, the FHWA CMF Clearinghouse contains a CMF of 0.79 (with a standard error of 0.05) for "install adaptive traffic signal control" for all intersection crash types and crash severities (CMF ID 6858). To illustrate the application of the CMF, assume an average of 12.3 crashes per year (of all types and severities) at a given intersection without adaptive signal control. If adaptive signal control was implemented at the intersection, the average number of crashes (of all types and severities) expected to occur after implementation would be 12.3 * 0.79 = 9.72 crashes per year. The standard error can be used to estimate a confidence interval for the CMF. In this case, the 95-percent confidence interval for the "install adaptive traffic signal control" CMF would be 0.69 to 0.89. This range is calculated as 0.79 +/- 2*0.05.

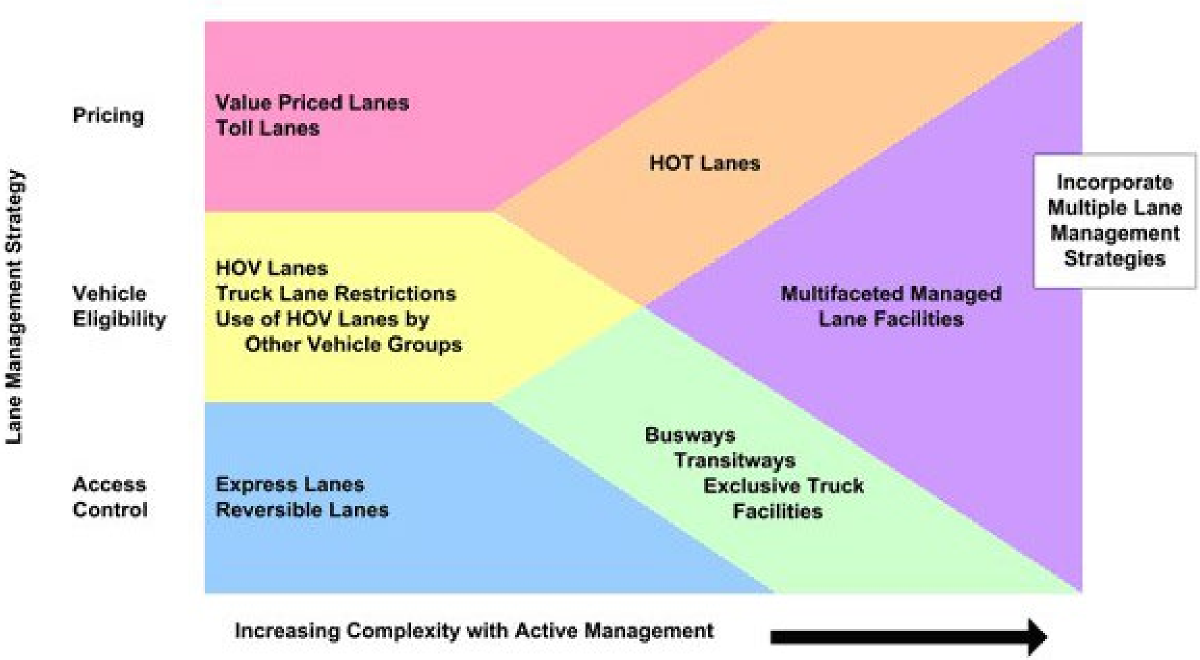
The CMF Clearinghouse is sponsored by the FHWA Office of Safety, and only includes CMFs produced from crash-based studies. A strategy may have multiple CMFs corresponding to specific crash types, road types, or crash severities. In addition to the information about the CMF itself, each entry contains the abstract of the study from which it was derived and a link to the paper or report if it is publicly available.(20)

Google Scholar is a search engine for scholarly literature that covers a wide array of subjects and formats. It includes peer-reviewed journals, conference proceedings, books, technical reports, and academic reports such as theses and dissertations. Given that Google Scholar is a general search engine, and not transportation-focused, even the most specific query will often provide tens of thousands of results. However, the results are ranked according to an index that takes into account the full text of each document, where it was published, and how frequently and recently it has been cited in other works.(21) For the purposes of data collection for this needs assessment, the project team considered the first 10 pages of Google Scholar results.

INDIVIDUAL STRATEGY SYNTHESES

Managed Lanes

General Description of Strategy: Managed lanes are highway facilities or sets of lanes on highway facilities where operational strategies are proactively implemented and managed in response to changing traffic conditions.[22] The spectrum of strategies that fall within the definition of managed lanes includes high-occupancy vehicle (HOV) lanes, high-occupancy toll (HOT) lanes, dynamic shoulder lanes, express lanes, and truck lanes. There are three forms of lane management – pricing, vehicle eligibility restrictions, and access control. These facilities range in complexity depending on the type of active management that is implemented (see figure 2).



Source: FHWA

Figure 2. Graphic. Typical U.S. managed lane facilities and applications.[23]

Managed lanes are implemented for a variety of reasons; however, the underlying goal is generally to reduce congestion and improve traffic flow and travel times. Their design and management can be flexible, allowing them to accommodate changes in demand patterns and operational needs over time. Some managed lanes that implement vehicle eligibility strategies, or a combination of vehicle eligibility and access control strategies, seek to reduce private automobile demand by providing transit preferential treatment (in the case of transitways or busways) or incentive travelers to increase vehicle occupancy (in the case of HOV lanes). Other managed lanes that implement vehicle eligibility/restrictions (e.g., truck facilities/restrictions) seek to improve vehicle flow and/or safety performance by separating vehicles with different characteristics. Managed lanes that implement pricing strategies seek to improve vehicle flow for a subset of vehicles by attracting some drivers from the general-purpose lanes to the managed lanes and charging them for the higher-quality service.

The road geometric considerations for implementing managed lanes are significant, largely because managed lanes have generally been implemented on existing urban facilities (though recently, managed lanes have increasingly been built as added capacity due to the popularity of priced lanes). In some cases, managed lanes are added by reducing the widths of other roadway elements, as opposed to overall roadway widening. This can have implications for lane width, shoulder width or provision of shoulders, and the type of buffer used. The type of separation between the managed lanes and general-purpose lanes is a key design decision and influences the extent and complexity of other design decisions, which include cross section, alignment, and access type and location. The separation ranges from not physically separated (e.g., designated using pavement markings) to fully separated facilities that may only be accessed from the general-purpose lanes at specific locations. Figure 3 shows an example of a fully separated managed lanes facility.

Source: FHWA

Figure 3. Photo. Separated express lanes with access points on I-495 in Fairfax County, VA.(24)

Safety Performance Evaluations: Researchers conducted a number of safety assessments of managed lanes during early stages of experience with the strategy.(25,26,27,28,29) Some of these early studies characterized general overall changes in safety performance resulting from implementation of managed lanes projects.(25,26,29) The early studies also provided initial insights to some factors influencing safety performance of facilities with managed lanes, including patterns of traffic and congestion, speed differentials between managed lanes and general-purpose lanes, access design, and widths of buffers between the managed lanes and general-purpose lanes. While these early studies had limitations with respect to sample sizes and analysis approaches, they set the stage for more recent research efforts.

HOV Implementation

Bauer et al. explored the issue of limited urban right-of-way in the context of the cross-sectional reallocation of widths.(30) The study was an observational before-after evaluation using the empirical Bayes (EB) method. It examined the safety performance of various directional urban freeway segments that had undergone four-to-five lane or five-to-six lane conversions through narrowing existing lanes and/or converting shoulders to full or partial travel lanes. The study sites comprised nearly 50 miles of urban freeway on four different routes in southern California, and, in most cases, the conversions were performed to implement managed lanes. The results showed that four-to-five lane conversions resulted in an increase in overall crash frequency (all types and severities) of 10.96-percent (standard error of 2.88-percent). Fatal and injury (KABC) crash frequency increased by 10.59-percent (standard error of 4.56-percent). These results were statistically significant at a 95-percent confidence level. The five-to-six lane conversions resulted in crash frequency increases of 3- to 7-percent for various crash severities (with standard errors ranging from of 4.56- to 7.22-percent), but these results were not statistically significant due to a limited sample size. The researchers noted the possibility that increasing the capacity at the treatment sites may cause bottlenecks to migrate downstream of the treatment sites, potentially leading to an increase in crashes at the treatment site.

Cooner & Ranft explored the implementation of retrofitted buffer-separated HOV lanes in Dallas, Texas, which were implemented by decreasing lane widths from 12 feet to 11 feet and converting the inside shoulder to a lane.(31) The study examined crash data from 1990 to 2000, and the HOV lanes were implemented in the mid-1990s. Results showed that injury crash rates increased by 56-percent on I-35E and 41-percent on I-635 following introduction of the HOV lanes. Fatal and suspected serious injury crash rates decreased following construction, while suspected minor injury and possible injury crash rates increased. The standard errors and confidence intervals of these results were not reported by the authors. Additionally, a substantial increase in crash frequency was found in the general-purpose lane adjacent to the HOV lane when compared to the before condition, with unsubstantial changes in the crash rate for the other general-purpose lanes. The study considered “Lane 1” to be the left-most lane in the before condition and the left-most general-purpose lane (adjacent to the HOV lane) in the after condition. I-35E showed a 153-percent increase in the number of crashes in Lane 1 and I-635 showed a 188-percent increase in the number of crashes in Lane 1 following the implementation of the HOV lane. Once again, standard errors and confidence intervals for these results were not reported. The increase in crash frequencies was primarily attributed to speed differentials between the HOV and general-purpose lanes.

HOV to HOT Conversions

Cao et al. conducted a before-after study of converting HOV lanes to HOT lanes on I-394 in Minnesota.(32) The authors used the before-after with EB study design and analysis approach with four years of before data and two years of after data. Results showed a 5.3-percent reduction in total crash frequency because of the conversion (standard error of 3.99-percent). The result was not statistically significant at a 95-percent confidence level. It was significant at an 80-percent confidence level.

Abuzwidah & Abdel-Aty conducted a similar study on 16 miles of I-95 in Miami, Florida which found that the HOV-to-HOT conversion did not significantly change the overall crash frequency. The researchers conducted a before-after with EB analysis of the whole roadway section, as well as separate analyses of the HOT lanes only and the general-purpose lanes only. The number of fatal and injury crashes (of all types) on the whole roadway segment decreased by 4-percent (standard error of 10-percent). The results were not statistically significant. The analysis of the HOT lanes showed that the number of fatal and injury crashes decreased by 28-percent (standard error of 12-percent). The number of lane change-related and rear-end crashes decreased by 38- and 39-percent (with standard errors of 7- and 10-percent). These results were all significant at a 95-percent confidence level. The analysis of the general-purpose lanes showed that rear-end and lane change-related crashes increased by 25- and 27-percent, and these results were significant at a 95-percent confidence level (with standard errors of 10- and 8-percent). Fatal and injury crashes in the general-purpose lanes increased by 8-percent (with a standard error of 5-percent). The change was not statistically significant at the 95-percent confidence level. It was significant at the 80-percent confidence level. The crash frequency reductions in the HOT lanes were attributed to lower traffic volume and more uniform flow compared to the general-purpose lanes and the previous HOV lanes.(33)

HOV/HOT Design Features

Jang et al. analyzed safety performance using crash rates and other descriptive statistics on extended stretches of eight freeway facilities with HOV lanes: four stretches with continuous access and four stretches with limited access.(34) The continuous access HOV lanes operated as HOV lanes during peak hours (5-9am, 3-7pm) and operated as regular lanes outside of the peak periods. The study considered only the crashes during the peak periods. The continuous access facilities were all located in the Bay Area in northern California, while the limited access facilities were all in Los Angeles in southern California. This may limit the comparability of the results. While the analytical methods used in the study had some weaknesses, results from the analysis are still informative:

- In limited access HOV lanes, there were larger proportions of rear-end crashes and smaller proportions of sideswipe crashes compared to continuous access lanes.
- Of all crashes that occurred along directional freeway segments with an HOV lane, a larger proportion occurred in the HOV lane and leftmost general-purpose lane for freeways with limited access HOV lanes than for freeways with continuous access lanes.
- Fatal and injury crash rates and no apparent injury crash rates were higher in the limited access HOV lanes than the continuous access HOV lanes. In the case of the leftmost general-purpose lane adjacent to the HOV lane, the fatal and injury crash rates were higher, and the no apparent injury crash rates were lower in lanes adjacent to continuous access HOV lanes.

In a follow-on study, Jang & Chan used three separate statistical analysis techniques to validate their previous results comparing limited- and continuous-access HOV lanes.(35) The techniques used were empirical cumulative density functions, Kolmogorov-Smirnov Tests, and Poisson Distributed Samples comparison of means. The results showed that the statistical tests supported the previous findings that distinguished safety performance characteristics of continuous-access HOV facilities versus limited-access facilities. The study also examined crash rates versus distance to access points on the limited access HOV segments. The distance was defined as the mid-point of the segment to the last transition area upstream or first transition area downstream. The results showed crash rates to be higher closer to transition areas, with crash rates decreasing and leveling out as the distance increases.

In another study, Jang et al. estimated four different count regression models for 1) number of no apparent injury crashes in the HOV lane, 2) number of fatal and injury crashes in the HOV lane, 3) number of no apparent injury crashes in the leftmost general-purpose lane, and 4) number of fatal and injury crashes in the leftmost general-purpose lane.(36) The authors estimated these four models using three years of crash, traffic, and roadway data from approximately 150 miles of freeways in Southern California with buffer-separated HOV lanes. The models estimated crash frequency as a function of HOV lane width, left lane width, lane-specific AADTs, left shoulder width, and buffer width. The model results showed that the numbers of no apparent injury and fatal and injury crashes in the HOV lane were associated with HOV lane width, average daily traffic volume in the HOV lane, left shoulder width, and buffer width. HOV lanes that were 11 ft or wider had fewer crashes than HOV lanes less than 11 ft. The number of crashes in the HOV lane decreased as the left shoulder width increased. The authors found that both the number of no apparent injury and fatal and injury crashes in the HOV lane increased by 7-percent (with a standard error of 7-percent) for every foot increase in buffer width but this finding was not statistically significant.

The study also found that the total numbers of no apparent injury and fatal and injury crashes in the left general-purpose lane were positively associated with the average daily traffic in the left lane and the results were significant at a 95-percent level. The number of crashes in the left lane decreased by 11-percent (with a standard error of 10-percent) for every foot increase in buffer width. This result was not statistically significant. Specification of average daily traffic volume in the models deviated from generally accepted approaches to SPF development.

Fitzpatrick & Avelar investigated the relationship between crash frequencies and flush buffer-separated managed lane dimensions.(37) Their dataset included approximately 190 miles of non-weaving managed lane segments in California and Texas with a single managed lane that was operational 24/7 and anywhere between three to five general-purpose lanes.(37) Based on the models, the researchers concluded that, for each additional foot of managed lane envelope (i.e., the sum of left shoulder width, lane width, and buffer width): the total number of crashes reduced by two to three percent (standard error of 0.5-percent), and the number of fatal and injury crashes decreased by 4.4 percent (standard error of 1.3-percent). Both results were significant at a 99-percent confidence level. Additional exploratory analysis indicated that buffers of three feet or less appeared to be associated with more crashes than buffers of four to six feet. The authors also concluded that changes in left shoulder width are not as influential on safety performance as changes in lane and buffer widths within the managed lane envelope.

Srinivasan et al. developed a crash prediction method for Florida DOT for freeways with HOV or HOT lanes, using data from California, Florida, and Texas.(38) Models were developed separately for six-, eight-, ten-, and twelve-lane freeways. The HOV lane sites included one managed lane in each direction, while the HOT lane sites included two managed lanes in each direction. Ten-lane freeways with a two- to three-foot buffer were associated with a 12.4-percent decrease in the number of fatal and injury crashes (with a standard error of 7.5-percent) when compared to facilities with a painted stripe (no buffer) or a zero- to two-foot buffer. This result was not statistically significant at a 95-percent confidence level (it was significant at a 90-percent confidence level). Additionally, facilities with only a painted stripe (no buffer) had more total crashes (all types and severities) than those with a zero- to two-foot or two- to three-foot buffer. The effect of buffer type was not found to be statistically significant for six-, eight-, or twelve-lane freeways. Sample size issues may have contributed to the lack of statistically significant results for the other models. The models for HOT lanes indicate that facilities with a one-foot buffer have more crashes than those with a three-foot buffer, which in turn have more crashes than those with 20 feet of separation between the managed and general-purpose lanes. However, the separation width values were unique to each site, and thus caution should be used in transferring these results, as other site-specific confounding factors could be present.

Exclusive Truck Facilities and Truck Restrictions

Examining potential lane management strategies that separate types of traffic, Lord et al. conducted an exploratory safety analysis of data from approximately eight miles of freeway sections in New Jersey where the inner and outer lanes were divided and the inner lanes restricted truck traffic (i.e., were for passenger cars only).(39) Results indicated that lanes without trucks had fewer crashes and lower crash rates than lanes with both passenger cars and trucks. Trucks were involved in 40-percent of crashes in the outer lanes, while making up 30-percent of the traffic stream. The authors concluded that additional work was needed to explore the contributing factors leading to truck-related crashes in the outer lanes with both passenger cars and trucks.

Das et al. analyzed the effects of truck lane restrictions (TLRs) on safety performance at 16 sites in the Dallas-Fort Worth region of Texas. Using a before-after EB evaluation, the study found that TLRs indicated safety performance improvements in terms of fatal and injury crashes and fatal and injury crashes involving large trucks.(40) However, the results of the before-after EB analysis showed that the crash frequency reductions for overall fatal and injury crashes and fatal and injury truck-involved crashes were only statistically significant at a 95-percent confidence level for 2 out of the 16 study sites (one additional site was significant at an 80-percent confidence level, and several sites showed statistically significant increases in crash frequency).

Fontaine et al. examined the safety effects of Virginia's TLR policy, which prohibits trucks from traveling in the left-most lane of interstates with three or more lanes by direction when the speed limit is 65 mph or higher; along all of I-81; along all interstates in the Northern Virginia District of VDOT; and in the left lane of two-lane directional interstate segments when a truck's speed is below the posted speed limit.(41) The study involved crash frequency analyses of 23 sites with three directional lanes and 20 sites with two directional lanes. A before-after EB study approach was used on the sites with three directional lanes, but due to a lack of comparison sites the two-directional-lane sites were examined using a naïve analysis approach. Only one year of "after" data was available for the analysis.

For sites with three lanes in each direction, the researchers identified a bifurcation in the results at 10,000 vehicles per day per lane. Results for overall crashes (all severities and vehicle types) showed that lower-volume sites experienced a 10-percent decrease in crash frequency (with a standard error of 3-percent), and higher-volume sites experienced a 12-percent increase in crash frequency (with a standard error of 1.5-percent). Analysis of fatal and injury crashes showed that lower-volume sites experienced a 17-percent reduction in fatal and injury crash frequency for all vehicle types (with a standard error of 4.6-percent), while higher-volume sites experienced a 14-percent increase in fatal and injury crash frequency for all vehicle types (with a standard error of 2.6-percent). Finally, the researchers analyzed truck-involved crashes. These results showed that lower-volume sites experienced a 29-percent decrease in truck-involved crash frequency for all crash severities (with a standard error of 5.1-percent), while higher-volume sites experienced a truck-involved crash frequency increase of 37-percent for all crash severities (with a standard error of 4.1-percent). Truck-involved fatal and injury crash frequency decreased by 34-percent (with a standard error of 4.1-percent) at lower-volume sites and increased by 27-percent (with a standard error 6.6-percent) at higher-volume sites. These results were all statistically significant at a 95-percent confidence level.

The researchers performed a similar analysis for sites with two lanes in each direction. Results showed that overall crashes (all severities and vehicle types) experienced a 23-percent decrease in crash frequency (with a standard error of 10.2-percent). Analysis of fatal and injury crashes showed a 31-percent reduction in fatal and injury crash frequency for all vehicle types (with a standard error of 15.3-percent). The results for all truck-involved crashes showed a 7-percent decrease in truck-involved crash frequency (with a standard error of 21.9-percent). There was a 53-percent reduction in truck-involved fatal and injury crash frequency (with a standard error of 21.4-percent). These results were all statistically significant at a 95-percent confidence level except for the decrease in all truck-involved crashes, which was not statistically significant.

Since the original study of Virginia TLRs was limited to one year of "after" data, Fontaine et al. performed a follow-on study to further examine the safety performance effects.(42) Once again, the researchers examined sites separately based on number of directional lanes (two vs. three or more), using a before-after EB approach for sites with three or more directional lanes and a naïve approach for sites with two directional lanes. In this study, only higher volume three-lane or greater sites (greater than 10,000 vehicles per lane per day) were examined. The results for three directional lane sites showed that overall truck-involved crash frequency increased by 23-percent (with a standard error of 5.6-percent). This result was statistically significant at a 95-percent confidence level. Truck-involved fatal and injury crashes on three directional lane roads increased by 4-percent (with a standard error of 7.1-percent), but this result was not statistically significant. For two directional lane sites, the naïve before-after crash frequency analysis showed no statistically significant change.

Fontaine studied another TLR strategy in Virginia that prevents trucks traveling more than 15-mph below the posted speed limit from using the left lane on four-lane freeways.(43) The strategy is generally implemented in mountainous terrain, and 19 study sites were identified in Virginia. The paper did not report the posted speed of the 19 sites. The study was unable to use the EB method due to a lack of appropriate reference sites, so a naïve before-after study of crash frequency was performed instead, using four years of before data and two years of after data. The results showed that the frequency of fatal and injury crashes for all vehicle types declined by 32-percent (standard error of 11.7-percent). This result was statistically significant at a 95-percent confidence interval. However, the changes in the frequency of truck-involved crashes and truck-involved fatal and injury crashes were not statistically significant. The confidence intervals for the truck-involved crash analyses were wide due to the small sample size of crashes at the study sites.

The implementation of managed lanes, particularly bus- or truck-only lanes and HOV or HOT lanes, can result in speed differentials between the managed lanes and the general-purpose lanes. Tao performed a safety surrogate analysis using Vissim microsimulation software and the FHWA Surrogate Safety Assessment Model (SSAM) to analyze various managed-lane scenarios in Montreal, Canada.(44) The scenarios included an exclusive bus/taxi arterial lane and a freeway

HOV and bus-on-shoulder configuration. The surrogate safety measures used in the study were estimated conflict angle, time to collision (TTC) and post-encroachment time (PET). TTC is the time required for two vehicles to collide if they were to continue on the same path without braking. PET is the time from the moment a vehicle departs a defined point to the moment the next vehicle arrives at that point. The study found that increasing the length of merge lanes and weaving sections (road segments that allow for vehicles to both merge into and out of a managed lane) can reduce the number of conflicts associated with high speed differentials and could be more effective than using physical separation methods for managed lanes.(44)

Adelakum performed a survey- and simulation-based study of the effects of potential interstate truck lane configurations on efficiency and safety in Tennessee.(45) The different scenarios included a) trucks must use the left lane, b) trucks must use the left two lanes, c) optional truck only lane (either concrete barrier or painted buffer divided), and d) trucks must use right two lanes (no-change scenario). The microsimulation portion, performed in Vissim, examined the rate of lane change maneuvers as a surrogate measure of safety. It showed that the smallest lane change rates (79,648 lane changes per hour for cars; 482 for sport utility trucks; and 2,825 for tractor-trailer vehicles) occurred under the optional, separated exclusive truck lane scenario. Furthermore, the highest lane change rates occurred under scenario (d) where trucks must use the right two lanes (137,975 lane changes per hour for cars; 3,259 for sport utility trucks; and 28,533 for tractor-trailer vehicles). The survey portion of the study showed that, of the 500 truck drivers surveyed, the majority preferred moving trucks to the left lanes to avoid conflicts with vehicles merging onto or off the roadway.

El-Tantawy et al. also used surrogate safety measures to evaluate the safety performance of truck lane restrictions but cautioned that there isn't an empirical link between crash occurrence and conflicts.(46) The study simulated an urban freeway segment in Toronto, Canada, and collected data to identify lane changing, merging, and rear-end conflicts. Four different scenarios were tested: no restriction, restricting trucks from the left-most lane, restricting trucks from the left-most two lanes, and dedicated left-most lane for trucks only. Each scenario was tested at three different levels of truck penetration (4-, 15-, and 30-percent). The simulation results indicate that truck lane restriction strategies reduced the simulated number of conflicts when truck percentage was at least 15-percent. Restricting trucks from the left-most lane did not substantially affect lane changing conflict frequency. Restricting trucks from the left-most two lanes decreased truck-related lane changing conflicts by 26- to 53-percent, depending on truck percentage. The provision of a truck-only lane (in the left-most lane) decreased truck-related lane changing conflicts by 17- to 21-percent. These results were significant at a 95-percent confidence level (standard errors were not reported by the authors).

Exclusive Bus Facilities

Duduta et al. explored the safety effects of BRT design features using data from nine BRT systems around the world.(47) The study incorporated crash analysis, road safety audits, and interviews with transit officials. Due to differences in crash reporting standards between countries, the researchers were unable to effectively compare results, but instead analyzed each city as a separate case study. Three cities presented adequate data for negative binomial crash frequency modeling: Mexico City and Guadalajara, Mexico; and Porto Alegre, Brazil. Difference of means tests were used to perform before-after analysis for the other cities where statistical models could not be developed (Bogota, Colombia; Delhi, India; Curitiba and Belo Horizonte, Brazil). Over 90-percent of crashes on BRT corridors did not occur in bus lanes and did not involve buses. Counterflow bus lanes were significantly correlated with higher overall crash rates. Additionally, center-lane bus systems tended to be associated with lower crash rates than curbside systems. The researchers identified notable tradeoffs between safety, capacity, and pedestrian accessibility in the design of BRT systems and facilities. They pointed out that reduction of crashes and crash severity would require measures that would affect operational efficiency: slowing down bus operations and not allowing buses to merge in and out of express lanes at stations.

Goh et al. performed a safety surrogate study of bus lane effects for a 1.6 km corridor in Melbourne, Australia using microsimulation techniques.(48) The study compared a base case of mixed traffic (no change) with two bus lane configurations: (a) a curbside lane reallocated for buses only and (b) a new additional curbside lane for buses only. TTC and deceleration rate to avoid a crash (DRAC) were used as the surrogate measures of safety performance. The researchers emphasized the fact that the study was limited to a single corridor and that results are likely to be influenced by geometric and operational characteristics. The results indicated that vehicle conflicts at intersection approaches and bus stops were lower in both bus lane configurations than in the base case (conflict reductions varied between 9.4 and 42.5 depending on traffic volume). For mixed traffic, in scenario (a) where traffic volumes were over 900 vehicles per hour (vph), vehicle conflicts increased on the corridor by 50.7 conflicts (1200 vhp), 195.2 conflicts (1500 vph), and 503.7 conflicts (1800 vph); and in scenario (b) vehicle conflicts reduced by 36.3 conflicts (1200 vhp), 54.2 conflicts (1500 vph), and 199.3 conflicts (1800 vph). These reductions, expressed as TTC, were all statistically significant at a 95-percent confidence level (standard errors were not reported by the authors). The differences between the two scenarios became negligible at volumes lower than 900vph.

Summary

The managed lane synthesis effort uncovered safety performance research in four general areas: 1) HOV/HOT conversions, 2) HOV/HOT design features, 3) exclusive truck facilities and truck restrictions, and 4) exclusive bus facilities. Table 2, table 3, table 4, and table 5 summarize these studies. Of these categories, HOV/HOT lanes have been the most extensively researched from a safety performance perspective and there are potentially implementable findings with respect to the quantification of safety effects associated adding an HOV/HOT lane to an existing roadway by narrowing lane and shoulder widths and with tradeoffs associated with elements of the managed lane envelop (i.e., the left shoulder width, lane width, and buffer width). The changes in crash type and severity with different separation strategies, specifically within the managed lane and adjacent general-purpose lanes, have been researched but are not fully understood. Similarly, safety performance near managed lane access points has not been fully researched. Work is ongoing to fill some of these gaps and produce a single source of information for policymakers and practitioners interested in evaluating safety performance of HOV/HOT lanes. At the time of this report, NCHRP project 17-89A, *HOV/HOT Freeway Crash Prediction Method for the Highway Safety Manual*, was initiated.(49) The objectives of NCHRP 17-89A, are to "1) develop a predictive methodology that can be used to estimate crash frequency and severity for freeway facilities, and associated ramps, with HOV or HOT lanes, and 2) provide a tool for highway agencies to quantify safety performance in planning, project development, and operation of freeways with HOV or HOT lanes."

Exclusive truck facilities, truck restrictions, and exclusive bus facilities have been researched to a much lesser extent from a safety performance perspective, with safety research on exclusive bus facilities occurring outside of the United States. Research on truck facilities and truck restrictions uncovered some potentially informative results using both crash- and surrogate-based approaches, but there is a need to repeat these types of studies with more robust datasets and analysis approaches.

A selected number of the studies in this section are included in the CMF Clearinghouse. A search of the CMF Clearinghouse for managed lanes-related CMFs results in the following:

- Three- and four-star CMFs for "four to five lane conversion" and "five to six lane conversion" (without widening the roadway, and in the context of managed lanes) based on the work of Bauer et al (CMF IDs 4 – 9).(30)
- Two- and three-star CMFs for "widen managed lane envelopes" based on the work of Fitzpatrick and Avelar (CMF IDs 9398 – 9400).(37)
- Two-star CMFs for converting continuous access HOV lanes to limited-access based on Jang et al (CMF IDs 2114 and 2115).(34)
- Two- and three-star CMFs for converting HOV lanes to HOT lanes based on the results of Cao et al. and Abuzwidah & Abdel-Aty (CMF IDs 2988 – 2993, 8801 – 8818).(32,33)
- A range of one-star to four-star CMFs for truck lane restrictions based on the work of Das et al. and Fontaine et al. (CMF IDs 9377 – 9380, 2720 – 2722, 2225 – 2228).(40,41) The highest-rated CMFs are those by Fontaine et al. showing:
    - Truck lane restrictions leading to reductions in the frequency of total (all types, severities), fatal-plus-injury (all types), truck-related (all severities), and truck-related fatal-plus-injury crashes when volumes are less than 10,000 vehicles per day per lane.

  - Truck lane restrictions leading to increases in the frequency of these same crash types when volumes are greater than 10,000 vehicles per day per lane.

Table 2. Summary of safety performance evaluation findings for HOV/HOT conversions.

Study	Location	Site type	Method	Findings
Bauer et al., 2004(30)	Los Angeles, CA; San Diego, CA	Urban freeway with lane and shoulder width conversion to accommodate HOV lane	Before-after with EB	Four-to-five lane conversion: • Overall crash frequency increase of 10.96% (SE 2.88%, significant at 95%) • Fatal and injury crash frequency increase of 10.59% (SE 4.56%, significant at 95%) Other conversions: • Five-to-six lane conversions did not generate statistically significant change in crashes
Cooner & Ranft, 2006(31)	Dallas, TX	Urban freeway with retrofitted HOV lanes	Naïve before-after	• Retrofitted buffer-separated HOV lanes resulted in increases in fatal and injury crash rates, particularly for non-incapacitating and possible injury crashes in the HOV lane and left GP lane. • Injury crash frequency increase of 41% - 56% following introduction of HOV lanes
Cao et al., 2012(32)	Minneapolis, MN	Urban freeway with HOV-to-HOT conversion	Before-after with EB	Overall crash frequency decrease of 5.3% for conversion of HOV to HOT (S.D. 3.99%, not significant at 95%)
Abuzwidah & Abdel-Aty, 2016(33)	Miami, FL	Urban freeway with HOV-to-HOT conversion	Before-after with EB	• Fatal and injury crash frequency decrease of 4% (S.E. 10%, not significant) • Overall HOT lane crash frequency decrease of 28% (S.E. 12%, significant at 95%) • Overall general-purpose lane crash frequency increase of 8% (S.E. 5%, not significant at 95%)

Table 3. Summary of safety performance evaluation findings for HOV/HOT design features.

Study	Location	Site type	Method	Findings
Jang et al., 2009(34)	Contra Costa, CA; Alameda, CA; Santa Clara, CA; Angeles, CA	Urban freeway with limited- or continuous-access HOV lane	Statistical hypothesis testing; crash concentration location analysis	• Limited access HOV lanes have larger proportions of rear-end crashes and smaller proportions of sideswipe crashes compared to continuous access lanes. • Larger proportion of crashes occurred in the HOV lane and leftmost GP lane for freeways with limited access HOV lanes than for freeways with continuous access lanes. • Fatal and injury crash rates and no apparent injury crash rates were higher in the limited access HOV lanes than the continuous access HOV lanes.
Jang et al., 2011(36)	Los Angeles, CA; Orange, CA	Urban freeway with HOV lane	Negative binomial regression	For each additional foot of buffer: • HOV crash frequency increase of 7% (SE 7%, not significant) • Left GP lane crash frequency decrease of 11% (SE 10%, not significant).
Fitzpatrick & Avelar, 2016(37)	Los Angeles, CA; Dallas, TX; Houston, TX	Urban freeway	Poisson and negative binomial regression	For each foot of managed lane envelope width: • Decrease of 2-3% in overall crash frequency (S.E. 0.5%, significant at 99%) • Decrease of 4.4% in fatal and injury crash frequency (S.E. 1.3%, significant at 99%) Changes in left shoulder width are not as influential as changes in lane and buffer widths within the managed lane envelope.

Study	Location	Site type	Method	Findings
Srinivasan et al., 2015(38)	CA; TX; WA; FL	Urban freeway with HOV or HOT lanes	Negative binomial regression	• Increasing buffer width for HOV and HOT lanes on 10-lane freeways resulted in 12.4% decrease in fatal and injury crashes and overall crashes (SE 7.5%, significant at 90%). • Effect of buffer width not significant for 6-, 8-, or 12-lane freeways.

Table 4. Summary of safety performance evaluation findings for exclusive truck facilities and truck restrictions.

Study	Location	Site type	Method	Findings
Lord et al., 2014(39)	Woodbridge Township, NJ	Urban freeway with Truck Lane Restrictions	Naïve crash analysis	• Lanes without trucks had fewer crashes and lower crash rates • In mixed-traffic lanes, trucks were 30% of the traffic stream but involved in 40% of crashes
Das et al., 2018(40)	Dallas-Ft. Worth, TX	Urban freeway with Truck Lane Restrictions	Before-after with EB	TLRs produced slight decrease in fatal and injury truck-involved crashes. Results were only significant at 95% for 2 out of 16 study sites.
Fontaine et al., 2007(41)	VA	Urban and rural freeway with Truck Lane Restrictions	Before-after with EB and naïve before-after	Truck-involved fatal and injury crash frequency: • 3+ lane interstates with volume >10,000 veh/day/lane increase of 27% (SE 6.6%, significant at 95%) • 3+ lane interstates with lower volume decrease of 34% (SE 4.1%, significant at 95%) • 2-lane interstates decrease of 53% (SE 21.4%, significant at 95%)
Fontaine et al., 2009(42)	VA	Urban and rural freeway with Truck Lane Restrictions	Before-after with EB and naïve before-after	Truck-involved crash frequency: • 3+ lane interstates with volume > 10,000 veh/day/lane overall increase of 23% (SE 5.6%, significant at 95%), fatal and injury increase of 4% (SE 7.1%, not significant) 2-lane interstates did not show significant effects.
Fontaine, 2008(43)	VA	Rural freeways with Truck Lane Restrictions	Naïve before-after	• Decrease of 32% in fatal and injury crash frequency (S.E. 11.7%, significant at 95%)

Study	Location	Site type	Method	Findings
				• Change in truck-involved crash frequency not significant.
Tao, 2015(44)	Montreal, Canada	Urban arterial and freeway	Simulation-based surrogate study	Increasing the length of merge lanes can alleviate safety effects of high speed differentials in managed lane configurations
Adelakum, 2008(45)	Knoxville, TN	Urban freeway	Simulation-based surrogate study	Lowest lane change rates occurred under scenario with separated truck-only lane
El-Tantawy et al., 2009(46)	Toronto, Canada	Urban freeway	Simulation-based surrogate study	All results significant at 95%: • Truck Lane Restrictions result in safety benefits when trucks make up at least 15% of traffic stream • Restricting trucks from left lane did not affect overall conflict frequency • Decrease in overall conflicts of 26-53% when restricting trucks from left two lanes • Decrease in overall conflicts of 17-21% with provision of truck-only lane

Table 5. Summary of safety performance evaluation findings for exclusive bus facilities.

Study	Location	Site type	Method	Findings
Duduta et al., 2012(47)	Mexico City & Guadalajara, Mexico; Porto Alegre, Brazil	Arterial BRT corridor	Negative binomial regression and statistical hypothesis testing of differences in means	• 90% of crashes on BRT corridors did not occur in bus lanes or involve buses • Counterflow bus lanes were correlated with higher overall crash rates • Center-lane bus systems tended to provide more safety benefits than curbside systems
Goh et al., 2013(48)	Melbourne, Australia	Arterial with bus lane	Simulation-based surrogate study	• Presence of bus lanes decreased vehicle conflicts at intersections and bus stops (significant at 95% for volumes greater than 900 vph) • At low volumes, bus lanes did not significantly affect conflict occurrence

Part-Time Shoulder Use

General Description of Strategy: This strategy allows the shoulder to be used as a travel lane to provide additional capacity when needed. It preserves the shoulder for typical shoulder uses (e.g., refuge and/or recovery area) during most of the day. The converted shoulder, vehicle-use options, operating options, and speed control characterize different part-time shoulder use alternatives, as listed below:(50)

- Converted Shoulder:
    - Right shoulder.
    - Left shoulder.
- Vehicle-Use Options:
    - Open shoulder to transit vehicles only.
    - Open shoulder as an HOV lane that permits carpools and transit vehicles to use it.
    - Open shoulder as a HOT lane that allows drivers to pay a toll to use it if their vehicle does not meet HOV requirements.
    - Open shoulder to all vehicles except trucks.
    - Open shoulder to all vehicles.
    - Open shoulder to slow-moving trucks in rural mountainous areas.
- Operating Options:
    - Dynamically open shoulder when defined congestion thresholds are reached (an ATM strategy referred to as “Dynamic Shoulder Use”).
    - Statically open shoulder during specified peak periods (i.e., set time of day).
- Speed Control Options:
    - Same speed limit as other lanes (at posted speed limits).
    - Same speed as other lanes (at a reduced speed relative to normal posted speed limits).
    - Lower speed limit than other lanes.

Figure 4 and figure 5 depict two of these alternative forms of part-time shoulder use.

Source: FHWA

Figure 4. Photo. Previous implementation of static part-time shoulder use on I-66 in Virginia.(50)

Source: FHWA

Figure 5. Photo. Bus-on-shoulder operations in Minneapolis-St. Paul, Minnesota.(50)

The strategy will have an effect at the freeway facility level, spanning multiple freeway segments and interchange ramps. It is possible that performance effects of part-time shoulder use may extend beyond the location where it is implemented because:

- The additional peak-period capacity may attract some drivers from parallel roadways.
- The removal of a bottleneck through part-time shoulder use could create another bottleneck downstream of the part-time shoulder use location, which could in turn affect performance at that location.

When the shoulder is in use, the strategy changes several geometric characteristics that may affect performance, including remaining shoulder widths, lateral clearance to roadside objects, shoulder cross-slopes, stopping sight distances on curves, and design characteristics at entrance and exit ramp locations.

Safety Performance Evaluations: FHWA's *Use of Freeway Shoulders for Travel – Guide for Planning, Evaluating, and Designing Part-Time Shoulder Use as a Traffic Management Strategy* (Part-Time Shoulder Use Guide) provided an overview of empirical studies and tools that quantify the safety performance effects of part-time shoulder use, noting that research in this area is limited.(50) The overview first summarized an analysis of data before and after implementation of priced dynamic part-time shoulder use on I-35W in Minneapolis. A before-after EB analysis of the data indicated that expected crash frequencies had increased by 28.4-percent for all crash types and severities after implementation of the part-time shoulder use strategy (standard error and confidence level were not reported). However, the Minnesota Department of Transportation (MnDOT) observed that a significant bottleneck upstream of the site had been removed at the same time part-time shoulder use was implemented. Traditional SPFs were not able to adequately capture the effect of the bottleneck removal on expected crash frequency of this downstream, part-time shoulder use site. MnDOT followed up with an analysis using the Second Strategic Highway Research Program (SHRP2) L07 models. These models relate expected crash frequency to traffic density. MnDOT used these models to predict what would have been the expected crash frequency without part-time shoulder use at the location of interest but with the upstream bottleneck removal. This follow-on analysis estimated that removal of the upstream bottleneck resulted in a 22-percent increase in expected crash frequency at the location with part-time shoulder use. Therefore, the increase in expected crash frequency related to implementation of priced dynamic part-time shoulder use was 6.4 percent when taking the removal of the upstream bottleneck into consideration.

Lee et al. developed a model of expected crash frequency using data from a 6.5 mile-long segment of I-66 in Virginia where, during peak hours, the left (i.e., inside) lanes served as HOV lanes and the right shoulder served as an additional travel lane.(51) The authors explored the use of negative binomial regression models to capture the effects of the HOV and part-time shoulder use operations on daily crash frequencies. The use of three years of crash data from only one location and the high level of crash count disaggregation (i.e., by day) led to modeling challenges, and almost none of the resulting independent variables were statistically significant, limiting the contribution of this study.

A subsequent study by Dutta et al. further explored the effects of Active Traffic Management on I-66 in Virginia, which included part-time shoulder use as well as other traffic management strategies such as variable speed limits and lane-use control. The safety evaluation analysis used the before-after EB method, showing that locations with part-time shoulder use reduced the number of crashes (all types and severities) by 25- to 40-percent (with standard errors from 6.5- to 11.3-percent). These results were significant at a 95-percent confidence level, while the other Active Traffic Management strategies did not result in any significant changes to crash frequency.(52)

Kononov et al. identified an inconsistency between the notion that decreasing congestion by implementing part-time shoulder use will result in some degree of improved safety performance and the idea that crash rates increase as the number of lanes increase. The researchers used neural networks to develop corridor-specific SPFs and explore the relationship between traffic characteristics (volume, speed, etc.) and crash data on a mountainous freeway in Colorado with volumes not exceeding 1,900 vphpl(53) The researchers found that there was a 63.2-percent decrease in the overall crash rate (all types and severities) following the introduction of part-time shoulder use. However, the study noted that this estimate is optimistic since the SPFs assumed the availability of full shoulders, which may be compromised under the part-time shoulder use scenario. The research team assumed an increase of 25-percent in the crash rate for segments with limited shoulder width compared to full shoulders, and modified the predicted crash frequency reduction to 53.6-percent. Standard errors and confidence levels were not reported by the authors. The study noted that the safety performance benefits were highly dependent on the number of lanes present and the level of congestion.

Guerrieri & Mauro examined part-time shoulder use on 128 km of freeway in Italy from both a capacity and safety perspective. The safety portion of the study adapted freeway predictive methods from the *HSM*, calibrated with three years of crash data, to estimate what was expected without part-time shoulder use versus what was observed with it. Results showed substantial increases in capacity (up to 35-percent), but no significant variations in safety performance.(54) Standard errors and confidence levels were not reported by the authors.

In addition to these studies, the FHWA Part-Time Shoulder Use Guide also demonstrated an adaptation of the *HSM* freeway and interchange predictive methods for estimating the safety effects of part-time shoulder use. However, the guide noted various significant limitations in the *HSM* approach, including:(50)

- Failure to capture changes to ramp-freeway junctions when part-time shoulder use is in operation.
- Cannot capture effects of "remaining" shoulder widths (during part-time shoulder use) less than four feet.
- Failure to capture potential increase in crash frequency downstream of the part-time shoulder use location if part-time shoulder use alleviates a bottleneck.
- Failure to address changes in barrier offset when part-time shoulder use is in operation.
- Assumed shoulder is in use 24 hours per day.
- Failure to address potential change in volume and crash frequency resulting from the additional capacity attracting drivers from adjacent, alternative routes.

The limitations are significant enough to question the applicability of the *HSM* Predictive Method for Freeways and Interchanges to evaluate part-time shoulder use.

The FHWA Part-Time Shoulder Use Guide also identified two studies from Europe where results indicated possible safety benefits of part-time shoulder use, but data and analysis approaches were limited.(50) The FHWA Part-Time Shoulder Use Guide authors also noted that "In Europe, part-time shoulder use is almost always accompanied by the construction of turnouts and a higher level of ATM than is typical in the U.S., including dynamic speed limits/lane assignment, full CCTV monitoring, and aggressive incident management." (50)

Aron et al. analyzed the safety effects of part-time shoulder use as an auxiliary lane between a motorway entrance and exit ramp near Paris. The study used a before-after with comparison group study design.(55) The authors divided both the treatment and comparison sites into "sub-sites" based on average speed and occupancy, recognizing the likely chance that these operational measures would affect safety performance. They observed a reduction in crash frequency at the location with part-time shoulder use and an increase in crash frequency downstream of the location, but none of these findings were statistically significant because of small sample sizes (standard errors and confidence levels were not reported by the authors).(55)

Summary

Safety research on part-time shoulder use focused primarily on the overall effect that implementation has on safety performance. Results vary significantly (see table 6), with previous studies illustrating that this is likely because safety performance effects are dependent on the number of lanes present, traffic volumes, the level of congestion, time-dependent characteristics, and any changes that may have occurred upstream of the part-time shoulder use location. No previous studies looked at the specific safety performance effects of the geometric considerations, including remaining shoulder widths, lateral clearance to roadside objects, shoulder cross-slopes, stopping sight distances on curves, and design characteristics at entrance and exit ramp locations.

Searches for "part-time shoulder use," "shoulder lane use," and "hard shoulder" in the CMF Clearinghouse do not result in any relevant CMFs. At the time of this report, NCHRP project 17-89, *Safety of Part-Time Shoulder Use on Freeways*, was initiated.(56) The objectives of NCHRP 17-89 are to "1) develop quantitative tools for practitioners to use to evaluate safety performance of freeways with part-time shoulder use as a function of temporal, operational, and other conditions when the shoulder is open and closed to traffic, and (2) use the tools to determine the safety performance of part-time shoulder use, in order to better inform State DOT decision making on their application."(56)

Also, at the time of this report, NCHRP project 15-59, *Horizontal Sightline Offset Design Criteria, Exceptions, and Mitigation Strategies*, was an ongoing project expected to include an evaluation of safety and operational performance of horizontal sightline offsets.(57) The project was also expected to include an analysis of the trade-offs and risks associated with state-of-the-practice mitigation treatments when horizontal sightline offset criteria and guidance are not met. The products of this project are expected to include recommendations for updates to AASHTO's *A Policy on Geometric Design of Highways and Streets* (Green Book) that will address horizontal sightline offset design criteria and guidance for assessing curved roadway alignments adjacent to barriers or other types of impediments that may affect a driver's line of sight.(57) While part-time shoulder use is not included in the online project description, the analyses and results may provide insights to sight distance effects when part-time shoulder use is implemented.

Table 6. Summary of safety performance evaluation findings for part-time shoulder use.

Study	Location	Site type	Method	Findings
Documented in Jenior et al., 2016(50)	Minneapolis, MN	Urban freeway	Before-after with EB	Overall crash frequencies increase 28.4%, but correcting for the removal of an upstream bottleneck indicated crash frequencies increase likely closer to 6.4% due to PTSU
Lee et al., 2010(51)	Northern VA	Urban freeway	Negative binomial regression	No significant safety performance effects
Dutta et al., 2018(52)	Northern VA	Urban freeway	Before-after with EB	Overall crash frequency decrease of 25-40% (SE 6.5-11.3%, significant at 95%)
Kononov et al., 2012(53)	Denver, CO	Urban and mountainous rural freeway	Neural network development of SPFs	Overall crash frequency decrease of 63.2% which the researchers modified to 53.6% in an attempt to account for the reduced shoulder width due to PTSU
Guerrieri & Mauro, 2016(54)	Northern Italy	Urban freeway	*HSM* predictive methods to compare what was expected with observed	No significant safety performance effects
Aron et al., 2013(55)	Paris, France	Urban freeway	Before-after with comparison group	No significant safety performance effects

Reversible Lanes

General Description of Strategy: Reversible lanes are a strategy that consists of the reversal of travel lanes to allocate capacity based on the directional traffic demand, thereby allowing directional capacity to better match traffic demand throughout the day. In an Active Transportation and Demand Management (ATDM) approach, the lane directionality is updated dynamically in response to real-time traffic conditions or in advance of anticipated traffic conditions.(58) Dynamic lane reversal is implemented to improve vehicle flow along freeways and arterials by providing capacity to the travel direction that most needs it at any given time.

The performance effects of dynamic lane reversal are likely primarily at the freeway or arterial facility level where it is implemented. However, it is possible that effects may extend beyond the facility level to the corridor level because the additional, directional peak-period capacity may attract drivers from parallel roadways. Dynamic lane reversal affects travel time reliability because it enables the capacity of specific directions to change in response to traffic conditions, even if the traffic conditions are unexpected.

Changing the travel direction of one or more lanes as part of dynamic lane reversal changes the freeway cross-section characteristics, including number of directional through lanes at any given time and the type/amount of separation between opposing directions of travel.

Safety Performance Evaluations: There are few known safety performance evaluations of dynamic lane reversal. Dey et al. performed a cursory evaluation of a 2.7-mile reversible lane operation on the Connecticut Avenue arterial in Washington, D.C.(59) The study did not include a before-after crash analysis. Instead, it compared crash data from Connecticut Avenue with crash data from two comparison sites that did not have reversible lanes. The comparison sites exhibited similar traffic characteristics and patterns to the study site. Additionally, the evaluation examined the percent of Connecticut Avenue crashes that occurred during reversible lane operations. Over the six-year study period, the results showed that Connecticut Avenue had a higher overall crash rate (for all times of day, normalized by volume), as well as a higher percentage of crashes occurring during the hours of reversible lane operation (standard errors and confidence levels were not reported). 44.3-percent of the weekday crashes on Connecticut Avenue occurred during reversible lane operations. Additionally, Connecticut Avenue showed a higher proportion of head-on and sideswipe crashes.

Searches for “reverse,” “reversal,” and “reversible” in the CMF Clearinghouse do not return any relevant results.

Dynamic Lane Use Control

General Description of Strategy: Dynamic lane use control involves dynamically closing or opening individual travel lanes as needed and providing advanced warning of the lane closure(s) or lane configurations (typically through overhead dynamic lane control signs). It is generally used as one element of an overall freeway traffic management strategy.(58) Dynamic lane use control is part of a larger group of other dynamic lane assignment strategies covered in this report (such as reversible lanes and dynamic junction control). These strategies are generally implemented to improve vehicle flow along freeways and arterials by providing capacity where it is most needed. Dynamic lane use control, sometimes implemented in combination with variable speed limits, is also implemented to support safety performance, particularly along stretches of freeway where shoulder widths are reduced because the same system can be used to warn drivers of closed lanes (e.g., during an incident).

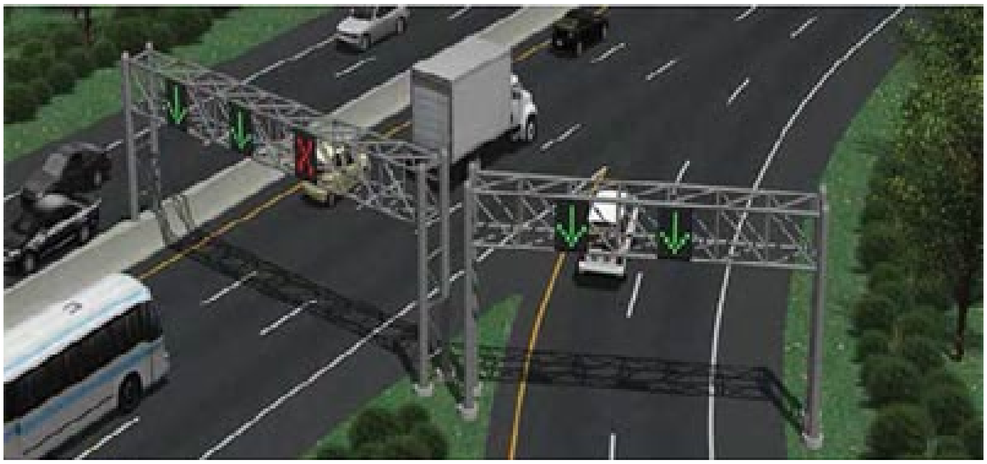
Dynamic lane use control has the potential to improve travel time reliability, especially when used in combination with other dynamic lane assignment strategies. This is because it enables lane arrangements to change in response to traffic conditions, even if the traffic conditions are unexpected.

Safety Performance Evaluations: There are few known safety performance evaluations of dynamic lane use control outside of those for part-time shoulder use (covered in a previous section). The analysis by Dutta et al. of the I-66 Active Traffic Management System in Virginia included evaluation of the safety performance of lane use control signals (LUCS).(52) The study used 21 weeks of before data and 13 weeks of after data to perform a before-after EB analysis and found no statistically significant change in crash frequency for road segments with LUCS.

A search of "lane use" and "lane control" on the CMF Clearinghouse did not return any relevant results.

Dynamic Junction Control

General Description of Strategy: Dynamic junction control (also known as dynamic merge control) is a strategy that dynamically allocates lane access based on downstream conditions. It is often used at interchanges with high traffic volumes and relative traffic demands between mainline and ramps that change throughout the day.(60,61) Dynamic junction control is implemented to improve vehicle flow at freeway entrance and exit ramp locations by providing capacity to vehicles entering the freeway. Figure 6 depicts an example of the signage required to operate a dynamic merge system.



Source: FHWA

Figure 6. Graphic. Rendering of a dynamic merge control arrangement in a freeway setting.(62)

FHWA's overview of Active Traffic Management approaches in *Guidance for the Use of Dynamic Lane Merging Strategies* includes examples of what dynamic junction control might look like at entrance and exit ramp locations.(63) For exit ramp locations, dynamic junction control could consist of assigning lanes dynamically either for through movements, shared through-exit ramp movements, or exit-only movements. For entrance ramp locations, it could involve a dynamic lane reduction on the freeway mainline upstream of a high-volume entrance ramp. It could also involve extended use of a shoulder lane as an acceleration lane to turn a one-lane entrance ramp to a two-lane entrance ramp.

The performance effects of dynamic junction control are likely concentrated at ramp-freeway junctions of individual interchanges. It is possible that different lane assignment options at the ramp-freeway junctions could have effects upstream and downstream of those locations. This strategy could be applied at one or more interchanges on a congested freeway facility. Dynamic junction control has a strong link to travel time reliability, because it enables the capacity of specific movements at freeway entrance and exit ramp locations to change in response to traffic conditions, even if the traffic conditions are unexpected.

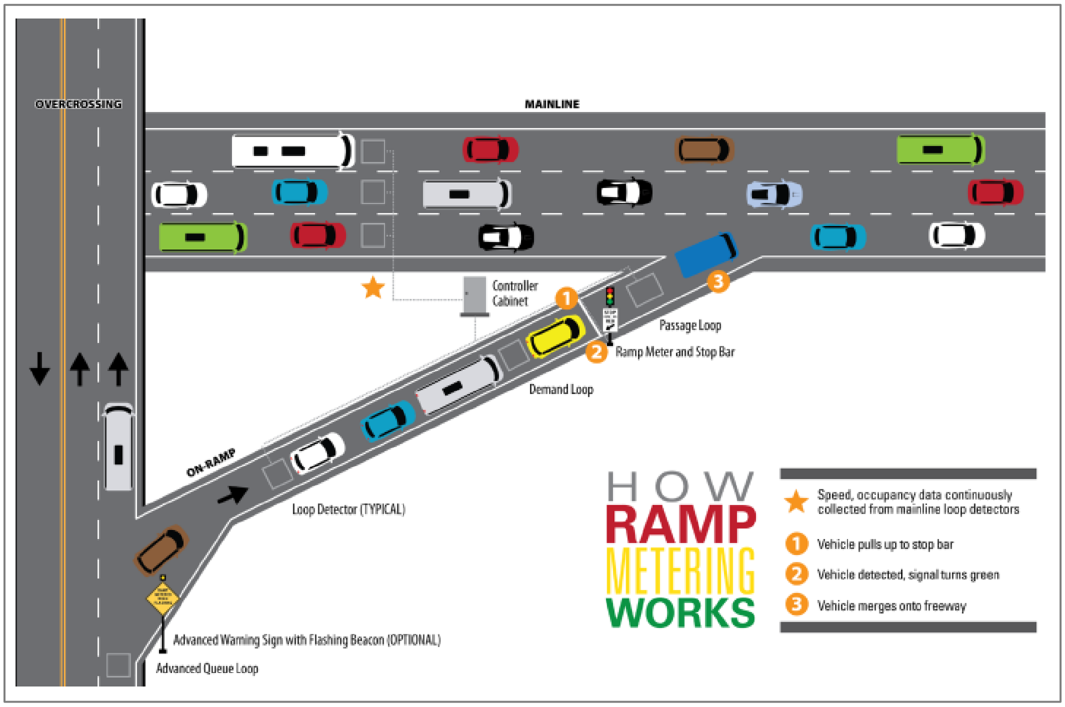
Dynamic junction control is also commonly deployed in temporary applications, especially in the case of work zone lane closures. Many work zone-specific systems are designed to alternate dynamically between early merging (most effective in low congestion conditions) and late, or zipper, merging (most effective in congested conditions).(63)

Changing lane access at interchanges as part of dynamic junction control changes the freeway cross section geometric characteristics, including number of through lanes on the freeway mainline as well as the cross-section design characteristics of the entrance and exit ramp terminals.

Safety Performance Evaluations: There are no known safety performance evaluations of dynamic junction control. Searches of "junction" and "merge" on the CMF Clearinghouse did not return any relevant results.

Ramp Metering

General Description of Strategy: Ramp meters are traffic signals installed on freeway on-ramps to control the rate at which vehicles enter the flow of traffic on the freeway mainline.(64) The rate at which the ramp meters release vehicles onto the freeway depends on the mainline traffic volume and speed. Figure 7 below shows the basic operation of a ramp meter.



Source: FHWA

Figure 7. Graphic. Basic ramp metering configuration.(65)

The primary reason to implement ramp metering is to improve vehicle flow by breaking up platoons of vehicles entering the freeway from an entrance ramp and by managing the entrance demand to a level that seeks to keep the freeway operating under capacity. However, ramp metering is also implemented based on the assumption that the strategy can reduce merge-related crashes.

Implementing ramp metering does not require changes to roadway geometrics, but there are some design and operational considerations for determining the location of the ramp meter. These include the distance from the crossroad to the ramp meter for queue storage and the distance from the ramp meter to the freeway entrance terminal to provide for vehicle acceleration.

Safety Performance Evaluations: MnDOT evaluated the effectiveness of ramp meters using data from four selected corridors in the Twin Cities Metropolitan region.(66) They collected data during five-week time periods when ramp meters were operating and then during a subsequent phase when ramp meters were deactivated. The results showed that the frequency of observed peak-period crashes (all types and severities combined) increased by 26-percent during the deactivation phase while controlling for seasonal variation using data from equivalent periods during the previous two years.(66) Exploration of crash types showed significant increases in rear-end (15-percent), side-swipe (200-percent), and run-off-road (60-percent) crashes, which are the most typical types of ramp-related crashes. An additional crash severity analysis showed a significant 33-percent increase in the frequency of no apparent injury crashes when ramp metering was deactivated, but no significant changes in the frequency of fatal or injury crashes (likely due to small sample sizes of these crashes). The standard errors and confidence levels for these findings were not reported by the authors.

Other cities have conducted similar studies to evaluate new ramp metering systems. While these studies generally focus on operational metrics and suffer from small crash data sample sizes and limited analysis, they can still provide information to inform future exploration of the safety effects of ramp metering. The Kansas and Missouri Departments of Transportation jointly operate a transportation program for Kansas City, which conducted an evaluation of a ramp metering pilot program. One year after the installation of the ramp meters, the results showed a 64-percent decrease in the frequency of all crashes, and an 81-percent decrease in the frequency of merge-related crashes.(67) A press release from the Colorado DOT reported that rear-end and side-swipe crashes were reduced by about 50-percent due to the implementation of a ramp metering pilot program in Denver (the analysis period was not reported).(68) However, neither study indicated any analysis of crash severity, and all of the analysis results were based on naïve comparisons of observed crash frequencies. Additionally, standard errors and confidence levels were not reported by the authors for either study.

Liu & Wang conducted a before-after safety evaluation of 19 metered on-ramps in Northern California.(69) The researchers collected data for three years before and three years after the ramp meters were implemented and compared before crash rates to after crash rates for the segments 0.1 miles upstream of the merge points to 0.1 miles downstream of the merge points. The study found a 36-percent reduction in the total crash rate (all types and severities combined) on the study sections (standard error and confidence level were not reported by the authors).

Drakopoulos et al. evaluated the incremental effectiveness of six new ramp meters (in addition to six previously existing meters) on US 45 in Wisconsin.(70) The study used six months of before data and six months of after data and revealed a 16-percent reduction in crash frequency and a 13-percent decrease in crash rate following the implementation of the additional ramp meters (standard errors and confidence levels were not reported by the authors). However, the study noted that during the installation of the ramp meters, additional geometric improvements and resurfacing operations were conducted that may have also affected the safety performance of the roadway.

Aydos & O'Brien analyzed 25 of 84 total ramp metering sites in Auckland, New Zealand that were operated through the Sydney Coordinated Adaptive Traffic System (SCATS) Ramp Metering System. The authors selected these sites based on data availability and to limit the effect of construction operations on the findings. A naïve before-after study of the crash data concluded that there was a 22.1-percent reduction in crashes (with a standard error of 4.3-percent) following the implementation of ramp metering.(71) This result was statistically significant at a 99-percent confidence level.

A variety of studies have attempted to assess the safety effects of ramp metering using simulation techniques and surrogate measures of safety. Lee et al. studied a section of I-880 in California as well as a hypothetical on-ramp network by incorporating a log-linear real-time crash prediction model into PARAMICS microsimulation software. The model estimated crash potential based on surrogate safety measures, including speed variation, speed difference between upstream and downstream points, and volume difference between upstream and downstream points. The model was calibrated using one year of crash data. The results indicated that ramp metering reduced crash potential (for all types and severities) by 5- to 37-percent, with the most notable results occurring in congested conditions.(72) The standard error was 2- to 3-percent, and the change was statistically significant at a 95-percent confidence level. Abdel-Aty et al. and Gayah also used PARAMICS to investigate ramp metering in Orlando, Florida. Abdel-Aty et al.'s study focused on the congested traffic regime, using a previously developed crash probability model that considered speed variance, loop detector occupancy, and volume variance.(73) The model found that metering more ramps compounds the benefit of reduced crash probability. Gayah's study used neural networks to convert the simulation results into rear-end and lane-change crash probability values based on geometric and loop-detector data. The neural network application showed that ramp metering can reduce the crash probability for rear-end and lane-change crashes, particularly under congested conditions. Furthermore, the performance of the ramp metering algorithm depends on the congestion condition. However, ramp metering showed the potential for inducing slight crash migration in some scenarios.(74) This means that implementation of ramp metering may reduce crash probability at the immediate location but result in an increased crash probability at an upstream or downstream location. Gayah found that, in most cases, the migration effect was negligible. In a subset of sites, the increase at upstream and downstream locations was significant, which indicates that careful site-specific analysis should be performed prior to introducing ramp metering.

Summary

The synthesis of ramp metering safety research discussed several safety evaluations based on an analysis of crash data. All indicated improvements in safety performance (see table 7), but all used what is generally thought to be the least reliable type of observational study design: a naïve before-after study comparing observed crash frequencies or rates. There is a need for a more robust and defensible safety performance evaluation to build on these previous results. Additionally, further guidance is needed regarding the spatial limits of the study area when analyzing crashes in the context of ramp metering. Ramp metering is likely to only affect crashes within a certain influence area surrounding the treatment site, as opposed to all crashes on the freeway mainline. A search for "ramp meter" in the CMF Clearinghouse results in only one CMF: a three-star CMF of 0.64 for all crash types and severities combined based on the Liu & Wang study (CMF ID 5436).(69) Safety evaluations based on surrogate measures of safety had similar results to the naïve before-after studies. One surrogate-based study showed the importance of crash analysis at upstream and downstream locations prior to finalizing selection of ramp metering because changes in the surrogate measures at these locations pointed to an increase in crash frequency at the upstream and downstream locations.

Table 7. Summary of safety performance evaluation findings for ramp metering.

Study	Location	Site type	Method	Findings
Cambridge Systematics, Inc., 2001(66)	Minneapolis-St. Paul, MN	Urban freeway	Naïve before-after	When ramp meters were deactivated: • Peak-period overall crash frequency increased 26% • Increase in rear-end (15%), sideswipe (200%), and run-off-road (60%) crash frequencies • 33% increase in no apparent injury crash frequencies, no significant change in fatal or injury crash frequencies
Kansas City SCOUT, 2011(67)	Kansas City, KS/MO	Urban freeway	Naïve before-after	• 64% decrease in overall crash frequency • 81% decrease in merge-related crash frequency
Liu & Wang, 2013(69)	Northern CA	Urban freeway	Naïve before-after	36% reduction in overall crash rate
Drakopoulos et al., 2004(70)	Milwaukee, WI	Urban freeway	Naïve before-after	13% reduction in overall crash rate (other geometric improvements confounded findings)
Aydos & O'Brien, 2014(71)	Auckland, New Zealand	Urban freeway	Naïve before-after	22.1% reduction in overall crash frequency (SE 4.3%, significant at 99%)
Lee et al., 2006(72)	Hayward, CA	Urban freeway	Simulation-based surrogate study	• Ramp metering reduced crash potential 5-37% (SE 2-3%, significant at 95%) • Most notable results occurred in congested conditions

Study	Location	Site type	Method	Findings
Abdel-Aty et al., 2007(73)	Orlando, FL	Urban freeway	Simulation-based surrogate study	Metering more ramps increases the potential safety benefits by decreasing estimated crash probability
Gayah, 2006(74)	Orlando, FL	Urban freeway	Simulation-based surrogate study	• Ramp metering can reduce the probability of rear-end and lane-change crashes, particularly under congested conditions • Different ramp metering algorithms perform better under different congestion conditions • Ramp metering showed potential for crash migration in some scenarios

Variable Speed Limits

General Description of Strategy: VSLs are a strategy that allows speed limits at a location to change based on prevailing road, traffic, and weather conditions. Variable speed limits harmonize operating speeds and improve driver expectation by providing information in advance on slowdowns and potential lane closures. Some publications have suggested that this strategy offers considerable promise in restoring the credibility of speed limits.(75,76) VSL systems utilize information on traffic speed, occupancy, volumes, weather, and road surface conditions to determine appropriate speeds and display them for drivers.(75) Figure 8 shows an example of VSL signage, though there are numerous types of VSL signs depending on different system or site characteristics. VSL may be implemented as either a regulatory or an advisory system (or both).

Source: FHWA

Figure 8. Graphic. Rendering of variable speed limit sign gantry in Seattle, WA.(77)

The primary reason to implement this strategy is to improve safety performance by decreasing the frequency of crashes associated with traveling at speeds that are higher than the speed appropriate for the prevailing conditions. The strategy also seeks to improve safety performance and traffic flow by reducing speed variance (i.e., improving speed harmonization) and reducing the probability for secondary crashes. VSLs are also implemented to mitigate adverse weather conditions or to slow faster-moving traffic as it approaches a queue or bottleneck

Safety Performance Evaluations: In May 2008, the Missouri Department of Transportation (MoDOT) installed signs with VSL on the I-270/I-255 loop around St. Louis with the objectives of improving traffic flow, preventing traffic flow breakdown, reducing congestion and delay, and improving safety performance. During rush hours and traffic incidents, an automated system set speed limits between 40 mph and 60 mph to support speed harmonization within and across lanes. More specifically, MoDOT sought to lower speed limits upstream of congestion to reduce the closing speed of incoming traffic.

Bham et al. examined the effect of this MoDOT VSL application on changes in travel time, travel time reliability, capacity, number of crashes, and crash severity.(78) The team conducted descriptive comparisons of observed crash counts, a naïve before-after study, and a before-after EB study. The analyses used one year of before data and one year of after data. The descriptive comparisons looked at safety performance by time of day. Results were mixed, showing reductions in the observed number of morning peak crashes and slight increases in the number of evening peak crashes. The naïve before-after analysis and EB analysis included all crashes from the before and after periods (not just peak period crashes). The before-after EB study found that the VSL system contributed to an estimated 8.4-percent overall reduction in crash frequency for all types and severities (with a standard error of 3.8-percent).(78) This result was statistically significant at a 95-percent confidence level.

Pu et al. evaluated a VSL deployment on a seven-mile section of I-5 in Washington, which displayed automated speed limits based on real-time traffic conditions.(79) The study used 3.5 years of before data and 2.5 years of after data to perform a before-after EB analysis. Results showed an average crash frequency reduction of 29-percent (with a standard error of 5-percent) for all crash types and severities. This result was significant at a 95-percent confidence level. Additional analysis showed that VSL implementation reduced property damage only crashes (O crashes) by 25-percent (standard error of 7-percent), possible injury crashes (C crashes) by 28-percent (standard error of 10-percent), and crashes with fatalities, suspected serious injuries, and suspected minor injuries (KAB crashes) by 19-percent (standard error of 24-percent). All of these crash severity results were significant at a 95-percent confidence level except for the decrease in KAB crashes.

Siddiqui et al. investigated safety effects of an advisory VSL system deployed along the Oregon (OR)-217 freeway in Portland, OR based on five months of after data.(80) This system was part of an OR-217 active traffic management project, which was intended to address safety performance and congestion along the corridor. Analysis of crash data and surrogate safety measures showed a decrease in total crash frequency, total crash rate, and the rear-end crash rate, despite an increase in VMT on the corridor. A naïve crash analysis showed a decrease of 14.8-percent in crash rate for total crashes (all types and severities) and a decrease of 10.5-percent in crash rate for rear-end crashes. Standard errors and confidence levels were not reported by the authors. Due to the recent deployment of the system, only five months of after data was available, which is why surrogate safety measures, in this case mean speed and speed variability, were explored and used. The system was found to generally reduce mean speed and speed variability within the same lane and between the median and outside lanes.

De Pauw et al. used a before-after EB study to assess the safety performance effects of a variable speed limit system on 60 km of freeways in Flanders, Belgium using crash data from 1999 to 2011.(81) The analysis showed that there was an 18-percent reduction in the number of injury crashes (KABC) following implementation of VSL (with a standard error of 6.6-percent). This result was statistically significant at a 95-percent confidence level. Other results, such as a decrease in fatal and suspected serious injury crashes and a decrease in rear-end crashes, were not statistically significant at a 95-percent confidence level.

Kuhn et al. evaluated a VSL pilot project in Texas which sought to examine the effectiveness of VSL for application in construction work zones, adverse weather conditions, and urban congestion. The study used six months of before data and one year of after data to conduct a naïve before-after analysis. Results showed a 31-percent decrease in overall crash frequency (all types and severities) after the implementation of the VSL pilot program, with associated decreases in crash severity, particularly in the proportion of fatal and incapacitating injury crashes. However, the authors stated that no statistical significance tests were conducted due to the short duration of the analysis period. (82)

Wyoming DOT installed four different weather based VSL systems on a combined 147 miles of I-80 with the goal of reducing the potential for crashes under adverse weather or road surface conditions. Buddemeyer et al. performed a preliminary crash analysis on the Elk Mountain corridor of I-80.(83) . The analysis used five years of before data and one year of after data and results showed a 30-percent decrease in crash rates (standard error and confidence level were not reported by the authors). Gaweesh et al. used negative binomial and multivariate adaptive regression splines (MARS) models along with before-after EB methodology to analyze six years of before data and five years of after data on another section of I-80 in Wyoming. The results showed that the implementation of VSL led to reductions in crash frequency for fatal and injury crashes (KABC crashes) that were significant at a 95-percent confidence level (standard errors were not reported by the authors). Decreases in no apparent injury crashes (O crashes) were not statistically significant at a 95-percent confidence level.(84)

Some studies have used simulation methods and surrogate measures of safety in an attempt to quantify how the implementation of variable speed limits effect safety performance. Abdel-Aty et al. combined previously-developed crash prediction modeling techniques with microsimulation in PARAMICS to explore the effectiveness of VSL as a strategy for improving safety on interstate roadways.(85) The crash prediction model considered two separate speed regimes, with the threshold speed being 37.5 miles per hour. The high-speed regime used average occupancy and flow as inputs, and the low-speed regime considered average volume, occupancy, and coefficient of variation of speed. The study found that changing the speed limit by large amounts (such as 15 miles-per-hour) through a combination of gradual speed change over time (five miles-per-hour change every 10 minutes) and abrupt speed change in space (no transition zone with graduated speeds) produced the greatest reduction in crash potential at the study location. Lee et al. performed a similar analysis using PARAMICS and a log-linear crash prediction model on a 4.7-km section of freeway in Toronto, Canada.(86) The study investigated the effect of VSL activation threshold, duration, and control strategy on crash potential and found that implementing VSL can lead to reductions in the overall crash potential by 5- to 17-percent (standard errors and confidence levels were not reported by the authors). The surrogate safety measures examined included speed variation at a point, difference in speed variation between upstream and downstream locations, and the covariance of the volume difference between upstream and downstream locations on adjacent lanes (a measure of lane changing behavior). The researchers observed higher reductions in crash potential based on these surrogates for lower VSL activation threshold values (where the activation threshold is based on crash potential). Mid-length VSL intervention duration (five-to-ten minutes) was found to balance reduced crash potential and travel time, while longer and shorter durations significantly increased travel times while not providing significantly better safety performance.

Habtemichael & de Picado Santos assessed the effect of VSL implementation on vehicle conflicts on a 12-kilometer freeway segment in Lisbon, Portugal.(87) The segment was simulated in Vissim and then processed through SSAM to identify vehicle conflicts, using TTC and PET as the primary surrogate safety measures. The study notably simulated VSL effects under a variety of driver compliance levels, ranging from 25-percent to 100-percent. Results showed that VSL provided safety performance benefits based on the surrogate measures under all traffic conditions, but the improvement was highest under congested conditions. Additionally, the safety benefits did not come at the expense of operational efficiency. The magnitude of the benefits was highly dependent on the level of driver compliance.

Islam et al. proposed a predictive VSL control strategy and evaluated its safety effects using microsimulation and a crash prediction model.(88) The crash prediction model relied on loop detector data and developed a surrogate relationship between the detector data (average detector occupancy, speed variation, and volume variation) and crash occurrence. The model was calibrated using crash data from the study location, a 9.2-kilometer urban freeway segment in Edmonton, Canada. The authors found that a high standard deviation in vehicle speeds is the most important variable for predicting a crash. Results revealed lower average crash probabilities for the tested VSL scenarios compared to the "no VSL" case in congested crashes, resulting in a 31- to 50-percent reduction in predicted crash probability (standard errors and confidence levels were not reported by the authors). The model showed no improvements in the uncongested case. The best VSL scenario for safety performance involved an update frequency (frequency with which the VSL system is changing the speed limit) of five minutes, the longest update frequency of any tested scenario. This indicates that frequent changes to the posted speed limit may introduce traffic disturbances that may increase crash risk.

Summary

The synthesis of VSL safety research describes several safety evaluations based on an analysis of crash data. Almost all indicated improvements in safety performance although some findings were not significant (see table 8). Study designs varied from the less reliable naïve before-after studies comparing observed crash frequencies or rates to more robust before-after EB approaches. In some cases, the durations of before and after periods were short (e.g., one year). A search for "variable speed limit" in the CMF Clearinghouse results in the following:

- Four CMFs (three four-star and one two-star) for "install variable speed limits" based on the Pu et al. work discussed above (CMF IDs 8730 – 8733).(79)
- A four-star CMF for "install variable speed limit signs" based on the Bham et al. work discussed above (CMF ID 3340).(78)

Safety performance evaluations based on surrogate measures of safety had similar results to the safety performance benefits shown by the crash-based studies. The surrogate-based studies were able to offer results related to VSL system parameters such as activation threshold, update frequency, and intervention duration. The studies showed that these factors have the potential to significantly alter the safety performance effects of VSL (as, for instance, in Islam et al.'s study of VSL update frequency).(88)

At the time of this safety analysis needs assessment, FHWA Office of Safety R&D had initiated a safety evaluation of VSL under *Evaluation of Safety Improvements, Phase X*.

Table 8. Summary of safety performance evaluation findings for variable speed limits.

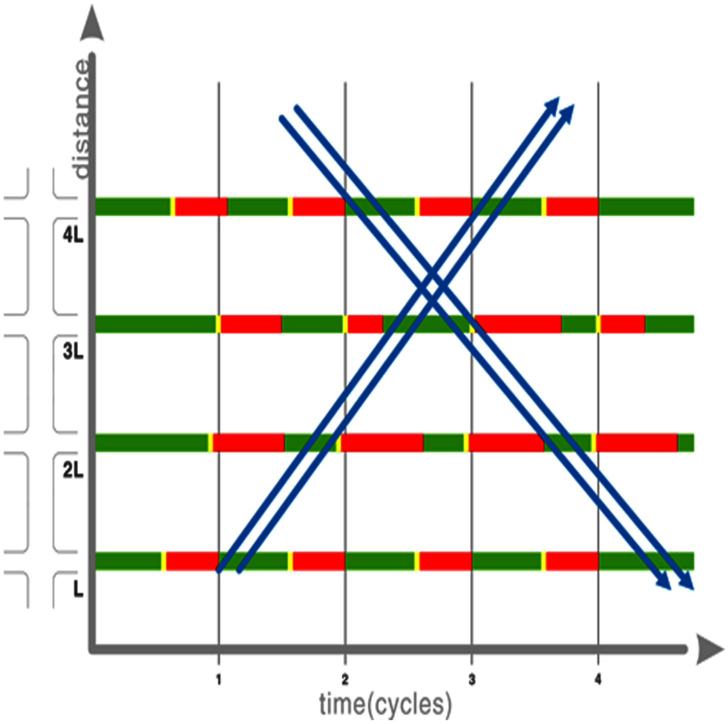
Study	Location	Site type	Method	Findings
Bham et al., 2010(78)	St. Louis, MO	Urban freeway	Before-after with EB	• Mixed results, with decrease in peak-period AM crashes and slight increase in peak-period PM crashes • Overall crash frequency decrease of 8.4% (SE 3.8%, significant at 95%)
Pu et al., 2016(79)	Seattle, WA	Urban freeway	Before-after with EB	• Overall crash frequency decrease of 29% (SE 5%, significant at 95%) • Reductions in no apparent injury (25%, SE 7%), possible injury (28%, SE 10%), and fatality/suspected serious injury/suspected minor injury (19%, SE 24%)

Study	Location	Site type	Method	Findings
				crash frequency (all results significant at 95% except for fatality/serious injury/minor injury)
Siddiqui & Al-Kaisy, 2016(80)	Portland, OR	Urban freeway	Naïve before-after and analysis of surrogate measures	• Overall crash rate decrease of 14.8% • Rear-end crash rate decrease of 10.5% Decrease in mean speed and speed variability both within the same lane and between the median and outside lanes.
De Pauw et al., 2018(81)	Flanders, Belgium	Urban freeway	Before-after with EB	• Minor injury crash frequency decrease of 18% (SE 6.6%, significant at 95%) • Minor injury rear-end crash frequency decrease of 20% (not significant at 95%)
Kuhn et al., 2015(82)	San Antonio, TX; Temple, TX; Ranger Hill, TX	Urban and rural freeway	Naïve before-after	Overall crash frequency decrease of 31%
Buddemeyer et al., 2010(83)	Southern WY	Rural freeway	Naïve before-after	Overall crash rate decrease of 30%
Gaweesh et al., 2018(84)	Southern WY	Rural freeway	Before-after with EB	Fatal and injury crash frequency reductions (significant at 95%). No apparent injury crash frequency reductions not significant.
Abdel-Aty et al., 2005(85)	Orlando, FL	Urban freeway	Simulation-based surrogate study	Changing the speed limit by large values, with gradual change over time and abrupt change in space produced the greatest reduction in crash potential
Lee et al., 2006(86)	Toronto, Canada	Urban freeway	Simulation-based surrogate study	• VSL can lead to overall crash potential reductions of 5-17% • Higher reductions in crash potential for lower activation threshold values

Study	Location	Site type	Method	Findings
				• Mid-length VSL intervention duration balanced reduced crash potential with increased travel time
Habtemichael & de Picado Santos, 2013(87)	Lisbon, Portugal	Urban freeway	Simulation-based surrogate study	• Safety benefits of VSL were highest under congested conditions • Safety benefits did not come at the expense of operational efficiency
Islam et al., 2013(88)	Edmonton, Canada	Urban freeway	Simulation-based surrogate study	• Crash probability decrease of 31-50% for best-case VSL scenario • No safety benefits in uncongested conditions

Traffic Signal Coordination

General Description of Strategy: Coordination of traffic signal phasing across multiple signalized intersections can enhance the operation of one or more directional movements in a system. Figure 9 shows a time-space diagram as a graphical representation of a well-coordinated signalized corridor, with the blue arrows showing 'green bands' or areas where vehicles, if travelling at the speed trajectory denoted by the arrow, will not have to stop. Vehicles traveling both directions on the corridor can pass through the four signals without being stopped by a red indication, improving the platooning and operational efficiency of the corridor. Example applications for traffic signal coordination include two signals controlling a diamond interchange, a series of signalized intersections along an arterial street, and downtown networks of actuated and fixed time signals controlling an arterial system.(89)



Source: FHWA

Figure 9. Graphic. Time-space diagram of a coordinated timing plan for a corridor with four signals.(89)

The primary reason to coordinate traffic signals is to improve vehicle flow along the coordinated street by reducing stops, delay, and travel times for the selected movements on which the coordination is based.(89) This responds to an FHWA operational objective of "Smooth Flow," which is intended to encourage improved progression through signalized arterial corridors. Additionally, arterial signal coordination can have secondary effects on other objectives, such as "Maximize Throughput" and "Manage Queues".(90) The performance effects of traffic signal coordination will be observed primarily along the facility containing the coordinated signals. Performance effects along the crossing facilities are also possible.

A Denver Regional Council of Governments (DRCOG) summary of 15 arterial traffic signal coordination efforts showed consistent travel time reductions (as well as reductions in fuel consumption and emissions). On local facilities, cross streets, left turns, pedestrians, and cyclists may experience higher delays depending on how coordination operation is programmed.

Safety Evaluations: Williamson et al. conducted a before-after analysis with comparison sites for five urban corridors in southern Illinois and combined results across the different sites using a meta-analysis method with weighting based on standard error.(91) The results showed that implementing arterial signal coordination decreased the frequency of all crash types and severities (though there were no fatal crashes in the dataset). Total crash frequency decreased by 21-percent and injury crashes decreased by 52-percent (when the results from individual sites were combined). However, the changes in total and injury crash frequency at several of the sites showed very high standard errors and were not statistically significant.

Rakha et al. attempted to estimate the safety performance effects of arterial signal coordination using before and after data from a 9.6-km corridor project between Tempe and Scottsdale, Arizona.(92) Safety performance effects were estimated by comparing observed before and after crash rates, which showed an overall corridor level 6.7-percent reduction following implementation of the signal coordination. This result was statistically significant at a 99-percent confidence level, but the standard error was not reported. However, results varied across intersections and likely suffered from small sample sizes at the individual intersection level and the less reliable study design and analysis approach.

Li & Tarko analyzed the safety performance effects of signal timing characteristics at 36 intersections that were part of coordinated systems in Indiana.(93) Their analysis focused on rear-end and angle crashes. The authors used a multinomial logit model to estimate the probability of either a rear-end crash, right-angle crash, other crash, or no crash during 15-minute intervals. They also developed a binary logit model to estimate the probability that a crash that did occur resulted in either an injury or no injury. The following were signal timing-related safety findings:

- Higher concentrations of vehicles arriving in the first half of the red signal were associated with higher probabilities of a rear-end or right-angle crash;
- Higher concentrations of vehicles arriving in the first two seconds of the green signal were associated with higher probabilities of a rear-end or right-angle crash;
- Higher concentrations of vehicles arriving during the second half of the green signal were associated with lower probabilities of a rear-end or right-angle crash;

- Higher concentrations of vehicles arriving during the second half of the green signal were associated with higher severities of rear-end crashes, but lower severities of right-angle crashes.

The model developed by Li & Tarko also includes variables related to intersection geometry, presence of turn lanes, and various signal timing parameters.

There are several studies that identify potential reductions in safety performance as a result of signal coordination. Jolovic et al. used negative binomial and multinomial logit techniques to model the effect of various traffic signal timing parameters on crash frequency and severity in Fort Lauderdale, Florida.(94) The researchers expected longer cycle lengths to reduce crash severity, as longer cycle lengths introduce more flexibility for implementing signal coordination and improving arterial progression. This in turn reduces the number of stops at an intersection, which could be correlated with the occurrence of rear-end crashes, one of the most common intersection-related crash types. However, the negative binomial model results showed that longer cycle lengths had the opposite effect, increasing crash frequencies. The researchers hypothesized that longer cycle lengths may be a sign of increased exposure on the corridor in question, implying increased time required to clear the intersection due to heavier traffic. The multinomial logit results indicated that crash severity decreased with longer cycle lengths. This may be because traffic speeds decrease due to congested conditions that might be more common when longer cycle lengths are present.

Tindale & Hsu contended that coordinated traffic signal systems may incentivize drivers to increase their speed to stay in or catch up to the progression platoon.(95) Their study focused on one-way roads, which are often easier to coordinate. The study involved a crash analysis based on a descriptive analysis of observed crash data in the Tampa-St. Petersburg metropolitan area in Florida. The results showed that coordinated urban one-way roads exhibited a disproportionate share of red light-running crashes, representing nearly 15-percent of crashes compared to an average of 3.3-percent across all road types.

Guo et al. assessed expected crash frequency (all crash types and severities combined) at four-leg, signalized intersections in Central Florida. The study used a variety of modeling techniques, including Poisson and negative binomial Bayesian models, mixed-effects models, and conditional autoregressive models. The Poisson spatial model provided the best fit based on Deviance Information Criterion (DIC). The results showed that the intersections in coordinated systems had 53-percent more intersection and intersection-related crashes than those that were not in coordinated systems.(96) The authors noted that it was unclear how much of this finding to attribute to the operational results of coordination (e.g., higher speeds) versus the confounding effects of variables omitted from their analysis. These omitted variables could distinguish intersections that are likely to be coordinated from those that are not (e.g., high volumes, proximity to other intersections).(96)

Stevanovic et al. performed a simulation-based study to examine the effects of signal timing optimization on surrogate measures of safety.(97) The study used Vissim microsimulation to produce vehicle trajectory data, which was then fed into the SSAM to assess the number of vehicle conflicts. The signal timings in the Vissim model were optimized using VISGAOST, a Vissim plug-in. Vehicle conflicts were identified based on threshold values of TTC and PET, and SSAM determined the type of conflict based on the conflict angle and geometric information. Results showed there is a balance between improving safety performance by reducing conflicts and increasing efficiency measured as intersection throughput. By using the ratio of the number of conflicts to throughput as the objective function in the optimization process, the optimal scenario decreased the estimated number of conflicts by 7-percent while the throughput remained steady.

Summary

The synthesis of safety research on traffic signal coordination uncovered several safety evaluations based on an analysis of crash data and one based on simulated safety surrogates. Results were mixed (see table 9) ranging from 21-percent and 53-percent reductions in total and injury crash frequencies, respectively, to 53-percent increases in intersection and intersection-related crashes. Study designs and analysis varied, likely leading to this mix in findings.

A search for “coordinate” in the CMF Clearinghouse results in the following:

- 18 CMFs (two-star to three-star) for “coordinate arterial signals,” for all crash types and various severities and areas, based on the Williamson et al. study summarized above (CMF IDs 9853 – 9870).(91)
- Two CMFs (one two-star and one three-star) for “presence of right turning lane on arterial with signal coordination,” for rear-end and angle crashes at all severities (CMF IDs 3071 and 3073). One three-star CMF for “change number of cycles per hour on arterial with signal coordination,” for rear-end crashes of all severities (CMF ID 3072). These three are based on the study by Li & Tarko.(93)

One surrogate-based study indicated a balance or trade-off between vehicle throughput and number of intersection conflicts.

The work of Li & Tarko offered an example of the effective use of a probabilistic model of crash occurrence in short time intervals to gain key insights that are not possible with more macro-level (i.e., annual) crash-based analysis. Their models were able to show how crash probabilities changes based on the number of vehicles arriving during different times of the red and green signal indications. Such an approach holds promise for several other TSMO strategies and could be used in combination with other study design and analysis approaches.

Table 9. Summary of safety performance evaluation findings for traffic signal coordination.

Study	Location	Site type	Method	Findings
Williamson et al., 2018(91)	Southern IL	Urban signalized arterial	Before-after with comparison sites; meta-analysis	• Overall crash frequency decrease of 21% (not significant) • Injury crash frequency decrease of 52% (not significant)
Rakha et al., 2000(92)	Tempe-Scottsdale, AZ	Urban signalized arterial	Naïve before-after	Decrease of 6.7% in overall crash rate (significant at 99%)
Li & Tarko, 2011(93)	Danville, IN; Frankfort, IN; West Lafayette, IN	Urban signalized arterial	Multinomial logit for occurrence of specific crash types Binary logit for crash severity	• More vehicles arriving in first half of red signal associated with higher probabilities of RE or RA crash; • More vehicles arriving in first two seconds of green signal associated with higher probabilities of RE or RA crash; • More vehicles arriving during second half of green signal associated with lower probabilities of RE or RA crash; • More vehicles arriving during second half of green signal associated with higher severities of RE crashes, but lower severities of RA crashes.
Jolovic et al., 2016(94)	Ft. Lauderdale, FL	Urban signalized arterial	Negative binomial regression for crash frequency Multinomial logit for crash severity	Longer cycle lengths increased crash frequencies, but decreased crash severities
Tindale & Hsu, 2005(95)	Tampa-St. Petersburg, FL	Urban one-way streets	Naïve comparison of descriptive statistics	Coordinated urban one-way streets represent 15% of crashes compared to average of 3.3% across all road types
Guo et al., 2010(96)	Orlando, FL	Urban signalized arterial	Poisson and negative binomial Bayesian models	Coordinated intersections had 53% more intersection-related crashes

Study	Location	Site type	Method	Findings
Stevanovic et al., 2013(97)	Boca Raton, FL	Urban signalized arterial	Conflict analysis (SSAM)	• There is a balance between increasing safety by decreasing conflicts and increasing efficiency measured as intersection throughput • Optimal timing scenario led to decrease of 7% in overall conflicts while throughput remained steady

Adaptive Signal Control Technology

General Description of Strategy: Adaptive Signal Control Technology (ASCT) uses vehicle detection technology and traffic control algorithms to continually adjust traffic signal timing parameters based on traffic conditions. ASCT includes algorithms that adjust split, offset, phase length, and phase sequence to better accommodate patterns in demand and therefore minimize delays and reduce the number of stops.(98) There are numerous private-sector ASCT products available, with a variety of unique methods, algorithms, and hardware and data implications. Some of the most common products include SCATS, SCOOT, InSync, RHODES, ASC Lite, and SURTRAC. ASCT is an FHWA Every Day Counts (EDC) – Round 1 innovation.

The primary reason to implement ASCT is to address high variability in traffic demand. High variability in demand can require frequent modification of traffic signal timing, which is difficult to accomplish using traditional time-of-day plans. ASCT can be particularly useful for intersections that are affected by special events or where conventional time-of-day cycles cannot be effectively determined because of highly-variable or unpredictable demand. ASCT is commonly applied to a series of intersections on a facility, though it may offer improvement in the case of isolated major intersections.(90) The spatial extent of ASCT performance effects would therefore depend on the application but is commonly observed at the arterial facility level.

Evaluations of ASCT have shown improvements in travel time, control delay, emissions, and fuel consumption, with the level of improvement dependent on characteristics of demand and the traffic signal systems that were replaced by ASCT.(98) This strategy also has a strong link to travel time reliability because it enables signal timing to adjust in response to changing traffic conditions, even if the changes are unexpected.

Safety Performance Evaluations: Ma et al. evaluated the safety performance effects of ASCT at 47 urban and suburban intersections in Virginia. The researchers employed a before-after with EB study design and analysis approach.(99) The analysis produced a total crash reduction (i.e., all types and severities) of 17-percent (with a standard error of 5-percent). This result was significant at a 95-percent confidence level. Fatal and injury crash frequency decreased by 8-percent (with a standard error of 8-percent). This result was not statistically significant. The authors pointed out that safety benefits varied by facility and traffic volume and noted that this could be due to the differences in operational changes that resulted from ASCT on those facilities. They could not, however, confirm this explanation through statistical analysis.

Fink et al. investigated the safety effects of the SCATS-based ASCT system known as FAST-TRAC in Oakland County, MI.(100) The study used a cross-sectional before-after design to compare intersections with FAST-TRAC in Oakland County to similar intersections without it elsewhere in Michigan. Crash frequencies were modeled using negative binomial models and crash severity was modeled using multinomial logit models. The resulting estimates showed that the frequency of angle crashes was 19.3-percent lower at intersections with SCATS-based controllers. There were no statistically significant differences in the frequencies of total (i.e., all types) and rear-end crashes at intersections with and without the SCATS-based controllers. The analysis of crash severity indicated that crashes occurring at intersections with SCATS-based controllers were less severe, but the results were not statistically significant.

Khattak et al. estimated CMFs for ASCT technologies at 41 urban and suburban intersections in three Pennsylvania cities and towns.(101) They used the before-after EB study design and analysis approach to estimate the changes in the frequency of multiple-vehicle crashes within 350 ft of intersections where ASCT was implemented. The dataset consisted of two types of ASCT systems, SURTRAC and InSync, which differ in their data collection and optimization methods. The number of before years for the intersections ranged from two to four and the number of after years ranged from three to five. Intersecting roads had speed limits ranging from 25 mph to 45 mph with average mainline AADTs of 26,700 vehicles per day. The article did not include details on signal phasing and timing in the before conditions. The analysis resulted in a decrease of 13-percent (with a standard error of 6-percent) for total multiple-vehicle crashes (i.e., all multiple-vehicle crash types and severities) and a decrease of 36-percent (with a standard error of 6-percent) for fatal and injury multiple vehicle crashes across all intersections. These results were significant at a 95-percent confidence level. Additionally, the study found statistically significant reductions in the frequency of fatal and injury multiple-vehicle crashes for both systems independently, while only the InSync system was shown to result in a statistically significant reduction in total multiple-vehicle crashes (at a 95-percent confidence level). Statistically significant reductions were found independent of the number of intersecting legs (three or four). The authors also performed an analysis of crash type proportions and found a 2.9-percent increase in the proportion of head-on crashes (significant at a 95-percent confidence level).

Khattak et al. performed a follow-on study of the effect of ASCT on injury severity, specifically focused on deployments of different products across different states.(102) The study used a naïve before-after analysis and a random parameters ordered probit model to examine crash and intersection data from 49 intersections in Virginia (3,836 crashes over 10 years) and 42 intersections in Pennsylvania (722 crashes over 7 years) where one of two ASCT products had been deployed (the products were not identified by name). The sample size of fatal crashes was too small to analyze so fatal crashes were discarded from the analysis and crashes were grouped into three crash severity categories: suspected serious and suspected minor injury crashes (AB in KABCO); possible injury crashes (C in KABCO), and property damage only crashes (O in KABCO). An overall model of both states and both ASCT product types revealed that the presence of ASCT decreased the potential for suspected serious injury and suspected minor injury crashes by 5.24-percent and possible injury crashes by 9.91-percent, while increasing the potential for property damage only crashes by 15.15-percent. These results were significant at the 99-percent level (standard errors were not reported by the authors). In analyzing crash types, the study found that rear-end crashes resulted in increased injury severity in the presence of ASCT. The researchers hypothesized that this could be due to increased speeds encouraged by improved traffic flow following the implementation of ASCT. Individual models were estimated for each state, and these models showed that the differences between the two states were negligible. Additionally, the results showed similar effects between the two different ASCT products.

Stevanovic et al. performed a simulation-based study of surrogate safety performance measures related to the implementation of SCATS on 14 intersections in Utah.(103) The study involved feeding the vehicle trajectory results of a Vissim microsimulation into the SSAM, using TTC, PET, and conflict angle as surrogate measures of safety performance. The results showed that implementing SCATS led to an 11-percent reduction in total vehicular conflicts (all types), which was primarily driven by a reduction in rear-end conflicts. However, implementation of SCATS increased the number of crossing conflicts (particularly for the side-street movements) by 28-percent. Standard errors and confidence levels were not reported by the authors. The researchers noted that most of these crossing conflicts occurred at the busiest intersection on the corridor, and also pointed to Gettman et al.'s study which reported that crossing conflicts are generally among the less reliable SSAM estimates.(104) The study also attempted to validate the link between SSAM conflict identification and crash data but was unsuccessful due to a small sample size of crash data as well as construction activities and other confounding factors.

Summary

The synthesis of safety research on ASCT uncovered several safety evaluations based on an analysis of crash data and one based on simulated safety surrogates (see table 10). Results indicated that ASCT reduces both crash frequency and severity. The extent of reductions will likely depend on the operational conditions along the facility with ASCT both before and after its implementation. As with some of the studies on traffic signal coordination, there were indications that the severity of some crash types could increase due to higher operating speeds that result from the improved operational performance of ASCT. A search of "adaptive" on the CMF Clearinghouse returned 25 different CMFs for "install adaptive traffic signal control." Most were three- and four-star, and came from the studies by Ma et al., Khattak et al., and Fink et al. detailed above (CMF IDs 6856 – 6861, 9764 – 9781, 7922).(99,100,101)

At the time of this report, FHWA Office of Safety R&D had initiated a safety evaluation of adaptive signal control technologies under *Evaluation of Safety Improvements, Phase X*.

Table 10. Summary of safety performance evaluation findings for adaptive signal control technology.

Study	Location	Site type	Method	Findings
Ma et al., 2014(99)	VA	Urban signalized arterial	Before-after with EB	• Overall CMF of 0.83 (17% crash frequency decrease, SE 5%, significant at 95%) • Fatal and injury CMF of 0.92 (8% crash frequency decrease, SE 8% not significant)
Fink et al., 2016(100)	Oakland County, MI	Urban signalized arterial	Naïve before-after, multinomial logit model of crash severity	• Decrease of 19.3% in angle crash frequency • No significant results for overall or rear-end crashes or crash severity
Khattak et al., 2018(101)	Pittsburgh, PA; Montgomery Township, PA; Upper Merion Township, PA	Urban signalized arterial	Before-after with EB	• Overall multiple-vehicle CMF of 0.87 (13% crash frequency decrease, SE 6%, significant at 95%) • Fatal/injury multiple-vehicle CMF of 0.64 (36% crash frequency decrease, SE 6%, significant at 95%) • Increase of 2.9% in proportion of head-on crashes (significant at 95%)
Khattak et al., 2019(102)	Pittsburgh, PA; Montgomery Township, PA; Upper Merion Township, PA; Winchester, VA; Stephens City, VA; Staunton, VA; Frederick, VA; York County, VA; Roanoke County, VA; Fauquier County, VA	Urban signalized arterial	Naïve before-after ordered probit model of crash severity	All results significant at 95%: • Decrease of 5.24% in suspected serious/moderate injury crashes • Decrease of 9.91% in minor injury crashes • Increase of 15.15% in no apparent injury crashes • Increase in severity of rear-end crashes
Stevanovic et al., 2011(103)	Park City, UT	Urban signalized arterial	Simulation-based surrogate study	• Decrease of 11% in overall conflict frequency • Increase of 28% in crossing conflicts, but heavily influenced by one intersection

Transit Signal Priority

General Description of Strategy: Transit signal priority (TSP) involves communications between transit vehicles and traffic signal controllers so that the controllers can alter signal timing to give priority to transit vehicles.(105) The *Signal Timing Manual: Second Edition*, published as NCHRP Report 812, identifies the two most common TSP strategies: 1) extending a phase to allow a transit vehicle to pass (i.e., green extension) or 2) terminating conflicting phases to allow early service to the transit vehicle and reduced red time (i.e., red truncation).(106) Implementation of TSP is based on the assumption that transit vehicles achieve higher person-throughput and that preferential treatment would improve reliability. Both of these factors could incentivize transit use, thus improving overall system efficiency.

While TSP can be implemented at isolated signalized intersections and have an effect on the performance of those intersections, it is commonly applied to a series of signalized intersections along a facility that serves a transit route.

Streets sometimes receive other transit preferential treatments in conjunction with transit signal priority. These additional treatments, such as bus turn-outs or queue jump lanes, could alter the roadway cross section.

Safety Performance Evaluations: Song & Noyce performed a before-after EB study of TSP implementation on 11 corridors in Washington over 13 years.(107) Nine of the 11 corridors showed a significant reduction in crash frequency due to TSP, while the other two showed a slight increase. Overall, the study found a 13-percent reduction in total crash frequency (for all types and severities) (standard error of 1.8-percent), as well as a 16-percent reduction in no apparent injury crashes (standard error of 2.1-percent) and 5-percent reduction in fatal and injury crashes (standard error of 3.2-percent). All reductions were statistically significant at a 95-percent confidence level.

Shalah et al. estimated negative binomial regression models of the expected frequencies of transit-involved crashes and total crashes (i.e., all types) using data from signalized intersections in Toronto, Ontario, Canada.(108) Model estimation results indicated that the presence of TSP at signalized intersections was associated with higher numbers of both transit-involved and total crashes. The authors advised caution in creating CMFs using their regression models because of the cross-sectional study design and uncertainty in the interpretation of the results.(108)

Goh et al. conducted a safety performance analysis of various transit priority treatments along four bus routes in Melbourne, Australia.(109) The study used three years of before data and one year of after data to conduct a before-after EB analysis to examine the trends in crash occurrence related to the implementation of TSP. The results showed decreases in overall crash frequency on segments with TSP, but none of the results were significant at a 95-percent confidence level. A naïve analysis of crash data showed an 18-percent reduction in overall crash frequency and a 31-percent reduction in fatal and serious injury crash frequency; however, these results were not significant at a 95-percent confidence level (they were significant at an 80-percent confidence level). Standard errors were not reported by the authors. The results showed that non-TSP bus priority improvements (such as exclusive bus lanes) may provide greater safety performance benefits than TSP, though the analysis of crash types indicated that adding bus lanes may increase pedestrian-related crashes (due to increased road-crossing distance).

In another study, Goh et al. modeled the expected frequency of crashes involving buses using mixed-effects negative binomial models and back-propagation neural networks.(110) Model results indicated more than 50-percent fewer bus crashes (of all severities) along bus routes with bus preferential treatments (this result was significant at a 95-percent confidence level). Standard errors were not reported by the authors. The models did not include details about the segments and intersections along the routes and did not distinguish between the types of preferential treatments (which included TSP along with other strategies).(110) The lack of these details, along with the cross-sectional study design, makes it challenging to create CMFs from the study results.

Nanzin et al. conducted a before-after EB study of eight tram routes in Melbourne, Australia.(111) The study included 29 intersections where tram signal priority was implemented and 23 road sections where tram lane treatments were implemented. The analysis period consisted of five years of before data and two years of after data. Results indicated that the tram signal priority treatments reduced the total crash frequency (for all crash types and severities) by 13.9-percent (standard error of 8.2-percent) at intersections, and the tram lane treatments reduced total crash frequency by 19.4-percent (standard error of 9.1-percent) along the study segments. This represented a 16.4-percent overall reduction along the eight tram routes (standard error of 6.1-percent).(111) The crash frequency reduction corresponding to tram signal priority was not statistically significant at a 95-percent confidence level (the result was significant at an 80-percent confidence level). The crash frequency reductions corresponding to lane treatment and the overall effect were significant at a 95-percent confidence level.

Subsequently, Nanzin et al. performed another statistical analysis of tram crash frequency in Melbourne.(112) The study used a random effects negative binomial model to examine 1,177 tram-involved crashes over five years. The model results indicated that route sections with a higher share of tram signal priority intersections were less likely to experience tram-involved crashes (this result was statistically significant at a 95-percent confidence level). The authors also noted distinct differences in signal priority implementation between Australia and other countries, particularly Canada, which may account for differences in results across studies.

Li et al. used microsimulation to explore the effects of various transit design alternatives, including TSP, on the safety performance of signalized intersections in Toronto, Canada.(113)

Vehicle trajectories were collected from a PARAMICS microsimulation and then processed in SSAM to identify vehicle conflicts. The simulation results showed fewer total vehicle conflicts (rear-end, angle, and side-swipe) occurred in the non-TSP scenarios; however, the differences were minimal (all less than 3-percent) and not statistically significant.

Summary

In summary, multiple safety evaluations of TSP appear in the literature (see table 11). Results vary with respect to safety performance effects of TSP, but most studies indicate safety performance benefits. In some cases, results did not distinguish between effects of TSP and effects of other transit preferential treatments implemented in combination with TSP. Some studies focused on transit-involved crashes, while others considered crashes of all types. It is unclear what mechanisms would lead to some of the observed reductions in crashes unrelated to transit vehicles. A search for "transit priority" on the CMF Clearinghouse results in different CMFs for various TSP installation scenarios (some include transit lane priority as well). The CMFs are all three- and four-star, and are derived from works by Nanzin et al., Song & Noyce, and Shalah et al. as described above (CMF IDs 7273 – 7275, 9664, 9819, 9820, 2078 – 2097).(107,108,111,112)

Table 11. Summary of safety performance evaluation findings for transit signal priority.

Study	Location	Site type	Method	Findings
Song & Noyce, 2018(107)	Seattle, WA	Urban signalized arterial	Before-after with EB	• 9 of 11 corridors showed significant reduction in crash frequency, while 2 showed slight increase. • Overall crash frequency decrease of 13% (SE 1.8%, significant at 95%) • No apparent injury crash frequency decrease of 16% (SE 2.1%, significant at 95%) • Fatal/injury crash frequency decrease of 5% (SE 3.2%, not significant at 95%)
Shalah et al., 2009(108)	Toronto, Canada	Urban signalized arterial	Negative binomial regression	TSP associated with higher frequency of total and transit-involved crashes
Goh et al., 2013(109)	Melbourne, Australia	Urban signalized arterial	Before-after with EB	• Decrease of 18% in overall crash frequency (11% attributable to TSP) • Decrease of 31% in fatal and serious injury crash frequency • No results significant at 95%
Goh et al., 2014(110)	Melbourne, Australia	Urban signalized arterial	Negative binomial regression	• Decrease of 50% in crash frequency along bus routes with bus-preferential treatment (significant at 95%) • Did not distinguish which routes had TSP
Nanzin et al., 2015(111)	Melbourne, Australia	Urban signalized corridor	Before-after with EB	Overall crash frequency decrease of 13.9% at intersections with tram signal priority (SE 8.2%, not significant at 95%)
Nanzin et al., 2016(112)	Melbourne, Australia	Urban signalized corridor	Negative binomial regression	Route sections with a higher share of tram signal priority were less likely to experience crashes of all types and severities (significant at 95%)
Li et al., 2017(113)	Toronto, Canada	Urban signalized corridor	Simulation-based surrogate study	No statistically significant results, but slight increase in total vehicle conflicts in TSP scenario

Truck Signal Priority

General Description of Strategy: Truck signal priority (TkSP) is another form of signal priority that gives preferential treatment to large trucks. Trucks take longer to accelerate and decelerate and can have detrimental effects on traffic flow, particularly in urban areas.(114) Additionally, frequent accelerations and decelerations of large trucks can have negative effects on pavement infrastructure, noise, and emissions, particularly on high-speed signalized roadways.(114,115)

TkSP generally operates by providing green time extension when a truck is detected on the approach. A common method for differentiating trucks from passenger vehicles is to use two separate loop detectors (or video detectors) spaced 20 to 30 feet apart and engage the TkSP extension when both detectors are occupied simultaneously. It is possible that this method could simply capture two separate passenger vehicles, though at free flow speed the headway between them would likely be smaller than is typical.(116) Other methods that have been explored include vehicle-to-infrastructure (V2I) technology, vehicle-to-vehicle (V2V) technology, model predictive control (MPC), and co-simulation optimization control.(114)

Summary of Safety Performance Evaluations: There are very few performance evaluations of TkSP reported in the literature, and no studies of its effects on safety performance. However, Mahmud contends that TkSP could result in safety benefits by potentially reducing the number of red light-running incidents involving trucks.(115)

There are no relevant results for truck signal priority in the CMF Clearinghouse.

Queue Jump Lanes

General Description of Strategy: A queue jump lane is a short bus-only lane at a signalized intersection that allows transit vehicles to bypass the queue of passenger vehicles.(117) Queue jump lanes are frequently combined with transit-specific signals or transit signal priority to allow buses to easily enter the traffic flow ahead of the queue.(118) Typically, green times for through-traffic passenger vehicles are reduced by three to five seconds to enable this transit movement.(119) Queue jump lanes are implemented to reduce delay to and improve service reliability of transit vehicles, thereby incentivizing transit use. Queue jump lanes can be applied at isolated intersections or a series of intersections along a facility.

Several geometric considerations play into the implementation of a queue jump lane. The roadway cross-section must provide enough space for a dedicated bus lane. In some cases where right-turning traffic is minimal, the queue jump lane can be combined with the right-turn lane. The queue jump lane should be long enough to allow buses to access it when peak-hour general traffic queues are present at the intersection. The design of the queue jump can be affected by the presence of either near- or far-side bus stops at the intersection. The Transit Cooperative Research Program's (TCRP) *Bus Rapid Transit Practitioner's Guide* advises extra signing and pavement marking due to potentially unexpected transit vehicle maneuvers.(119)

Summary of Safety Performance Evaluations: There are no known safety performance evaluations of queue jump lanes. A search for "queue jump" in the CMF Clearinghouse does not return any relevant results.

Safety Warning Applications

General Description of Strategy: Safety warning strategies provide drivers information about downstream conditions. This is intended to improve driver expectation of the downstream conditions and therefore mitigate potential negative safety effects of the conditions. There are several different forms of safety warning strategies. The most common are 1) intersection warning, 2) curve warning, 3) queue warning, and 4) animal warning. Intersection warning strategies give motorists advance warning of upcoming stop- or signal-controlled intersections or the presence of other vehicles on other intersection approaches. Curve warning systems serve to make drivers aware of upcoming horizontal curves that may necessitate a speed reduction for maneuvering comfortably within the travel lane. Queue warning strategies warn travelers about downstream queues on facilities with frequent congestion.(120) Animal warning systems may be placed at locations where vehicle-animal (particularly large mammal) crashes are more frequent or more likely than normal and may include systems for detecting animal presence. These strategies can be implemented in a variety of ways, but most consist of some sort of signage (static or dynamic), and many also include flashing beacons.

Summary of Safety Performance Evaluations: Safety performance evaluations of safety warning applications cover a range of intersection warning, curve warning, queue warning, and animal warning strategies.

Intersection Warning

Simpson & Troy studied the safety performance effectiveness of intersection conflict warning systems (ICWS) at 74 stop-controlled intersections in North Carolina.(121) ICWS use vehicle detection to trigger warning messages alerting motorists of incoming vehicles on an intersecting approach. The specific form of ICWS examined by this study was “Vehicle Entering When Flashing” (VEWF) systems, which include actuated flasher sign assemblies at or near intersections. The study used the before-after EB method, and results indicated a 6.8-percent reduction in total crash frequency (all types and severities) following installation of the VEWF systems (with a standard error of 2.2-percent). This decrease in crash frequency was statistically significant at a 95-percent confidence level.

Himes et al. performed an analysis of ICWS as part of an FHWA pooled-fund study of low-cost safety strategies.(122) The study analyzed the effect of ICWS deployments in Minnesota, Missouri, and North Carolina on crash type and severity using the before-after EB method. The study examined 93 ICWS installation sites across the three states, with 66 coming from North Carolina. The results across the three states indicate an overall safety performance improvement due to implementation of ICWS. The results for two-lane/two-lane intersections showed a CMF of 0.73 (crash frequency reduction of 27-percent, standard error of 4-percent) for all crash types and all severities. The CMF for fatal and injury crashes was 0.70 (crash frequency decreased by 30-percent, standard error of 5-percent) and the CMF for right-angle crashes was 0.80 (crash frequency decreased by 20-percent, standard error of 5-percent). The results for four-lane/two-lane intersections showed an overall CMF of 0.83 (crash frequency reduction of 17-percent, standard error of 6-percent). The CMF for fatal and injury crashes was 0.80 (crash frequency reduction of 20-percent, standard error of 7-percent), and the CMF for right angle crashes was 0.85 (crash frequency reduction of 15-percent, standard error of 8-percent). The CMFs were all statistically significant at the 95-percent confidence level, except for the CMF for right angle crashes at four-lane/two-lane intersections (which was significant at a 90-percent confidence level). Frequencies of nighttime crashes for two-lane/two-lane intersections and rear-end crashes for four-lane/two-lane intersections did not decrease by statistically significant magnitudes. The results indicated greater benefits than the study by Simpson & Troy had identified. The researchers contributed this to several factors, including the use of data from multiple states, the use of SPFs to account for changes in traffic volumes, and the use of annual multipliers to account for trends over time at the treatment sites. A disaggregate analysis indicated additional safety benefits for sites with intersection lighting and for sites with higher crash frequency in the before period. Additionally, the study performed an economic analysis using estimates for cost and service life, with the benefits based on total crash reduction. The benefit-cost (B/C) ratio was 27:1 for two-lane at two-lane intersections and 10:1 for four-lane at two-lane intersections.

Appiah et al. examined the effect of actuated advance warning systems at 26 signalized intersections in Nebraska.(123) Actuated advance warning systems combine the functionality of advance detection systems and advance warning systems to both extend green time and warn drivers as they approach a high-speed signalized intersection. The study used the full Bayesian (FB) method to analyze crash data from a 13-year period (all intersections had at least one year of before and after data). The results indicated a total crash reduction (all types and severities) of 8.2-percent (standard error of 5.8-percent). The frequency of injury crashes showed an 11.3-percent reduction (standard error of 10.5-percent), and right-angle crash frequency decreased by 43.6-percent (standard error of 5.6-percent). Of these results, only the decrease in right angle crash frequency was statistically significant at a 95-percent confidence level (the decrease in total crash frequency was significant at an 80-percent confidence level). Reductions in the frequencies of rear-end crashes and heavy vehicle crashes were negligible.

Schultz & Talbot evaluated an advance warning signal (AWS) system in Riverton, Utah.(124) The system consisted of an overhead sign, flashers, and advance video detection, and was installed in response to concerns about safety and pavement damage caused by large trucks coming to abrupt stops at three intersections along a corridor. The study used two years of before data and two years of after data to conduct a naïve before-after analysis. Results showed that observed crash rates (for all crash types and severities) decreased by an average of 10.9-percent, including a 19.4-percent decrease at the key intersection on the corridor. Standard errors and confidence levels were not reported by the authors. Operating speeds were not affected by the installation of the system. The authors noted that it may be difficult to make strong conclusions based on these results, as many different factors changed at the intersection over the course of the study period that could not be accounted for by the naïve before-after approach.

NCHRP Report 705, *Evaluation of Safety Strategies at Signalized Intersections,* presents safety evaluations and CMFs for a variety of safety strategies at signalized intersections.(125) Implementation of dynamic advance warning flashers was included in the list of Tier I priority treatments. The report involved a critical review of existing research, surveys of agencies, and prioritization of strategies. Advance warning flashers were chosen as one of the top three priority strategies and further evaluation was conducted using data from Nevada, Virginia, and North Carolina. A variety of analysis methods were used, including cross-sectional analysis, before-after with comparison group, and before-after with EB. The results showed a consistent reduction in total crashes (all types and severities) across the three states, as well as reductions in angle, fatal and injury, and heavy vehicle crashes. The CMF for total crashes (all types and severities) was 0.81 (crash frequency reduction of 19-percent, standard error of 6-percent), and the CMF for fatal and injury crashes was 0.82 (crash frequency reduction of 18-percent, standard error of 8-percent). These CMFs were statistically significant at a 95-percent confidence level. An effect on rear-end crashes could not be clearly identified.

Curve Warning

Lyon et al. performed a safety evaluation of two different curve warning treatments: in-lane curve warning pavement markings and chevron signs.(126) The study used the before-after EB method and data from a variety of sites in Iowa, Kansas, Missouri, and Pennsylvania to examine specific crash types and severities. Results for in-lane curve warning pavement markings showed significant reduction in total crash frequency (all types and severities), equating to a CMF of 0.62 (crash frequency reduction of 38-percent, with a standard error of 9-percent). The reduction was due exclusively to the significant reduction in nighttime crashes, as neither the injury nor run-off-road categories (for both daytime and nighttime crashes) produced statistically significant results at a 95-percent confidence level. Results for chevron signs showed a reduction in the frequency of total crashes, as well as injury and nighttime crashes, though none of the reductions were statistically significant at a 95-percent confidence level.

Montella studied the safety performance effects of various curve warning enhancements at 15 sites in Italy.(127) The various improvements consisted of installation of chevron signs (five sites); installation of curve warning signs and chevron signs (six sites); and installation of curve warning signs, chevron signs, and flashing beacons (four sites). An example of a warning sign with flashing beacons is shown in figure 10. The study employed the before-after EB analysis method. Overall, for all 15 sites, the results indicated a 28.2-percent reduction (standard error of 7-percent) in total crash frequency (all types and severities) due to the implementation of curve warning enhancements. Excluding one site due to confounding issues of pavement skid resistance degradation resulted in a 39.4-percent reduction in total crash frequency (standard error of 7-percent). Results also showed that treatments were more effective for curves with smaller radii (defined by the authors as curves with radius of 300 meters or less). Total crash frequency reduction was 52.2-percent (standard error 8-percent) for small radius curves and 25.4-percent (standard error 11-percent) for large radius curves. A disaggregate analysis showed statistically significant total crash frequency reduction for curve warning signs and chevron signs (40.8-percent, standard error 10-percent) and curve warning signs, chevron signs, and flashing beacons (47.6-percent, standard error 9-percent). The crash frequency reduction for installing only chevron signs was not statistically significant. However, all other listed results were statistically significant at a 95-percent confidence level.

Source: FHWA

Figure 10. Photo. Curve warning sign with flashing beacon.(128)

Khan et al. performed a study of safety performance on horizontal curves in Wisconsin and used negative binomial modeling to estimate the relationship between crash frequency on curves and various geometric and signage factors.(129) The results indicated that fewer crashes occurred on curves with a curve sign (MUTCD W1-2) as opposed to a turn sign (MUTCD W1-1). However, sign usage was not a significant factor in crash frequency on sharper curves, indicating that other factors may influence crash occurrence on sharper curves.

Srinivasan et al. produced an analysis of the safety performance effects of improved curve warning treatments for the previously-mentioned FHWA pooled-fund study regarding low-cost safety strategies.(130) The study examined curves on rural, two-lane roads (89 curves in Connecticut and 139 curves in Washington). Treatments included chevrons, horizontal arrows, advance warning signs, and the introduction of fluorescent yellow sheeting. A before-after EB analysis was performed, and the results revealed a statistically significant 18-percent reduction in fatal and injury crash frequency (standard error of 8.6-percent), as well as statistically significant reductions in nighttime crash frequency (27.5-percent, standard error of 7.3-percent) and nighttime lane departure crash frequency (25.4-percent, standard error of 7.8-percent). These results were all statistically significant at a 95-percent confidence level. The results also indicated that the treatments were more effective on sharp curves in Connecticut, but there was no clear trend regarding curve radius in Washington or when the data from the two states were aggregated.

Queue Warning

Elvik et al. developed CMFs for changeable "Queue Ahead" warning sign installations on urban freeways by combining results from three international studies (Erke & Gottlieb, 1980; Cooper et al., 1992; Persaud et al., 1995).(131,132,133,134) The combined CMFs indicate a 16-percent reduction in the frequency of fatal and injury crashes and a 16-percent increase in the frequency of no apparent injury crashes. Elvik et al. do not go into detail on the analysis methods used in the individual studies, and both the Erke & Gottlieb and Cooper et al. studies are not available online. However, Elvik et al. do indicate that the combined CMFs for both fatal and injury crashes and no apparent injury crashes are statistically significant at a 95-percent confidence level.

The Persaud et al. study consists of a safety evaluation of a system of 13 overhead changeable message signs used to warn motorists of downstream queuing and congestion on a 19-mile stretch of highway in Toronto, Canada.(134) The study defined conventional, collector, and express segments along the length of the corridor and used separate regression models to estimate the safety performance of the freeway before and after the implementation of the queue warning system. The models focused on fatal and serious injury rear-end crashes, as these were the target crashes for the implementation of the system. The results indicated reductions in fatal and serious injury rear-end crash frequency across express sections (18.3-percent decrease, significant at a 95-percent confidence level), collector sections (27.7-percent decrease, significant at a 95-percent confidence level), and conventional sections (25.7-percent decrease, not significant at a 95-percent confidence level). The standard errors of the changes in crash frequency were not reported by the authors. The study showed the effectiveness of the queue warning system in reducing the target crashes, as reductions in all non-target crashes (i.e., non-fatal/serious injury, non-rear-end crashes) were minimal and not statistically significant at a 95-percent confidence level.

Source: FHWA

Figure 11. Photo. Portable dynamic end-of-queue warning sign in Wisconsin.(135)

Ullman et al. evaluated an end-of-queue (EOQ) warning system at a work zone on I-35 in Texas.(136) Figure 11 shows one type of portable queue warning sign for implementation in work zones. The EOQ warning system consisted of a portable system of radar speed sensors linked to one or more portable changeable message signs and portable transverse rumble strips. The EOQ system was deployed upstream of nighttime lane closures where queues were expected to develop. The authors implemented a variation of a before-during study design with the EB analysis approach: the base condition was a freeway segment with no work zone, and the two treatment conditions were a work zone with no EOQ warning system and a work zone with an EOQ warning system. The authors developed the EOQ warning system CMF by comparing the relative safety performance of the work zones with and without the EOQ warning systems to their no work zone conditions. The computed CMF attributed to EOQ warning system deployment in work zones was 0.559 (a crash frequency reduction of 44.1-percent with a standard error of 25.5-percent). This result was not statistically significant at a 95-percent confidence level (but was significant at a 90-percent confidence level). Additionally, crashes that did occur tended to be less severe.(136)

Animal Warning

An example of a dynamic animal warning sign is shown in figure 12. Huijser et al. performed an analysis of a similar animal detection and motorist warning system in Montana.(137) The system was optimized to detect large mammals, particularly elk. The study used ten years of crash and wildlife mortality data to perform a naïve before-after analysis. The preliminary results from the before-after analysis indicated a 66.7-percent decrease in vehicle-large mammal crashes on the road section served by the warning system. Also, after system implementation, the vehicle-large mammal crash frequency on the study section was 57.6-percent lower than on the control sections. However, a small sample size of crashes and only one year of after data limited the statistical significance of the results. Standard errors and confidence levels were not reported by the authors.

Source: FHWA

Figure 12. Photo. Animal-activated dynamic warning sign in Arizona.(138)

Dai et al. examined the effectiveness of an animal detection and motorist warning system on a 1.36-mile segment of U.S. 191 in Wyoming.(139) The system was geared toward preventing crashes between vehicles and deer. The study used two years of before data and two years of after data to perform naïve before-after analysis with statistical hypothesis testing. The results of the analysis indicated that there was no statistically significant difference in crash frequency or crash rate following the implementation of the warning system, though a slight downward trend was identified. However, the researchers noted that more post-implementation crash data should be collected before conclusions are drawn.

Summary

The safety warning application synthesis effort uncovered safety performance research in four general areas: 1) intersection warning, 2) curve warning, 3) queue warning, and 4) animal warning. Table 12, table 13, table 14, and table 15 summarize these studies. It was common to see application of the before-after with EB study design and analysis approach for evaluations across all four areas, and statistically significant reductions in crash frequencies for at least some of the crash types and severities considered. Unlike several other TSMO strategies, safety warning applications have been the focus of key safety-related funding mechanisms for both implementation and evaluation, including the Evaluation of Low-Cost Safety Improvements Pooled Fund Study (ELCSI-PFS).

A search of "warning" in the CMF Clearinghouse results in many CMFs, with three-, four-, and five-star CMFs derived from works summarized above for the following applications:

- Elvik et al.(131):
    - Install changeable crash ahead warning signs (CMF ID 75).
    - Install changeable "Queue Ahead" warning signs (CMF IDs 76 and 77).
    - Install changeable speed warning signs for individual drivers (CMF ID 78).
- Lyon et al.(126):
    - Install in-lane curve warning pavement markings (CMF IDs 9167 – 9171).
- Appiah et al.(123):
    - Installation of an actuated advance warning dilemma zone protection system at high-speed signalized intersections (CMF IDs 4853 – 4857).
- Montella(127):
    - Install a combination of chevron signs, curve warning signs, and/or sequential flashing beacons (CMF IDs 1851 – 1885).
- Himes et al.(122):
    - Install an intersection conflict warning system (ICWS) with a combination of overhead and advanced post mounted signs (various messages) and flashers (CMF IDs 8432 – 8476) .
- Srinivasan et al.(125,130):
    - Install dynamic signal warning flashers (CMF IDs 4198 – 4202).
    - Install new fluorescent curve signs or upgrade existing curve signs to fluorescent sheeting (CMF IDs 2431 – 2435).
    - Install chevron signs on horizontal curves (CMF IDs 2436 – 2440).

Table 12. Summary of safety performance evaluation findings for intersection warning applications.

Study	Location	Site type	Method	Findings
Simpson & Troy, 2012(121)	NC	Stop-controlled intersection	Before-after with EB	Decrease of 6.8% in overall crash frequency (SE 2.2%, significant at 95%)
Himes et al., 2016(122)	NC; MN; MO	Stop-controlled intersection	Before-after with EB	Two-lane at two-lane intersections: • Overall CMF of 0.73 (crash frequency decrease of 27%, SE 4%, significant at 95%) • Fatal and injury CMF of 0.70 (crash frequency decrease of 30%, SE 5%, significant at 95%)

Study	Location	Site type	Method	Findings
				• Right-angle CMF of 0.80 (crash frequency decrease of 20%, SE 5%, significant at 95%) Four-lane at two-lane intersection: • Overall CMF of 0.83 (crash frequency decrease of 17%, SE 6%, significant at 95%) • Fatal and injury CMF of 0.80 (crash frequency decrease of 20%, SE 7%, significant at 95%) • Right-angle CMF of 0.85 (crash frequency decrease of 15%, SE 8%, significant at 90%) B/C ratio of 27:1 for installation of ICWS for two-lane at two-lane and 10:1 for four-lane at two-lane intersections
Appiah et al., 2011(123)	NB	Signalized intersection	Before-after with full Bayesian (FB)	• Overall crash frequency decrease of 8.2% (SE 5.8%, not significant at 95%) • Injury crash frequency decrease of 11.3% (SE 10.5%, not significant at 95%) • Right-angle crash frequency decrease of 43.6% (SE 5.6%, significant at 95%)
Schultz & Talbot, 2008(124)	Riverton, UT	Urban signalized arterial	Naïve before-after	• Overall crash rate decrease of 10.9% • Overall crash rate decrease of 19.4% at key intersection on corridor
Srinivasan et al., 2011(125)	NV; VA; NC	Signalized intersection	Cross-sectional analysis, before-after with comparison groups, before-after with EB	• Overall CMF of 0.81 (crash frequency decrease of 19%, SE 6%, significant at 95%) • Fatal/injury CMF of 0.82 (crash frequency decrease of 18%, SE 8%, significant at 95%)

Table 13. Summary of safety performance evaluation findings for curve warning applications.

Study	Location	Site type	Method	Findings
Lyon et al., 2017(126)	IA; KS; MO; PA	Roadway curve	Before-after with EB	• In-lane curve warning pavement markings resulted in overall CMF of 0.62 (crash frequency decrease of 38%, SE 9%, significant at 95%) • Chevron signs did not generate significant results, but showed slight decrease in overall crash frequency
Montella, 2009(127)	Naples, Italy	Roadway curve	Before-after with EB	• Decrease of 28.2% in overall crash frequency (SE 7%) (39.4%, SE 7% when excluding one outlier). Significant at 95%. • Decrease in total crash frequency of 52.2% (SE 8%, significant at 95%) for small radius curves, 25.4% (SE 11%, significant at 95%) for large radius curves • Decrease in crash frequency for installation of curve warning and chevron signs (40.8%, SE 10%, significant at 95%) and curve warning signs, chevron signs, and flashing beacons (47.6%, SE 9%, significant at 95%), but no significant results for installation of chevron signs only
Khan et al., 2012(129)	WI	Roadway curve	Negative binomial regression	Fewer overall crashes occurred on curves with a curve sign as opposed to a turn sign
Srinivasan et al., 2009(130)	WA; CT	Roadway curve	Before-after with EB	• Decrease of 18% in fatal/injury crash frequency (SE 8.6%, significant at 95%)

Study	Location	Site type	Method	Findings
				- Decrease in overall nighttime crashes (27.5%, SE 7.3%, significant at 95%) and nighttime lane departure crashes (25.4%, SE 7.8%, significant at 95%)

Table 14. Summary of safety performance evaluation findings for queue warning applications.

Study	Location	Site type	Method	Findings
Elvik et al., 2012(131)	Numerous international locations	Urban freeway	Synthesis of previous studies	- Decrease of 16% in fatal/injury crash frequency - Increase of 16% in PDO crash frequency
Persaud et al., 1996(134)	Toronto, Canada	Urban freeway	Regression modeling	Fatal/serious injury rear-end crash frequency: - Decrease of 18.3% on express freeway (significant at 95%) - Decrease of 27.7% on collector freeway (significant at 95%) - Decrease of 25.7% on conventional freeway (not significant at 95%)
Ullman et al., 2016(136)	Central TX	Urban and rural freeway	Before-after with EB	Overall CMF of 0.559 for EOQWS (crash frequency decrease of 44.1%, SE 25.5%, not significant at 95%)

Table 15. Summary of safety performance evaluation findings for animal warning applications.

Study	Location	Site type	Method	Findings
Huijser et al., 2009(137)	Yellowstone NP, MT	Rural highway	Naïve before-after	Decrease of 66.7% in vehicle-large mammal crashes
Dai et al., 2008(139)	Trapper's Point, WY	Rural highway	Naïve before-after with statistical hypothesis testing	No significant results due to implementation of animal warning system

Work Zone Management and Temporary Traffic Control Applications

General Description of Strategy: Work zone management is a holistic approach to the planning and implementation of roadway construction operations, addressing road users, vehicles, workers, infrastructure, the environment, and the management system itself.(140) Specific work zone management applications include strategies that pertain to traffic control, traveler information, worker and traveler safety, or other facets of work zone operation.(141) Driving conditions in work zones differ from normal driving conditions, and often vary significantly from work zone to work zone. The U.S. road infrastructure system has reached a stage of increased maintenance and repair operations of existing facilities and decreased construction of new facilities. This increases the exposure of the traveling public to work zones.

Work zone management strategies are implemented to mitigate potential negative effects associated with road construction activities, while at the same time accommodating construction and maintenance operations aimed at improving the safety, operations, and condition of road infrastructure in the long run. The geometric effects of work zone management applications are often site-specific given the individual characteristics and needs of the construction project, though they commonly involve the closure of one or more lanes of the roadway.

Summary of Safety Performance Evaluations: There has been no exploration of the overall effect of work zone management on safety performance. This is because work zone management involves a wide spectrum of specific strategies and techniques and is difficult to broadly assess. Researchers have studied the safety performance effects of work zones and factors associated with work zone crashes from a variety of perspectives.(142,143,144,145,146,147,148,149) These studies have established the consensus that work zones, on average, increase the potential for crashes. Safety performance evaluations of specific work zone management and temporary traffic control strategies aimed at mitigating this increased crash potential have also been conducted.

Some agencies increase police patrolling and enforcement in active work zones in an effort both to alert drivers of upcoming queues or congestion and to increase compliance with reduced speed limits. Chen & Tarko performed a survey of construction project managers in Indiana and analyzed various other data to model crash frequency in work zones and contributing factors.(150) The crash frequency model showed that presence of enforcement in work zones resulted in a 41.5-percent reduction in crash frequency for all types and severities. This analysis relied on the project managers' memory of police presence. Standard error and confidence level were not reported by the authors.

Tudor et al. examined the effectiveness of an Automated Work Zone Information System (AWIS) in preventing crashes at a work zone in Arkansas.(151) The AWIS included traffic sensors and changeable message signs and was designed to detect queues, report delay times, and suggest speed reductions to travelers. The study compared the work zone equipped with AWIS to two other work zones in Arkansas without AWIS, using one year of crash data. The results showed that the observed rate of fatal crashes at the work zone where AWIS was implemented was significantly lower than at the other two sites (2.2, compared to 3.2 and 3.4). The rate of rear-end crashes at the AWIS site was in between the crash rates of the other two sites (33.7, compared to 43.2 and 29.5). The standard errors and confidence intervals were not reported by the authors. This type of with-without study design using observed crash rates tends to produce less reliable results.

Li & Bai used crash data to evaluate the effectiveness of various temporary traffic control methods including the use of flagger/officer control, stop signs/traffic signals, flasher devices, "no passing zone" control, and center and edge lines.(152) Logistic regression was used to investigate the effects of these strategies on crash severity and the occurrence of various crash report descriptors such as "disregarded traffic control," "inattentive driving," and "followed too closely." The study used two months of fatal and injury work zone crash data, which consisted of 29 fatal crashes and 626 injury crashes, from the Kansas DOT crash database. The results showed that using flagger control in a work zone could lower the likelihood of a fatal crash occurring by 4-percent. Implementing "no passing zone" control could lower the fatal crash likelihood by 3-percent. Additionally, the presence of center/edge lines in a work zone could lower the likelihood of a fatal crash by 2-percent. However, the presence of stop signs or traffic signals in work zones increased the risk of fatal crashes, particularly in the case of "followed too closely" crashes. These results were all statistically significant at a 95-percent confidence level (standard errors were not reported by the authors).

Ullman & Schroeder synthesized case studies regarding the use of work zone ITS technology.(153) One of the case studies detailed the implementation of smart work zone traffic monitoring systems at two work zones in Indiana. Both sites were rural interstates, and agency officials were concerned about increased crash potential due to unanticipated congestion because of lane closures and work zone activities. The researchers noted that the capacity of the facility adjacent to work zones was reduced, even when lanes were not closed. This could be due to decreased lane or shoulder widths, or other factors. Different ITS systems were deployed at the two locations, but both involved sensors for monitoring traffic conditions and changeable message signs for communicating information to drivers. Preliminary naïve before-after analysis using one year of before data (with the work zone active but no ITS technology) and one year of after data (with both the work zone and the ITS technology active) showed a 14-percent decrease in the frequency of queuing-related crashes and an 11-percent decrease in injury crashes, despite a 52-percent increase in the number of days with temporary lane closures. Standard errors and confidence levels were not reported by the authors.

Tarko et al. modeled a wide variety of factors surrounding work zone operations for the Super 70 project on I-70 in Indiana, particularly the safety effects of various work zone traffic management strategies.(154) The study used crash data, geometric data, traffic data, weather data, and enforcement data, and employed a binary logistic regression crash likelihood model. The findings showed that the most significant safety improvement resulted from rerouting heavy vehicles (those over 13 tons) to alternate interstate routes. Other significant improvements came through traffic management strategies such as increased police enforcement and reduced speed limits. Together, these two aspects contributed to an estimated safety benefit of around

100 work zone crashes prevented during the nine-month duration of the project. Widening the inner and outer shoulders contributed to an incremental additional safety benefit. A naïve before-during study using a negative binomial test for change in crash frequency and 27 months of before data and 9 months of during data showed that the frequency of all types and severities of crashes on I-70 decreased during the Super 70 project, but crashes increased on I-456, a ring road which experienced increased traffic due to the construction operations.

Many agencies perform extensive roadway construction operations during overnight hours to minimize the effects of construction-related lane closures on mobility during peak travel hours. There are some concerns that decreased visibility at night may contribute to increased risk of crashes in nighttime-operating work zones. However, some studies indicate that nighttime work has no effect on safety performance or may even result in a net benefit. Turochy et al. analyzed work zone-related crashes in Alabama from 2007 to 2014 and developed an ordered probit model to explore crash severity in work zones.(155) The study showed that crash severity increased from 6 PM to 6 AM when compared to the 6AM to 6PM periods. The researchers attributed the increase in severity to reduced visibility as well as the possibility of traveling at higher speeds during nighttime hours than during the day when roads are more congested. However, the study was not able to identify whether the work zones were active during these nighttime crashes. Ullman et al. studied nighttime work zone activity in Texas in a similar manner.(156) Analysis of three years of crash records showed mixed results depending on how frequently the district in question performed nighttime work zone operations. However, as with the study by Turochy et al., crash data only indicated whether the crash occurred in a work zone, but not whether the work zone was active. In response to this, the researchers performed a more focused investigation of eight projects, reviewing project records to determine when work zones were active. The results showed that crash frequency for all types and severities increased by 48.7-percent in inactive nighttime work zones compared to the same segments prior to work zone implementation. This change was significant at a 95-percent confidence level. Alternately, exploration of active nighttime work zones showed that most of the sites experienced no significant increase in crash frequency compared to the inactive nighttime status, except at two locations where substantial queuing was associated with a much greater increase in crash frequency. The study also identified a divide in previous literature regarding the effect of nighttime work zones on traffic safety, with some studies concluding that crash frequency increased while others showed the opposite. Ullman et al. attributed this to confounding effects due to the lack of information surrounding nighttime work zone activity status.

NCHRP Report 627, *Traffic Safety Evaluation of Nighttime and Daytime Work Zones,* contains extensive research on the issue of nighttime work zone safety performance effects.(157) The study investigated work zone crashes in New York, California, North Carolina, Ohio, and Washington using the before-after EB method. The results of the data analysis showed that nighttime work zone operations do not significantly affect crash frequency, as the increase in crash frequency resulting from a lane closure was nearly identical between daytime and nighttime work. Additionally, the study accounted for lower traffic volumes during nighttime hours. Crash frequency (for all crash types and severities) increased by 66-percent during daytime work zone operations (standard error of 7.3-percent) and by 61-percent during nighttime work zone operations (standard error of 5.7-percent) when compared to times when work zones were not present. These results were both statistically significant at a 95-percent confidence level. However, the difference in crash severity between daytime and nighttime work zone operations was not statistically significant at a 95-percent confidence level.

Interestingly, the only category that showed a statistically significant difference between daytime and nighttime conditions was when the work zone was inactive (and no lane closures in effect). Inactive nighttime work zones represented an increase in crash frequency of 23.7-percent (standard error of 2.9-percent) compared to 12.7-percent during the daytime (standard error of 1.4-percent) (for all crash types and severities). These results were significant at a 95-percent confidence level. The study was unable to identify the cause of this difference, though the researchers speculate it may be due to degradations in the geometric conditions relative to non-work zone conditions, or reduced driver expectancy and increased likelihood of drowsiness or impairment. Overall, the change in crash occurrence was most noticeable for no apparent injury crashes, indicating that while work zones increase crashes, they tend to be less severe. In analyzing crash type, the researchers found that the proportion of rear-end and fixed-object crashes increased at night, but side-swipe crashes were not affected by time of day.

NCHRP Research Report 869, *Estimating the Safety Effects of Work Zone Characteristics and Countermeasures: A Guidebook,* documents the results of different analyses related to understanding the safety effects of work zones and selected countermeasures.(159) The report shows that congestion and queueing caused by work zones both significantly contributed to increased crash potential, especially in the case of freeway work zones. Researchers analyzed data from a multi-state database of interstate work zones to develop CMFs for different work zone features (e.g., shoulder widths, lane closures, lane shifts, etc.), but the analysis did not yield statistically significant results for any specific geometric features.

The report also contained a safety analysis of combined end-of-queue warning system (EOQWS) and portable rumble strip (PRS) implementation during nighttime construction activities on 96 miles of I-35 in Texas. Using Bluetooth sensors to identify queues and a before-after EB analysis, the study revealed a 53-percent crash reduction due to implementation of EOQWS and PRS (standard error of 30.1-percent). This result was not statistically significant at a 95-percent confidence level (it was significant at a 90-percent confidence level). Additionally, results showed that only 16-percent of crashes resulted in fatal and injury (KABC) severities when queues were present and safety treatments were deployed, compared to 50-percent when queues were present but safety treatments were not deployed.

Summary

Several studies have evaluated individual aspects of the safety performance effects of work zones and various related strategies. Most of these studies employed statistical modeling of crash data, and two used the before-after EB study design. The findings varied due to the specific details of the study but generally indicated that police enforcement, AWIS, flagger control, edge lines, rerouting of heavy vehicles, and other work zone safety countermeasures decrease overall crash frequency. Results were mixed regarding the safety performance effects of nighttime work zone operations.

A search for "work zone" on the CMF Clearinghouse results in about 80 different CMFs that relate to specific aspects of work zone implementation, in the following categories:

- Active work with no lane closure (compared to no work zone).
- Active work with temporary lane closure (compared to no work zone).
- Implement left-hand merge and downstream lane shift (Iowa weave).
- Increase work zone duration.
- Increasing the inside shoulder width inside the work zone by one foot.
- Increasing the outside shoulder width inside the work zone by one foot.
- Modify work zone length.
- TLTWO (two-lane, two-way traffic operation – crossover closures) in work zones.

Most of the CMFs come from NCHRP Report 627, with others from Tarko et al.(156,157,154) Both studies are described above. Additionally, NCHRP Research Report 869 contains an extensive catalogue of work zone-related CMFs.(159)

Table 16. Summary of safety performance evaluation findings for work zone applications.

Study	Location	Site type	Method	Findings
Chen & Tarko, 2012(150)	IN	Freeway work zone	Survey of construction managers and project records, negative binomial model of crash frequency	Presence of enforcement in work zones resulted in 41.5% decrease in overall crash frequency
Tudor et al., 2003(151)	Lonoke County, AR	Freeway work zone	Comparison of observed crash data	Fatal crash rate at AWIS site was significantly lower than at comparison sites
Li & Bai, 2009(152)	KS	Work zone with temporary traffic control	Logistic regression on crashes that occurred	• Use of flagger control, flashing devices, and/or center and edge lines significantly reduce likelihood of a crash being fatal by 2-4% (significant at 95%) • Use of stop signs or traffic signals increased risk of a crash being fatal/injury (significant at 95%)
Tarko et al., 2011(154)	Indianapolis, IN	Freeway work zone	Logistic regression of crash occurrence	Rerouting heavy vehicles, increased police enforcement, and decreased

Study	Location	Site type	Method	Findings
				speed limits resulted in reduction of around 100 crashes
Turochy et al., 2017(155)	AL	Work zone	Ordered probit	Crash severity in work zones increased during overnight periods
Ullman et al., 2004(156)	TX	Work zone	Cross-sectional analysis	Most nighttime work zone sites experience no significant increase in crash frequency, though some that experienced substantial queueing showed increased crash frequency
Ullman et al., 2008(157)	NY; CA; NC; OH; WA	Work zone	Before-after EB	• Increase in overall daytime crash frequency of 66% (SE 7.3%) and overall nighttime crash frequency of 61% (SE 5.7%) during nighttime (difference between the two not significant at 95%) • Change in crash frequency most notable for no apparent injury crashes
Ullman et al., 2018(159)	TX	Urban and rural freeway work zone	Before-after EB	• Decrease of 53% in crash frequency due to EOQWS and PRS (SE 30.1%, not significant at 95%) • 50% of crashes were categorized as "severe" when queues were present and safety treatments were not deployed, compared to 16% when queues were present and safety treatments were deployed

Traffic Incident Management Strategies

General Description of Strategy: Traffic incident management (TIM) is any combination of strategies designed to lessen the time required to respond to and clear traffic incidents. It consists of planned and coordinated multi-disciplinary processes to detect, respond to, and clear traffic incidents so that traffic flow may be restored as quickly as possible. Public and private sector partners in a TIM program include law enforcement, fire and rescue, emergency medical services, transportation agencies, public safety communications, emergency management, towing and recovery, hazardous materials contractors, and traffic information media.(160)

Effective TIM reduces the duration and effect of traffic incidents, thereby reducing delay caused by incidents. TIM also seeks to improve the safety of people involved in incidents, emergency responders, and other road users.

Implementing traffic incident management strategies does not require changes to roadway geometrics, but there are some roadway features (e.g., wider shoulders) that may support improved TIM. Studies reviewed in the next section do indicate that some road geometric features influence primary incident duration, which in turn likely influences the probability of a secondary crash.

Summary of Safety Performance Evaluations: TIM is designed to reduce emergency response times, enabling quicker treatment of injured road users. Quicker clearance of incidents by police and other responders results in less exposure. Several transportation agencies and researchers have attempted to quantitatively evaluate the benefits and costs of incident management programs.(161,162,163,164,165) However, none of these studies have presented defensible, crash-based safety performance assessments. Most rely on broad assumptions of crash reduction, traffic diversion, and other factors of incident management without specific empirical evidence. This is likely because incident management often manifests in a broad, campaign-based approach which can involve numerous individual strategies and is difficult to perform experimental analysis on.

Safety performance evaluations of TIM that have linked incident duration to the occurrence of secondary crashes have found more success. Secondary crashes are crashes that occur in the timeframe beginning with the time of incident and within the boundaries of the incident scene or resulting queue. Various studies indicate that secondary crashes account for 14- to 25-percent of all crashes.(163,164,166,167) The identification of secondary crashes is complex and rarely noted on crash reports, making the assessment of these crashes challenging. Multiple TIM studies in the literature related the chances of secondary crashes to incident characteristics, including incident duration.

Khattak et al. developed an online tool called the Incident Management Integration Tool (iMiT) that dynamically predicts incident durations, secondary incident occurrence, and associated incident delays.(168) The authors developed the prediction models using data provided by Hampton Roads Traffic Operations Center that spanned January 2004 through June 2007. The authors used a binary logit model to estimate the probability of a secondary incident as a function of primary incident characteristics, including incident duration.(168) However, due to data limitations it was not possible to validate the tool's secondary incident occurrence predictions.

Goodall developed methodologies to 1) identify crashes as secondary using third-party travel time data and 2) estimate the probability of secondary crash occurrence based on the duration of the primary incident, congestion levels, and the total number of vehicles that encounter the incident or its queue.(169) The study involved collecting data from the entire 75-mile I-66 corridor in Virginia and used a binary logit model to estimate the probability of secondary crash occurrence.

Yang et al. used logistic regression to estimate the probability of a secondary crash but made the case that traditional binary logit models could be problematic because of "class imbalance" (i.e., only a relatively small number of primary incidents result in a secondary crash). They instead implemented rare event logistic regression and found the probability of a secondary crash to increase with primary incident duration.(170)

Latoski et al. demonstrated how to incorporate reductions in secondary crashes along with other benefits into a B/C analysis of a freeway service patrol incident management strategy.(166)

Summary

Results of these studies indicate the probability of a secondary crash increases by 1.2 to 3.2 percent for every additional minute of primary incident duration. However, given the widely varying characteristics of TIM programs and of crash incidents themselves, all of the existing studies relied on assumptions in developing estimates of safety performance effects. However, these studies do provide a foundation for further examination of incident duration, TIM response time, secondary incident occurrence, and benefit-cost relationships.

Searches of "TIM," "incident management," "incident," and "clearance" in the CMF Clearinghouse do not return any results.

Table 17. Summary of safety performance evaluation findings for traffic incident clearance strategies.

Study	Location	Site type	Method	Findings
Khattak et al., 2012(168)	Hampton Roads, VA	Urban freeway	Binary logit	Produced tool for predicting incident duration, secondary incident occurrence, and associated delays. Validation of secondary incident prediction was not conducted due to data limitations.
Goodall, 2017(169)	Northern VA	Freeway	Binary logit	Probability of secondary crash increases 1% for every additional 2-3 min of primary incident duration
Yang et al., 2014(170)	NJ	Freeway	Rare event logistic regression	Probability of secondary crash increases 1.2% for every additional min of primary incident duration
Latoski et al., 1999(166)	Northwest IN	Freeway	Logistic regression	Hoosier Helper program could reduce secondary crash likelihood by 18.5% in winter and 36.3% in other seasons

CHAPTER 3 — RELATIONSHIPS BETWEEN TRAFFIC OPERATIONAL PERFORMANCE AND SAFETY PERFORMANCE

INTRODUCTION

TSMO strategies generally have known and quantifiable direct effects on measures of traffic operations. By affecting traffic operations, these strategies may also have indirect effects on traffic safety performance, measured by the frequency and severity of crashes. Background discussion in Chapter 1 of this report noted, however, that many safety performance analysis methods based on an analysis of crash data incorporate average traffic volumes – specifically AADT – and do not consider the safety performance effects of the changes in and interactions between speed, flow, capacity, and density.

To gain a comprehensive understanding of the potential for TSMO strategies to influence safety performance outcomes, it is necessary to understand the relationships between traffic operational and safety performance measures. This chapter summarizes the methods and findings of a representative set of studies that have investigated the relationships between traffic operations and safety performance using these two distinct approaches. Such studies generally fall within one of two distinct categories: 1) those that focus on traffic operational and safety performance measured over long time periods (e.g., annually); and 2) those that focus on traffic operational and safety performance measured in real-time (e.g., on the order of a few minutes). Studies in the first category tend to relate annual traffic volumes (i.e., AADTs) or representative hourly traffic metrics (e.g., flows, speeds, densities) over the course of a year to annual crash frequencies. Studies in the second category seek to relate traffic metrics measured at specific locations and times with the crash potential at these locations and times.

ANNUAL RELATIONSHIPS

The most common method used to relate safety performance and traffic metrics at the annual level is to estimate safety performance functions (SPFs). FHWA's *Safety Performance Function Development Guide: Developing Jurisdiction-Specific SPFs* defines SPFs as crash prediction models that relate the number of crashes of different types and severities at a site to the characteristics of that site.(171) The *SPF Development Guide* notes that some SPFs may include only traffic volume and segment length (if the site type is a segment) as predictor variables. Others may include additional site characteristics, such as cross section geometry, alignment, and roadside characteristics. SPFs can be developed for various spatial scales (e.g., National, State, regional) for individual or aggregated crash types, and for any specific level or combination of severity. The main advantage of this approach is that using annual data helps to address some of the randomness associated with crash occurrences. The limitation is that these models also require annual estimates of traffic metrics (e.g., annual traffic volumes), and therefore do not reflect safety performance effects of traffic fluctuations on sub-annual time scales.

Typical Data

The data required to estimate an SPF depends on the facility and site type. For roadway segments, the minimum required data for each segment and year are AADT, the number of subject crashes reported, and the segment length.(171) Additional data, such as those describing the cross-section geometry, alignment, or roadside can also be included in the SPF to improve its predictive ability. For intersections, the required data are the number of observed crashes and AADT on the major and minor roadways for each intersection-year considered. Like roadway segments, other intersection-specific features (such as presence of crosswalks, left-turn phasing, or exclusive turn lanes) can be collected and integrated directly into an SPF or incorporated as adjustment factors into a larger predicted method.

Some published research has incorporated traffic metrics into SPFs. Zhou & Sisiopiku used data from a 16-mile segment of I-94 in Detroit, Michigan to investigate the relationship between crash rate and volume-to-capacity (V/C) ratio.(172) Volumes were obtained from hourly traffic counts taken from count stations on the study segment, while segment capacities were estimated using the 1994 *Highway Capacity Manual* (*HCM*) methodology.(173) Lord et al. incorporated hourly traffic flow, density, and V/C data into their crash frequency models.(174) Both studies collected crash, roadway, traffic volume, density, and capacity data for their models. The methods used by the researchers and results of these studies will be discussed later in this chapter.

Methods

Observed crash frequencies are count data which show a right skew when plotted and thus are often modeled using count regression. The most typical count model is the Poisson model, which assumes that the count data follows a Poisson distribution in which the mean value is equal to the variance. However, crash data are usually over-dispersed, meaning that the variance of crash frequency is greater than the mean crash frequency. To accommodate this, analysts typically use negative binomial regression models to estimate SPFs.(175) The use of negative binomial regression results in the proportional relationship between crash frequency and AADT described in figure 13, which is a power function, where the regression coefficient β_{AADT} describes the shape of the relationship. A constant term, an adjustment for length, and other adjustment factors are also included in a standard SPF, with the standard functional form for a segment SPF shown in figure 14.

$$N_{pr} \propto AADT^{\beta_{AADT}}$$

Figure 13. Equation. Proportional relationship between crash frequency and AADT in traditional SPFs.

$$N_{pr,y,z} = e^{\beta_0} * L^{\beta_L} * AADT^{\beta_{AADT}} * \prod e^{\beta_i} * C_{y,z}$$

Figure 14. Equation. Standard functional form of a segment SPF.

Where:

$N_{pr,y,z}$ – the annual number of predicted crashes of type *y* and severity *z*, in crashes per year;

L^{β} – segment length, in miles, with a regression coefficient β_L which is typically fixed as one;

$AADT^{\beta AADT}$ – AADT, in vehicles per day, with a regression coefficient β_{AADT} which can be less than, equal to, or greater than one;

$\Pi e^{\beta}{}_{i}$ – a series of adjustment factors for geometry, roadside characteristics, and other features, typically referred to as CMFs; and

$C_{y,z}$ – a local calibration factor, which can be used to adjust an SPF for crashes of type *y* and severity *z* to local conditions.

The power function relationship between crash frequency and AADT can be modified using CMFs. An example of this is in the freeway segment predictive method from the *HSM*, which includes a CMF for "high volumes."(176) As shown in figure 15, the CMF is a function of a regression coefficient (α) and the proportion of daily traffic occurring during hours in which the volume exceeds 1,000 vehicles per hour per lane (*P*). The baseline of 1,000 was selected because freeway speeds typically drop once volume exceeds 1,000 vehicles per hour per lane.(177,178) The increase in density and reduction in speed is hypothesized to be correlated with increases in multiple-vehicle crash frequency.

$$CMF = e^{\alpha * P}$$

Figure 15. Equation. *HSM* CMF for high volume on freeway segments.

There are two notable exceptions to modeling the crash frequency-AADT relationship via the power function. The first was in Bonneson et al., which used the Hoerl function to describe the relationship on freeway ramp segments.(177) The Hoerl function relates crash frequency and

AADT via figure 16 where β_0 and β_1 are regression coefficients. The authors found the Hoerl function produced a better-fitting model than the traditional power function.

$$N_{pr} \propto AADT^{\beta_0} * e^{AADT*\beta_1}$$

Figure 16. Equation. Proportional relationship between multiple-vehicle crash frequency and AADT for ramp segments in the *HSM*.

The second notable exception to the power function relationship was in Kononov et al., who pointed out that the power function is commonly used because analysts often limit themselves to the readily available predictive capabilities of their selected software package.(179) To challenge the power function, the authors used a neural network to analyze five years of freeway segment crash data from California, Colorado, and Texas, developing a relationship between crash rates (crashes per mile per year, labeled APMPY on the y-axis in figure 17) and AADT. Regardless of State and for both six-lane and eight-lane cross sections, the authors found that a sigmoid shaped function (illustrated in figure 17) best represented the data. Such results may be transferable to other locations or may only be applicable to the locations studied. The transferability of SPFs across space (i.e., locations) and time remains an area of ongoing research.

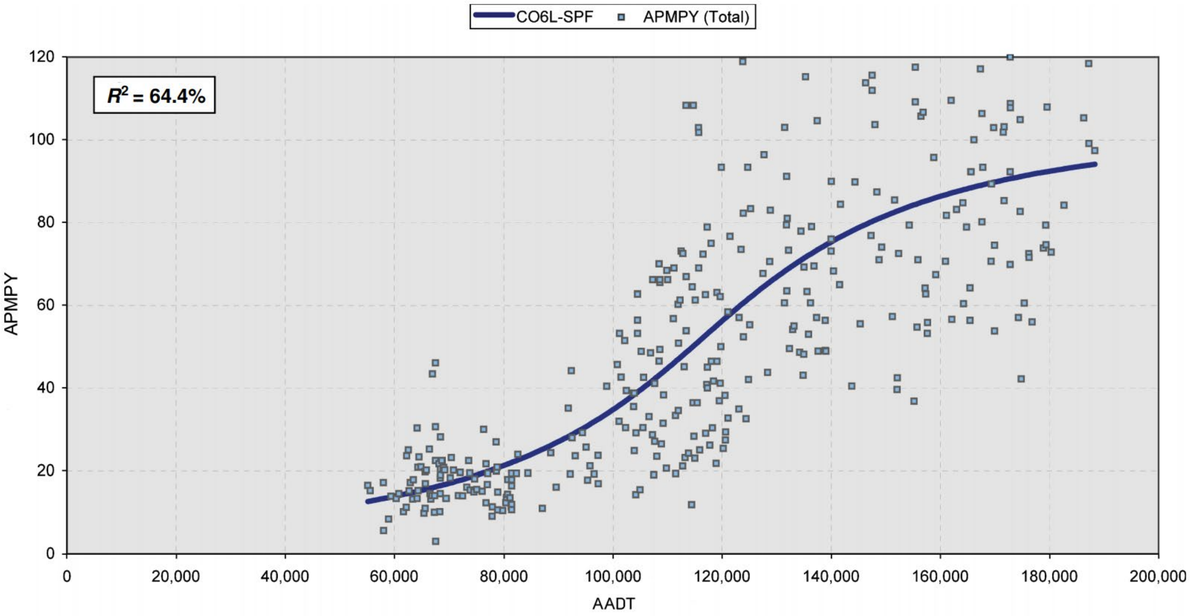


Figure 17. Graphic. The Sigmoid-shaped SPF estimated for Colorado six-lane freeways.(179)

As noted previously, some authors have incorporated traffic metrics into SPFs. Zhou & Sisiopiku plotted the relationship between average V/C ratio and crash rate to estimate a best-fit curve describing that relationship.(172) It is important to note that crash rate assumes a linear relationship between crash frequency and traffic volumes. Research has shown that this assumption is false in many cases. Crash rates are therefore being phased out as a reliable metric for safety performance.

Lord et al. developed models of annual crashes observed during specific hours (12:00-1:00, 1:00-2:00, etc.) on specific days (weekdays, Saturdays and Sundays) for freeway segments in Quebec.(174) Three different model forms were considered: crash frequency as a function of hourly traffic volume (figure 18), crash frequency as a function of volume and density (figure 19), and crash frequency as a function of volume and V/C ratio (figure 20). To better understand the effect density and V/C ratio have on crash frequency, the authors fixed traffic volume as an offset variable (forcing the model to relate traffic volume and crash frequency linearly). Models were estimated assuming a negative binomial distribution and using a Generalized Estimating Equation procedure. Capacity for each segment was calculated using the procedure described in the 2000 edition of the *HCM*.(178)

$$N_{pr} = \beta_0 * L * F^{\beta_1}$$

Figure 18. Equation. Predicted annual crash frequency for a freeway segment as a function of hourly flow.

$$N_{pr} = \beta_0 * L * F * e^{\beta_1 * D}$$

Figure 19. Equation. Predicted annual crash frequency for a freeway segment as a function of hourly flow and density.

$$N_{pr} = \beta_0 * L * F * e^{\beta_1 * {V}/{C}}$$

Figure 20. Equation. Predicted annual crash frequency for a freeway segment as a function of hourly flow and V/C ration.

Where:

N_{pr} = predicted annual crash frequency for the freeway segment;

L = segment length, in kilometers;

F = hourly traffic volume for the segment, in vehicles per hour; and

β_0, β_1 = estimated regression coefficients for the models.

For each functional form, Lord et al. estimated seven models.(174) For both rural and urban contexts, the authors estimated models predicting the frequencies of all crashes, single-vehicle (SV) crashes, and multiple-vehicle (MV) crashes. Additionally, the authors developed a model for fatal and suspected serious injury (KA) crash frequency on rural freeways.

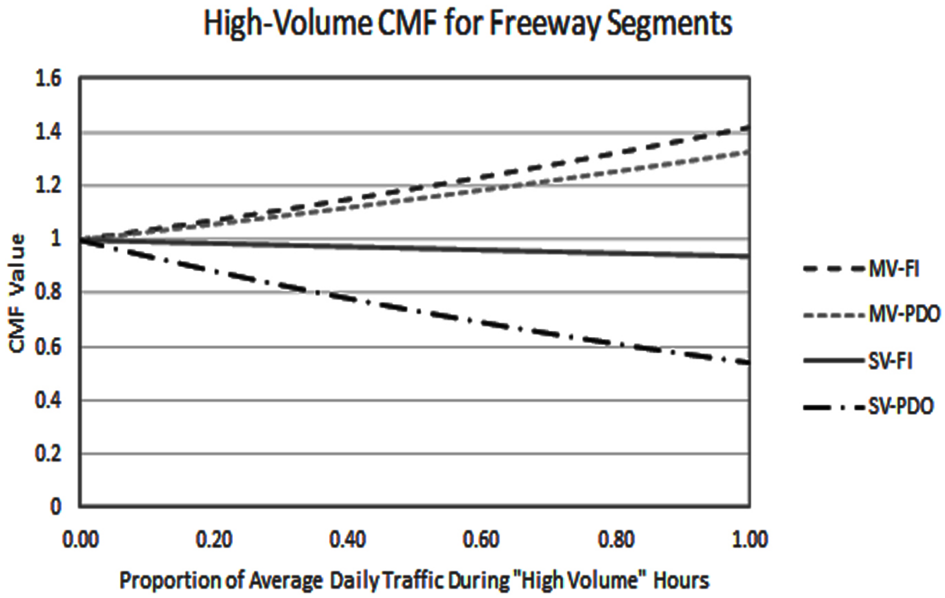
Notable Results

The *HSM* contains numerous SPFs estimated using the power function. The coefficient β_{AADT} in figure 14 varies across SPFs in the *HSM*, with some having β less than one, some equal to one, and some greater than one:

- Where β is less than one, the elasticity of the crash frequency-AADT relationship decreases as AADT increases, meaning a one-percent increase in AADT results in a larger increase in crash frequency when AADT is low compared to when AADT is high.
- When β is equal to one, the elasticity is uniform as AADT increases.
- Finally, when β is greater than one, the elasticity increases as AADT increases.

This β value helps to explain the effect of additional traffic on crash frequency and varies based on the type of crash being modeled. Consider two hypothetical SPFs: one that predicts SV crash frequency and another that predicts MV crash frequency. As AADT increases, an errant vehicle is less likely to depart the roadway without striking another vehicle and more likely to strike another vehicle. In this scenario, β would be less than one for the SV crash SPF and greater than one for the MV SPF.

Bonneson et al. showed how changes in traffic density affect the types of crashes observed by developing a "high volume" CMF for freeway segments in California, Maine, and Washington (figure 15).(177) This study found that for MV crashes, the coefficient α is positive, which indicates crash frequency is likely to be higher than under base conditions. α is negative for SV crashes, which indicates crash frequency is likely to be lower than under base conditions. Figure 21 provides a visual representation of this CMF as a function of the proportion of daily traffic that occurs while hourly traffic volume is greater than 1,000 vehicles per hour per lane (less than 1,000 vehicles per hour per lane is considered the base condition). These findings imply that as density on the freeway segment increases, MV crash frequency tends to increase, and SV crash frequency tends to decrease.



Source: FHWA

Figure 21. Graphic. High volume CMF for the freeway segment predictive methodology in the *HSM*[1].

Lord et al. found a similar effect with their data and models.(174) The coefficients in figure 18 through figure 20 relating the subject traffic metrics to predicted annual crash frequency varied by traffic metric and crash type.

Coefficient estimates for the flow, density, and V/C models in figure 18 through figure 20 are summarized in table 18. As one example finding, increases in density and V/C ratio are associated with decreases in SV crash frequency and increases in MV crash frequency, both of which are expected results, given that as the number of vehicles on the roadway increase, errant vehicles are more likely to strike another vehicle than have an SV crash. Figure 22 through figure 24 illustrate the relationships estimated by Lord et al. for rural freeway segments; the results were similar in shape for urban segments.(174) Lord et al. pointed out the differences in results between the "All" models and the sums of the multiple-vehicle and single-vehicle models (MV+SV). Note that the "All" models predict fewer crashes as volume, density, and V/C increase than the sum of the individual MV and SV models. Lord et al. cite this as evidence supporting Mensah and Hauer's proposed modeling approach, which suggested disaggregated SPFs by crash types where appropriate.(180) Ultimately, Lord et al. recommend

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[1] FI = fatal and injury crashes

drawing conclusions based on the combined models (MV+SV), which indicate increases in volume, density, and V/C ratio are all associated with increases in the frequency of total (MV+SV) crashes.

Table 18. Summary of rural model coefficients (standard errors) for the models developed by Lord et al.(174)

β_1	**All**	**KA**	**SV**	**MV**
Figure 18– Flow	*0.542* *(0.071)*	*0.354* *(0.111)*	*0.412* *(0.061)*	*1.156* *(0.158)*
Figure 19– Density	*-0.209* *(0.038)*	*-0.294* *(0.061)*	*-0.294* *(0.033)*	0.056 (0.039)
Figure 20– V/C	*-3.666* *(0.808)*	*-5.116* *(1.808)*	*-5.216* *(0.713)*	0.964 (0.680)

Table 19. Summary of urban model coefficients (standard errors) for the models developed by Lord et al.(174)

β_1	**All**	**SV**	**MV**
Figure 18– Flow	*0.355* *(0.125)*	-0.660 (0.980)	*1.085* *(0.085)*
Figure 19– Density	*-0.017* *(0.007)*	-0.077 (0.067)	*0.012* *(0.002)*
Figure 20– V/C	*-1.957* *(0.538)*	*-4.965* *(0.690)*	*0.375* *(0.134)*

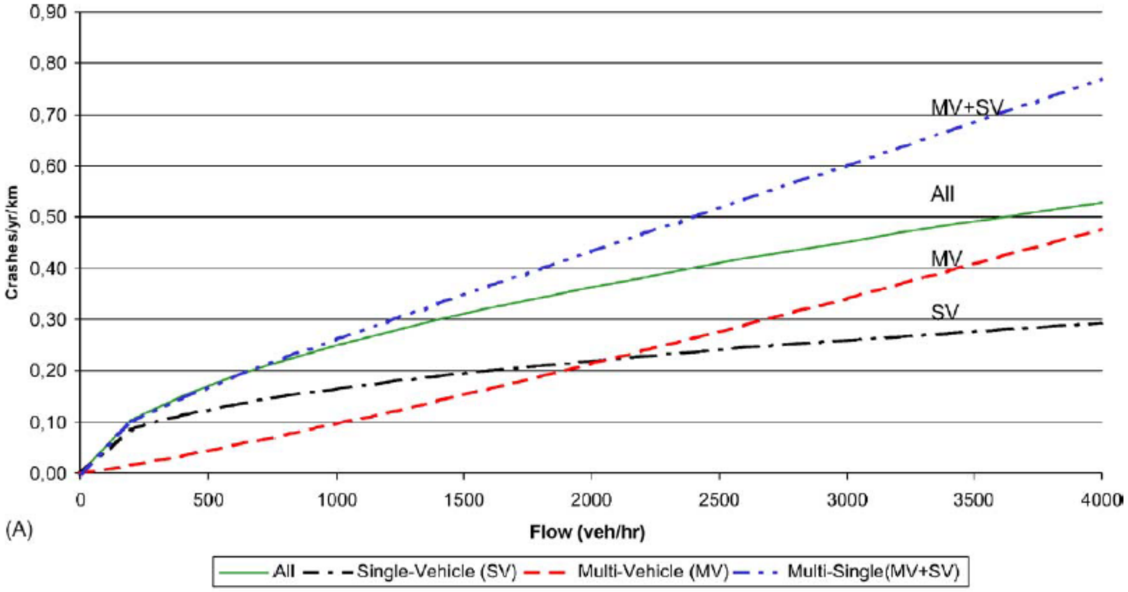

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Figure 22. Graphic. Predicted crash frequency per kilometer for one freeway lane as a function of traffic flow.(174)

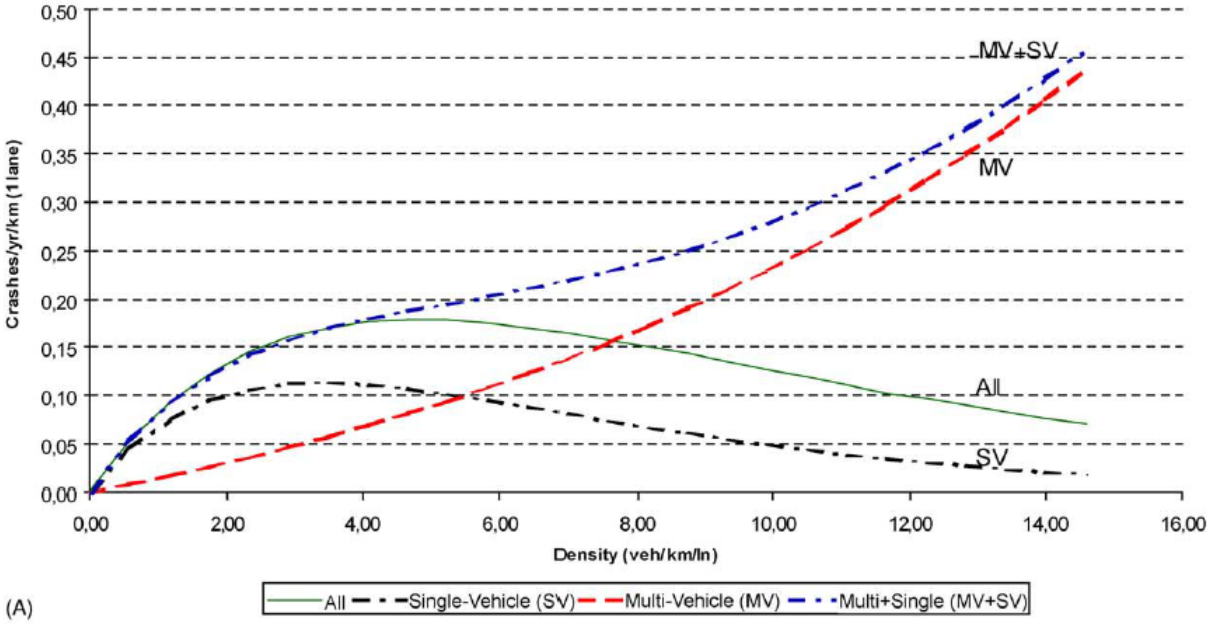

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Figure 23. Graphic. Predicted crash frequency per kilometer for one freeway lane as a function of vehicle density.(174)

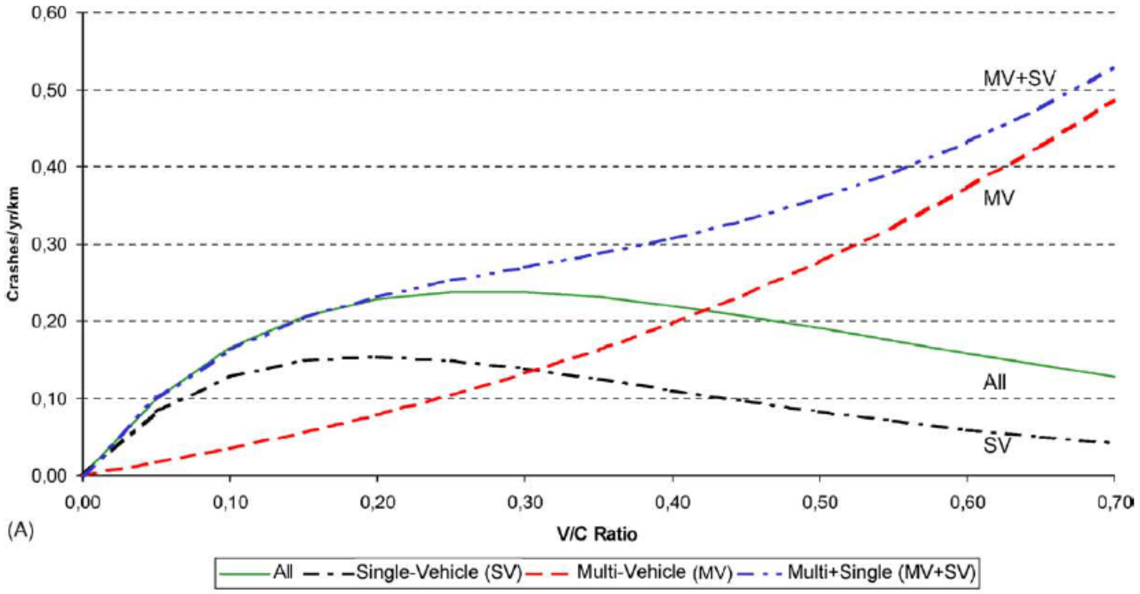

Figure 24. Graphic. Predicted crash frequency per kilometer for one freeway lane as a function of V/C ratio.(174)

This concept of relating traffic volume, density, and safety performance was also captured in the neural network SPFs estimated by Kononov et al.(179) On the AADT-crash frequency plot, the authors defined three regions of AADT (see figure 25):

1. Sub-critical zone.
2. Transitional zone.
3. Super-critical zone.

In the sub-critical zone, traffic is generally free-flowing, and increases in AADT result in moderate increases in crash frequency. The relationship becomes more elastic after reaching a "critical density" point, so a change in AADT results in a steeper increase in crash frequency. The authors theorize that in this zone, the mix of higher vehicle speeds with the increasing density of traffic results in a more rapid increase in the probability of a crash occurring. Finally, a second "super-critical density" point is reached where overall vehicle speeds are reduced and density is high. For densities larger than this second critical point, the elasticity of the AADT-crash frequency relationship is reduced. At this point, traffic is congested, speeds are low, and the probability of crashes, while high, is not nearly as sensitive to increases in traffic.

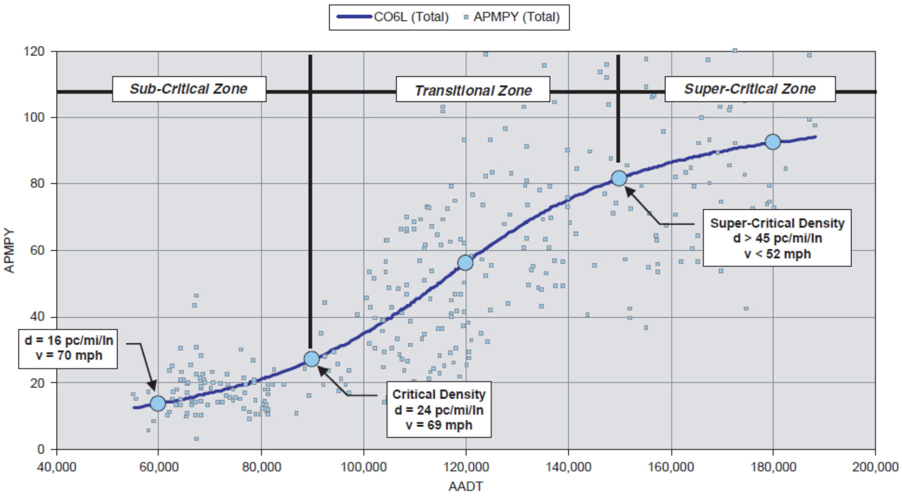

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Figure 25. Graphic. Six-lane freeway SPF for Colorado with zone labels based on critical density.[179]

Kononov et al. also compared these three AADT zones to freeway level of service (LOS) using the methodology in the *Highway Capacity Manual*.[178] Freeway LOS is based on vehicle speeds, traffic flow, and density. LOS and crash frequency were plotted in figure 26. The figure reveals that LOS A and B are associated with the sub-critical zone, LOS C occurs near the density at which the elasticity of crash rate begins to increase, LOS D and E are associated with the transitional zone, and LOS F is associated with the super-critical zone. The comparisons between LOS and predicted crash frequency are summarized in table 20. It is notable that the average slope for LOS D and E is more than double the next steepest average slope (LOS C).

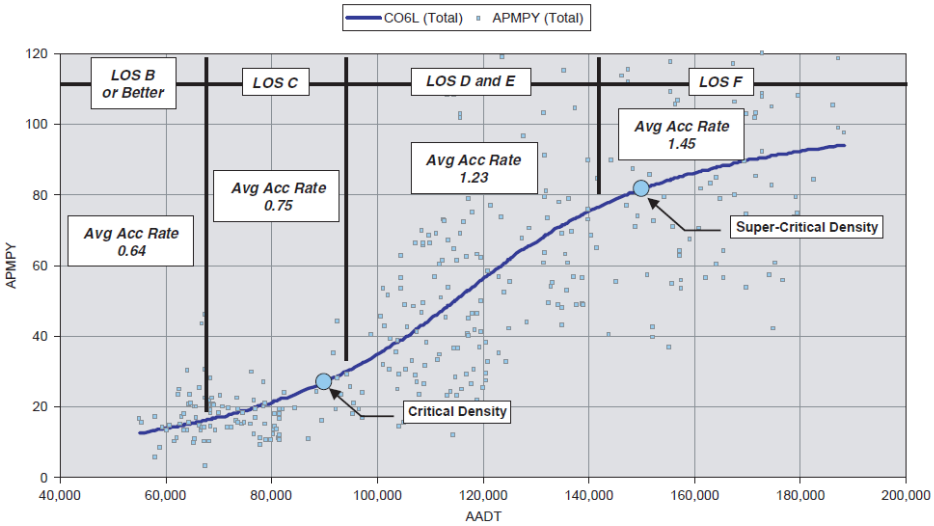

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Figure 26. Graphic. Relating the six-lane freeway SPF to level of service.[179]

Table 20. Comparing freeway LOS with predicted crash rates for six-lane freeways in Colorado, adapted from Kononov et al.'s plot in figure 26.(179)

LOS	LOS Description[2]	AADT Range from the Model [thousand vehicles per day]	Predicted Crash Rate Range [crashes per mile per year]	$\frac{\Delta Crash\ Rate}{\Delta AADT}$
A	Vehicles able to freely maneuver in the traffic stream	55 – 67.5	12 - 17	0.40
B	Slight restrictions on vehicle maneuverability within the traffic stream			
C	Noticeable restrictions on vehicle maneuverability	67.5 – 94.2	17 - 29	0.47
D	Noticeable decline in speeds and strict limitations on vehicle maneuverability	94.2 – 142.1	29 - 76	0.97
E	Traffic is near capacity and highly volatile to even minor disruptions			
F	Congested conditions with a breakdown of traffic operations	142.1 – 190	76 - 94	0.38

REAL-TIME RELATIONSHIPS

Studies that are focused on the relationship between safety performance and traffic metrics in real-time are based on predicting the probability of a crash occurring for a given set of traffic conditions. Models are developed by merging crash data, roadway data, and high-resolution traffic operations data acquired from various detection systems. This approach has the advantage of providing information about what specific operational states are most closely associated with crash events. Some skepticism has been expressed as to the usefulness of these

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[2] As defined in the 6th edition of the *Highway Capacity Manual*.(170)

models given reporting errors around the time of crash. However, these models are mostly developed for urban freeway facilities which are likely to have minimized reporting errors because of factors such as the presence of traffic management centers that track incidents and the fact that urban freeways have high traffic volumes, which increases the likelihood of crashes being reported at or near the time of the crash.

Typical Data

The real-time models are typically developed by integrating crash data with freeway detector data (usually from loop detectors). Crash data typically include crash type, severity, date, location, and time, while operational data include vehicle speeds, traffic flow, and occupancy at regular intervals (e.g., every 5 or 15 minutes).(181,182,183,184,185) Some efforts have also included data on real-time weather conditions at the time of the crash.(186,187)

Methodology

In the annual methods previously discussed, observed crash frequencies are count variables. Generally, one crash at most occurs at the shorter time intervals required for real-time analysis. Thus, the variable being modeled is often a binary variable where 1 represents a crash occurrence for a given set of conditions and 0 represents no crash. The principal statistical analysis approach used for these real-time models is the binary logit model. This model can be used to estimate the probability of an event occurring or not based on a series of independent variables.(188) In safety analyses, traffic data over the short analysis period are used to predict the probability of a crash occurring within that period or not. This contrasts with the annual approach, which predicts the number of crashes expected to occur within a year. The traditional form of the binary logit model is provided in figure 27. As an example of this approach, Lee et al. used a binary logit to model the real-time likelihood of a crash on Toronto freeway segments.(187)

$$P_{crash} = \frac{e^{X_i\beta}}{1 + e^{X_i\beta}}$$

Figure 27. Equation. Typical functional form of a binary logit prediction the probability of a crash occurring.

Where:

P_{crash} – the probability of a crash occurring.

$X_i\beta$ – a vector of independent variables (X_i) and associated regression coefficients (β).

Abdel-Aty et al. incorporated the binary logit into a matched case-control analysis of seven months of crash and loop detector data from 13 miles of Florida freeway.(181) The analysis was meant to identify relationships between traffic operations and the risk of a crash occurring. For every crash that occurred, the authors identified 11 cases with similar characteristics (time of day, day of week, season) where a crash did not occur to create the population against which the crash characteristics could be compared. For each crash, traffic data in five-minute intervals were obtained from loop detectors both upstream and downstream of the crash location. Three traffic variables were considered for this analysis: traffic volume, traffic speed, and detector occupancy. Detector occupancy is the proportion of a fixed amount of time during which a vehicle is sensed by a detector. It is a surrogate for density, where occupancy is proportional to the product of density and vehicle length.(189) For each traffic variable, the authors reviewed the effect of the average, standard deviation, and coefficient of variation (calculated as the standard deviation divided by the average).

This case-control binary logit approach has been used in other studies. Hourdos et al. used the approach to model crash risk on a section of I-94 in Minneapolis/St. Paul, Minnesota.(186) Abdel-Aty et al. used this approach to produce a histogram comparing average speed with crash frequency. The histogram revealed a two-peak distribution, with a proportion of the data centered at 25 mph and the rest of the data centered at 60 mph (see figure 28).(182) The researchers saw this as indicating the need for two separate models for low (0 to 35 mph) and high (40 to 80 mph) speeds.

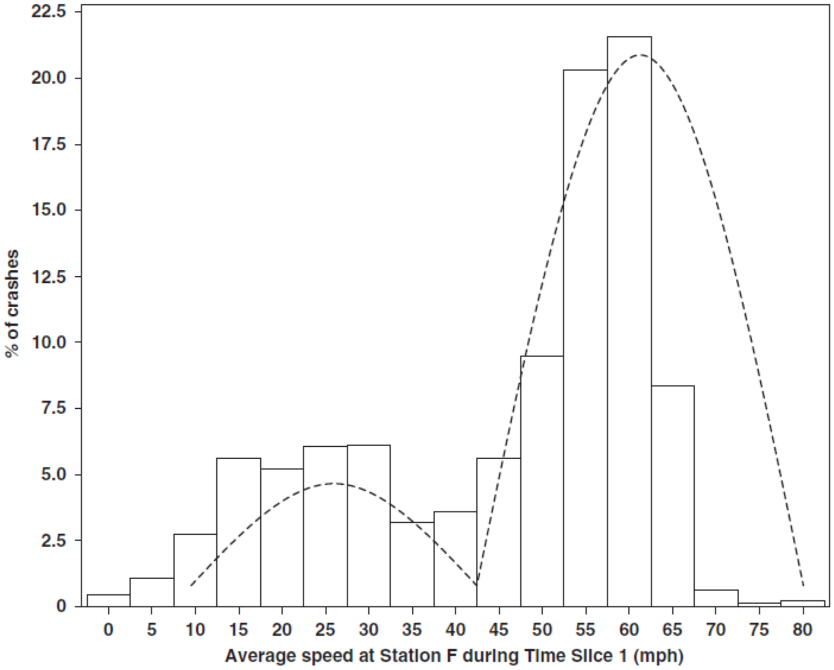

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Figure 28. Graphic. Histogram of freeway crashes based on average vehicle speed across all three lanes at the loop detector immediately upstream of the crash location (Station F).(182)

Pande et al. incorporated a spatial component, using the matched-case modeling approach to develop spatial risk maps.(183) Three-dimensional contour maps were developed for each predictive variable showing locations within a series of loop detectors and across a given amount of time when crash probability is highest as a result of changes to a traffic metric.

The binary logit model can also be used to estimate the probability of a crash resulting in an injury given that the crash occurred. Golob et al. used freeway loop detector data to develop eight traffic metrics and identify correlations between these characteristics and various crash outcomes.(185) A binomial logit model was used to correlate these traffic characteristics with the likelihood of a crash resulting in an injury (compared to property damage only). Additionally, a multinomial logit model was developed to describe the crash type; specifically, to differentiate between the chances of the crash type being sideswipe, rear-end, or hit-object (compared to an overturn or broadside crash).

Neural networks were also used to analyze crash occurrence using this real-time framework. Pande et al. used random forests and multilayer perceptron neural networks (MLPNN) to identify relationships between traffic operation conditions and rear-end crash occurrence.(184)

Notable Results

The modeling efforts described above all had similar results. Abdel-Aty et al. found the biggest predictors of real-time crash probability around a subject location were the coefficient of variation of speed (CVS) downstream of the location and the occupancy upstream of the location (based on loop detectors within a quarter-mile upstream and downstream).(181) Figure 30 is a box-and-whisker plot that compares the differences in CVS, defined in figure 29, between crash and non-crash events. Figure 31 provides the box-and-whisper plot for occupancy. For both CVS and occupancy, it is clear from the figures that increased rates are associated with increased crash probabilities.

$$CVS_i = \frac{\sigma_i}{\mu_i}$$

Figure 29. Equation. Coefficient of variation of speed at loop detector I.

Where:

CVS_i – coefficient of variation of speed for loop detector *i*.

σ_i – standard deviation of speed at loop detector *i*.

μ_i – average speed at loop detector *i*.

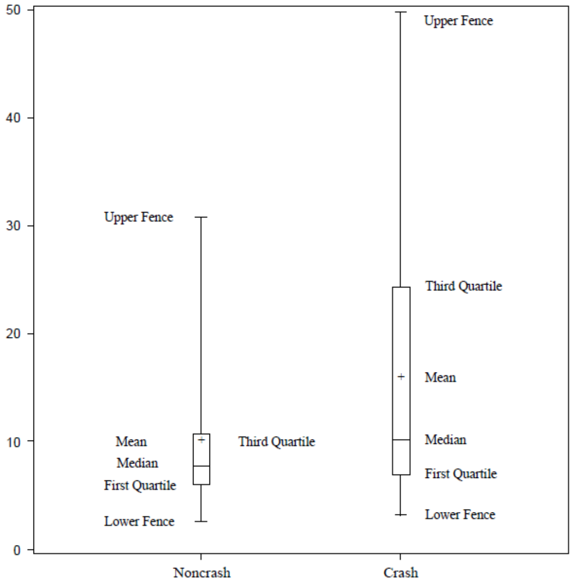

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Figure 30. Graphic. Comparison of coefficient of variation of speed at the downstream detector for non-crash and crash events.(181)

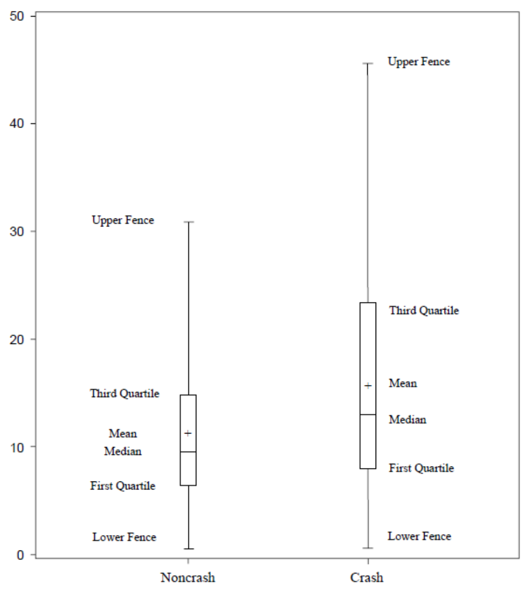

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Figure 31. Graphic. Comparison of occupancy at the upstream detector for non-crash and crash events.(181)

In a similar study, Hourdos et al. found that the traffic characteristics associated with an increase in crash probability include:(186)

- Transitions from uncongested flow to congested flow at the study section;
- Increased uncongested speed upstream of the study section;
- Transition from low speed variance to high speed variance in the right lane; and
- Increased range of speeds in the right lane.

In general, the Abdel-Aty et al. and Hourdos et al. results were like the results of an analysis performed by Lee et al. on a section of freeway in Toronto.(187) Lee et al. found that the likelihood of a crash increases as speed variance increases, density increases, hourly volume increases, and weaving increases.(187)

Pande et al. found upstream density, downstream speed, and downstream coefficient of variance of volume to be significant predictors of crash occurrence.(184)

When Abdel-Aty et al. improved upon the 2004 study using significantly more data, the researchers developed separate models for low-speed conditions and high-speed conditions.(182) For crashes under low-speed conditions, the model identified statistically significant correlations between the risk of a crash and the coefficient of variance for speed as well as average occupancy both upstream and downstream of the crash. As both increased, indicating higher frequencies of stopping and starting from congestion, the risk of a crash occurring increased.

The authors interpreted this as being representative of the likelihood of rear-end crashes occurring under congested conditions.

The model for crashes under high-speed conditions had different results. Increased occupancy upstream of the crash was found to be correlated with a decrease in the likelihood of a crash, while increased occupancy downstream was associated with an increased likelihood of a crash. Increased volume upstream of the crash was associated with increased crash probability, while increased volume downstream of the subject loop detector was associated with decreased crash probability. Ultimately, it was theorized by the authors that the combined occupancy and volume characteristics are associated with a congestion-causing event occurring downstream and propagating towards the location of the crash (i.e., a shockwave). Where congestion is already present (high occupancy upstream of the crash), it is less likely a crash would occur.

Pande et al. used the matched-case control modeling approach to develop spatial risk maps.(183) They developed three-dimensional contour maps for each predictor variable showing the location within a series of loop detectors and the amount of time into the future when a crash is most likely to occur. Figure 32 is one of the plots developed by the authors. As the contour map gets darker, the chances of a crash increases. Stations B thru H indicate a series of loop detectors along a highway segment, with Station F being the study station, stations G and H being downstream, and B through E being upstream. The x-axis indicates time into the future. In practical terms, figure 32 shows that, based on increases in CVS, crash probability is highest at or just downstream of the subject loop detector (detector F) within the next five minutes. From here, traffic managers can take actions to either reduce crash potential (such as introducing speed harmonization countermeasures) or to prepare responses (e.g., relocating freeway incident patrols to the area of this loop detector). Note that the research discussed in this section did not consider crash severity.

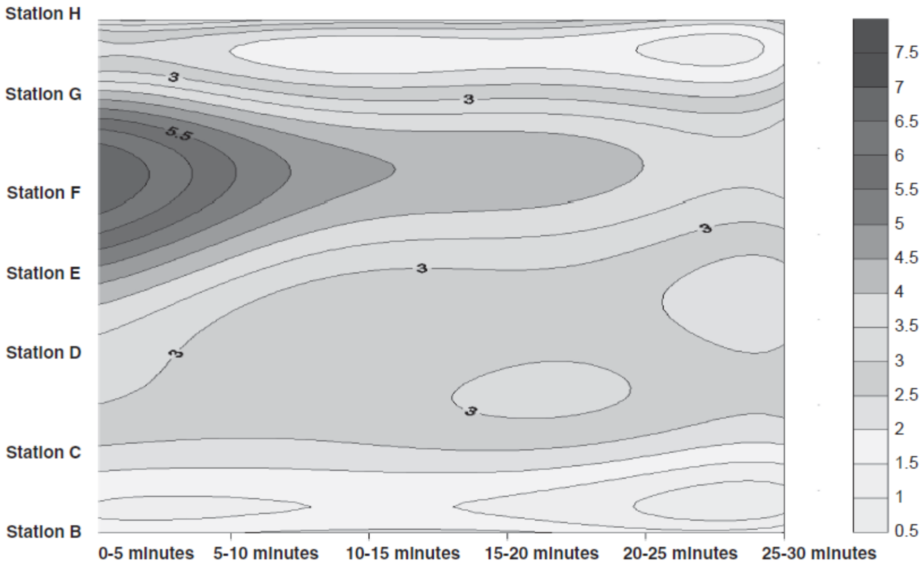

Figure 32. Graphic. Contour map showing relative odds of a crash as a function of changes in coefficient of variation in speed along a segment of highway.(183)

Golob et al. used binary and multinomial logit models to relate traffic operations to discrete crash outcomes; the results are summarized qualitatively in table 21.(185) Scores were assigned to eight traffic operations factors that were derived from loop detector data. Golob et al. found that only some of these factors (summarized in table 21) were predictors for crash type and severity.

1. Congestion in Left and Middle Lanes – this score increases as density increases.
2. Traffic Volume – this score increases as traffic volume increases.
3. Synchronization Between Lanes – when traffic characteristics change across lanes, the score increases as the changes are more aligned.
4. Perturbation in the Right Lanes – this score increases as congestion in the right lane increases and speed variance increases.
5. Variance in Traffic Volume Across Lanes – this score increases as volume variance across the lanes increases.
6. Relationship Between Volume in the Right Lanes and the Other Lanes – this score increases as the variance in congestion levels between the right lane and the other lanes is reduced.
7. "Systematic" Changes in Traffic Volume – score based on statistically significant changes in traffic volumes, such as entering or exiting AM peak period.
8. Synchronization in the Left and Middle Lanes – the score increases as traffic operations in the middle and inside lanes becomes more synchronized.

Table 21. Correlations between traffic factors and the probability of crash severity and type as found by Golob et al.[3] (185)

Traffic Factor to be Increased	Probability of an Injury Crash	Probability of a Sideswipe Crash	Probability of a Rear-End Crash	Probability of a Hit Object Crash
1	*Decrease*	*Increase*	*Increase*	Increase
2	*Decrease*	Increase	*Increase*	Increase
3	*Decrease*	Increase	*Increase*	Increase
4		*Increase*	*Increase*	Increase
7		Increase	*Increase*	Decrease
1*6	*Decrease*			
1*7	*Increase*			
2*2		Decrease	*Increase*	Increase
2*4	*Decrease*			
3*3		*Decrease*	*Decrease*	Decrease
4*6	*Increase*	*Increase*	*Increase*	*Increase*
5*5			*Increase*	Increase

It is notable that the models indicate an inverse relationship between the probability of a crash resulting in an injury and the probability of a crash being a sideswipe or rear-end. This seems reasonable as these crash types commonly occur in low-speed, high-congestion scenarios and thus are likely to be of lower severity. Overall, while these findings are helpful, they provide no indication of whether a crash will occur based on traffic conditions, only the characteristics of the crash given that it does occur. Additionally, while the general direction of the correlations is presented in table 21 for simplicity, assessments of elasticities would help determine whether effects are large enough to form the basis of subsequent policy or management decisions.

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[3] Italics indicate the relationship was statistically significant at the 95-percent confidence level.

KEY TAKEAWAYS

It is clear from the literature reviewed in this chapter that traffic flow, speed, and density are all related to safety performance. In general, increases in traffic volume are associated with increases in crash frequency. Lord et al. demonstrated that the rate at which SV crash frequency increases with traffic volume decreases while the rate at which MV crash frequency increases with traffic volume remains roughly constant.(174) Kononov et al. showed that the power function may not accurately describe the traffic volume-crash frequency relationship and showed different operational levels of service (thus different states of density) exhibit different safety performance profiles.(179) Bonneson et al. used a CMF to show that density affects the frequencies and relative frequencies of SV and MV crashes on freeway segments.(177) Lord et al. identified unique shapes that relate changes in density and V/C ratio with SV and MV crash frequencies.(174) For both traffic metrics, SV crash frequency reaches a peak and then steadily declines as density and V/C increase. The MV crash-density relationship varied based on area type, being best described as a power function with a coefficient greater than one for rural freeways and less than one for urban freeways for the range of densities observed on each respective facility type. The MV crash frequency-V/C ratio relationship was found to be a power function with a coefficient slightly greater than one for both rural and urban freeways.

Various results showed that short-duration traffic operations observations can provide valuable predictions of crash likelihood. Significant increases in density as well as the coefficient of variation of speed are both associated with increased likelihood of a crash.(181,187) Additionally, freeway crash likelihood has been shown to differ based on average speed, with low-speed and high-speed traffic flows having different crash potential indicators.(182) Shockwaves have also been shown to be associated with increased crash probability.(186) Crash type and severity outcomes are likely to vary based on operational conditions, as evidenced by the models developed by Golob et al.(185) For practical purposes, these relationships provide valuable insights for agencies that can implement strategies to reduce crash potential, whether through reducing speed variance,(181,182,186,187) producing more uniform flow across lanes,(185) or mitigating the effect of shockwaves.(186)

CHAPTER 4 — EFFECTS OF WEATHER AND WEATHER-RELATED ROAD CONDITIONS ON SAFETY PERFORMANCE

INTRODUCTION

Many factors that characterize the driver, vehicle, and roadway environment may contribute to the occurrence of a crash. Of these, weather directly influences the roadway environment. Adverse weather can create a less forgiving driving environment with reduced road friction and limited visibility, which can in turn affect the performance of the driver or the vehicle. In these ways, weather can adversely affect safety performance, which is measured in terms of the frequency and severity of crashes. FHWA reports that 21-percent of crashes on U.S. roadways are weather-related, meaning they occur in inclement weather (e.g., rain, snow, high wind, etc.) or on pavement that is slick due to precipitation.(190) Road weather management is therefore a key tactical program area falling under the incident/event management category of TSMO strategies (see figure 1).

There are three broad categories of strategies that can be employed to mitigate the adverse safety performance effects of weather on roadways: advisory strategies, control strategies, and treatment strategies.(191) Advisory strategies provide information to motorists on impending adverse weather events, which can influence trip planning and driving behavior. Examples of advisory strategies include 511 interactive telephone services, transportation agency web sites, and on-road motorist warning systems, such as variable message signs. Control strategies utilize roadway devices to permit or restrict traffic flow in adverse weather. Examples include access control, speed management—such as variable speed limits— and signal timing. Treatment strategies involve the addition of agents to the roadway to minimize or eliminate the effect of weather. Examples include snowplowing, anti-icing, and deicing. There are numerous management, maintenance, and operations techniques that fall into these three categories. However, the effects on safety performance of both adverse weather and these mitigation techniques are not always well understood. To set the stage for identifying safety performance analysis needs in this area, this chapter summarizes the analysis approaches and findings of a representative set of studies that have investigated the relationships between weather and safety performance, as well as the effect of various weather mitigation strategies.

DATA

Weather Conditions

The availability of data is a crucial first step in exploring and quantifying the effect of weather on safety performance. Weather data are available from a variety of sources, with different applications and objectives in mind. To maximize the utility and transferability of analysis techniques, it is crucial to use weather data that is widely accessible.(192) The primary sources of weather data geared toward transportation applications are Road Weather Information Systems (RWIS). The main purpose of an RWIS is to efficiently process weather data and condense it into an actionable format to support decision-making. Often managed at the State level, an RWIS is comprised of Environmental Sensor Stations (ESS), a communications system, and a central data collection system. The ESS are placed in and near the roadway to collect atmospheric, pavement, and/or water level data. Newer systems may also contain vehicle-based mobile RWIS sensors. There are over 2,400 RWIS ESS owned by State transportation agencies across the U.S., with at least one ESS in 49 States and Washington, D.C.(193) Atmospheric data include air temperature, humidity, visibility, distance, wind speed and direction, precipitation type and rate, cloud cover, tornado or waterspout occurrence, lightning, storm cell location and track, and air quality. Pavement data include pavement temperature, freezing point, condition, chemical concentration, and subsurface conditions. Water data include water level near the roadway and tide level (for assessment of storm surge). RWIS stations also often have video data collection capability. A given RWIS may only collect a subset of these data elements, which is determined by agency needs and available resources. Ewan & Al-Kaisy surveyed 24 U.S. States and 2 Canadian provinces, and determined that most agencies consider pavement and air temperature, pavement condition, wind speed and direction, and precipitation information to be the most essential data.(194) Operational data, such as traffic speeds and volumes, are not widely collected at RWIS sites, though this is beginning to become more common. Figure 33 shows the various data components of RWIS, as well as some uses of each component.

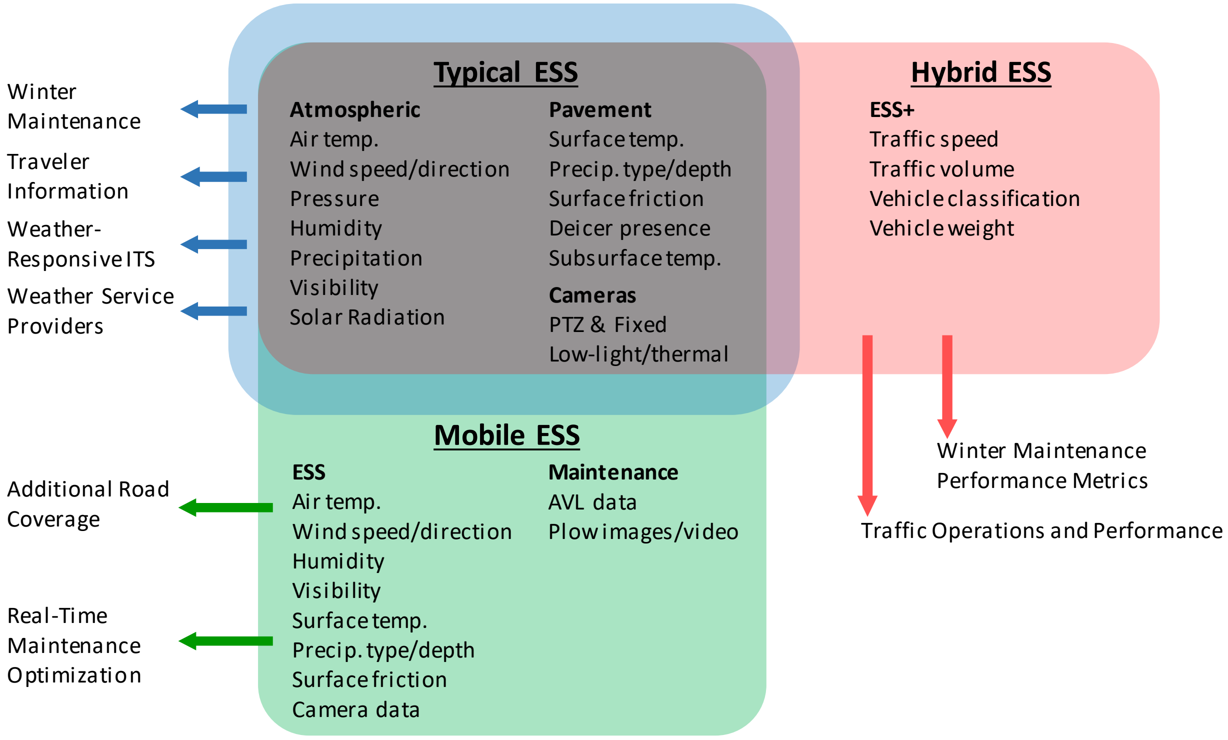

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Figure 33. Graphic. Various sensor and data components of RWIS.(194)

The original purpose of RWIS was for winter maintenance support, though its use has expanded significantly in recent years to include traveler information, operations activities, and ITS applications. Additionally, agencies have begun to approach RWIS more systematically, with many defining protocols for the placement of ESS. In the past, some agencies used techniques such as geo-spatial analysis and thermal mapping for optimizing ESS placement, but most relied on personnel expertise. Most agencies are currently expanding their RWIS networks, enhancing the capabilities of existing data collection locations, and/or expanding mobile RWIS efforts.

There are many other secondary sources of weather data. Depending on the application, these sources may be more suitable than RWIS data for examining specific facets of weather and the relationship between weather and safety performance. The National Weather Service (NWS) and the National Oceanic and Atmospheric Administration (NOAA) collect a variety of general weather data through local weather forecast offices, weather satellites, and cooperative observer programs. Additionally, the Federal Aviation Administration (FAA), U.S. Geological Survey, Department of Agriculture, Forest Service, and Environmental Protection Agency, among others, have deployed their own weather systems. Many State DOTs collect their own weather data and reports, often in relation to road maintenance operations. They may employ vehicle-based sensors, such as snowplow automated vehicle location (AVL) data and images. Figure 34 and figure 35 depict snowplow image data used by the Iowa DOT to assess road conditions when investigating crashes. Additionally, there are numerous private weather data vendors—called Value Added Meteorological Services (VAMS)—that collect various data elements that are often tailored to a specific purpose, region, or industry.

Source: FHWA

Figure 34. Graphic. Map showing location of crash and location of snowplow image.(195)

Source: FHWA

Figure 35. Photo. Snowplow image, taken 11 minutes after the crash occurred.(195)

Finally, another frequent source of weather data are crash reports, which often include a field for law enforcement to record the weather or roadway condition at the time of the crash. This can help determine if weather was a contributing factor to a crash (i.e., if the crash was weather-related). Because of the ease of use, especially in the case of safety performance studies which generally already have access to crash data, this is a very commonly-used resource. However, it is widely understood that these weather reporting fields (and crash reports in general) often suffer from inaccuracies and incomplete data. This is a result of subjectivity and the inconsistent interpretation of reporting fields involved in the process of individual law enforcement officers completing crash reports. In some cases, for instance, the road surface condition field may reflect the conditions when the form was filled out, not when the crash occurred. Additionally, many law enforcement agencies use a shortened crash report form in inclement weather, which provides much less detail of the crash than the normal report.

Data Integration

The FHWA has recently developed the Weather Data Environment (WxDE) as part of the USDOT's Data Capture and Management (DCM) Research Data Exchange. The WxDE is a web platform for collecting and sharing transportation-related weather data, with a focus on connected vehicle applications. It aggregates data from RWIS and mobile RWIS installations, as well as other data providers, and computes additional metrics. Prior to development of the WxDE, FHWA Road Weather Management Program partnered with the USDOT ITS Joint Program Office to implement the Clarus Initiative, an eight-year effort to develop an integrated surface transportation weather data management system. The initiative concluded in 2013, at which point 37 U.S. States and 4 Canadian provinces were participating and contributing data to the system.(196) The Clarus Initiative was a form of a mesonet, or regional network of weather information formed by integrating observational data from a variety of sources. Mesonets are common in weather agencies such as the NWS, but the Clarus Initiative represented a major step towards weather data integration with a transportation focus. The FHWA has also supported the integration of weather data into Transportation Management Center (TMC) operations, including implementing weather alert systems.(197)

Many of the studies reviewed for and referenced in this synthesis involved data integration operations on a smaller scale. Often this constituted joining weather data with crash data, maintenance data, roadway geometry data, and/or transportation operations data. Techniques for performing this sort of data integration vary based on the scale and format of the data. Hans et al. recommended that advancement of spatial and temporal integration techniques could allow for more effective analysis of weather data in conjunction with traffic operations and safety data, specifically suggesting an opportunity to combine local speed monitoring with weather data to identify unstable and changing conditions, and to facilitate after-action assessment and investigation of conditions that may have influenced the occurrence of a crash.(195)

ANALYSIS APPROACHES

Strong et al. identified two broad approaches used by studies seeking to explore relationships between adverse weather and safety performance.(198) Macroscopic studies examine large geographic areas and long time periods, which is often preferred for weather and safety research applications since both types of data are prone to significant noise. However, the simplicity of macroscopic studies can make it difficult to generate precise, meaningful conclusions from the analysis. Microscopic studies, on the other hand, concentrate on a much smaller study region, both spatially and temporally, and generally focus on a single aspect of the data, such as one weather variable, a subset of roadway segments in a region, or a crash type. Microscopic studies are generally less common in the field of weather and safety performance, though improvements in data availability are making them more prevalent. The main concern with microscopic studies, from a safety performance perspective, is that there must be a large sample of crash data to produce statistically reliable results. Andrey et al. warn against this issue, saying "the stochastic nature of collisions and heterogeneity of driver response… limit the utility of statistical models in explaining collision risk for small spatial or temporal units."(199) The distinction between macroscopic and microscopic studies is usually the scale on which they operate. Beyond that, there may be many similarities in analysis approaches between the two.

Researchers have employed a wide variety of methods to analyze various aspects of the relationship between weather and safety performance. One of the most common techniques in safety performance research is the before-after EB method (see Chapter 1 for further information). Veneziano et al. used the before-after EB method to examine the safety effects of fixed automated spray technology (FAST) systems for deicing, and Hans et al. used it to systematically prioritize sites based on weather-related crash occurrence.(200,201)

Another common analysis approach used in numerous studies is the matched pair framework, by which a candidate event is compared to one or multiple control events to detect variations between the two. In the case of weather and safety performance, this means comparing crash data from a day or time period with adverse weather to a similar one with clear weather. In theory, this allows the researcher to control for time-dependent variables that may affect crash occurrence, and thus changes in the likelihood of crash occurrence can largely be attributed to weather. The notable caveat is that this method does not directly account for exposure (e.g., traffic volumes), which may change in response to certain weather conditions. Andrey et al. used the matched pair framework to examine long term trends in crash risk due to weather by comparing six-hour precipitation periods with six-hour control periods that were on the same day of the week, exactly one week apart, with clear weather.(202) Other studies have performed similar analysis at the day level. Strong et al. examined weather-related crash and injury risk in Canada by comparing crash data for storm event days with control days exactly one week apart.(192) Knapp et al. observed the effects of extreme weather by comparing storm days (here defined as days containing a weather event lasting at least four hours, with an average snowfall intensity of 0.20 inches per hour or higher) with three or four control days (the same day of the week but with clear weather) in the same month.(203)

Statistical modeling techniques are also commonly used to predict crash occurrence and determine the factors that most contribute to it. A wide variety of modeling approaches have been used, even within the relatively specific realm of weather and safety performance. Arguably the most popular model for use with count data (of which crash frequency data is one variety) is the Poisson regression model. It has frequently been applied to crash data, including studies of weather and safety performance.(203,204) However, the Poisson model requires the mean of the count process to be equal to its variance.(205) Crash data frequently exhibit overdispersion, where the mean is less than the variance.(206) Yu et al. used Poisson regression to model mountainous freeway crash data in winter weather but employed random effects to counter the issue of overdispersion.(207) El-Basyouny et al. applied a multivariate lognormal form of the Poisson model for this same reason to study weather effects on crash types.(208)

While it may be possible to avoid some of the shortcomings of the Poisson model by altering its formulation, the negative binomial (NB) regression model presents a more straightforward solution. The NB model is suited to address the issues of non-normal distribution and overdispersion and has been used in numerous safety performance studies. There are several different variations of the NB model, and each adjusts the formulation of the model slightly to better address aspects of the data or model conditions. Some of these which have been applied to studies of weather and safety performance include the NB model with fixed effects,(209) the generalized NB model, and the zero-inflated NB model.(210)

In addition to these two primary families of count models, numerous other statistical methods have been applied to safety performance studies in the context of weather. These include multinomial logit,(211) fixed and random parameter logits,(212) and Bayesian logistic regression.(213,214) In the case of logistic regression, the dependent variable must be binary. In safety performance studies, this often manifests in the modeling of a crash as either "occurring" or "not occurring",(214) or a crash result being either "severe" or "non-severe".(212) Some studies of the effect of weather on safety performance employ multiple models (either from the same or different families) and assess their relative effectiveness using tools such as Deviance Information Criteria or Akaike's Information Criteria, which quantify the trade-off between goodness-of-fit and model simplicity.(211,212) Generally, the better-performing model depends on specifics of the data and study formulation. Additionally, some studies have attempted to utilize neural networks and other artificial information techniques such as the support vector machine model; while these methods have consistently been outperformed by other methods in estimating the relationship between weather and safety performance, they represent an area for future exploration.(211,212)

FINDINGS TO DATE

Effects of Weather on Safety Performance

Most agency and research efforts focus on winter weather (i.e., snow and ice), though a significant amount of research has also focused on the effects of rain and wet weather. Fewer studies have dealt with other weather events such as fog and high winds, as these generally represent a more isolated threat to traveler safety. The emphasis on winter weather is likely because winter weather is seen as actively "treatable" using physical techniques. There are few treatment strategies that can be applied in the presence of rain or high winds. But while it is understood that winter weather can produce more threatening conditions, the majority of weather-related crashes in the U.S. occur on wet pavement (70 percent) and during rainfall (46 percent).(190) This is due in large part to the fact that snow is only prevalent during certain times of the year and in certain regions of the country, while rain is more prevalent both spatially and temporally.

Eisenberg & Warner produced one of the seminal explorations of weather's effect on crash likelihood and severity, studying crash and weather data from 48 U.S. States from 1975 to 2000.(209) They concluded that, while injury and no apparent injury crashes increased in the presence of snow (compared to dry days), the number of fatalities during snow conditions decidedly decreased. Black & Mote analyzed crash severity and weather data for 13 U.S. cities, and concluded that while winter precipitation was associated with an increase in crashes over dry days, the chance of a crash being fatal did not increase significantly during winter precipitation. The study results showed that winter precipitation resulted in a 19-percent increase in no apparent injury crashes (with a standard error of 0.51-percent) and a 13-percent increase in injury crashes (with a standard error of 0.51-percent), both of which were statistically significant at a 95-percent confidence interval, while fatal crashes showed no statistically significant change.(215) This result has been supported elsewhere in the literature.(216,217,218) One explanation could be that drivers behave more cautiously in the presence of winter weather, decreasing speeds and increasing following distances, thus decreasing the likelihood of fatal crashes. Strong et al. postulated that drivers may not reduce speeds enough in the presence of wet roads or rain, but perceive snowy conditions to be more dangerous and adjust their behavior accordingly.(198) As part of their study, Strong et al. synthesized previous research on the effects of road surface condition on driving speed and crashes.(198) A summary of the findings is shown in table 22. The crash adjustment factors represent the expected crash frequency under the given weather condition compared to the crash frequency observed under normal weather conditions. The speed adjustment factors depict the expected percent reduction in in speeds for each condition. These findings show a substantial increase in crash frequency in the presence of snow and ice (particularly in the case of "snow-covered," "icy," and "very icy" conditions). However, the speed adjustment factor shows that while drivers are compensating for adverse weather conditions by decreasing their speeds, these speed reductions do not reflect the magnitude of the associated increases in crash frequency. This indicates that drivers may, in general, be underestimating the level of crash risk due to adverse road surface conditions. For example, the adjustment factors imply that "very icy" road surface conditions exhibit double the increase in crash frequency of "icy" conditions, but drivers only decrease their speeds another two percent on average.

Table 22. Adjustment factors for crashes and average driving speed under various road surface conditions, as synthesized by Strong et al.(198)

Road Surface Condition	Crash Adjustment Factor (%)	Speed Adjustment Factor
Dry	100	1.00
Damp	100	1.00
Wet	150	0.96
Chemically wet	150	0.96
Lightly slushy	150	0.90
Slushy	175	0.87
Deep slushy	200	0.84
Frost	370	0.94
Dusting of snow	150	0.96
Lightly snow-covered	210	0.89
Snow-covered	870	0.84
Lightly icy	200	0.94
Icy	800	0.85
Very icy	1600	0.83

In addition to the possibility that drivers behave more cautiously in the presence of winter weather, another explanation for decreased fatal crashes in the presence of winter weather could be that winter precipitation influences more drivers to delay or even cancel trips, leading to lower traffic volumes during winter storms events. Variations in traffic volume significantly affect crash occurrence.(213) Indeed, research shows that both explanations may contribute to the noted decrease in fatal crashes in snowy conditions. Knapp et al. found that winter storm characteristics decreased traffic volumes by 29-percent (with a standard error of 3.4-percent) and vehicle speeds by 16-percent (with a standard error of 7.6-percent). Both results were statistically significant at a 95-percent confidence level. Numerous other studies have reported a range of similar volume and speed decreases.(203) Yu & Abdel-Aty reported that high speed variation in the traffic flow on a roadway significantly increased the likelihood of severe crashes, where severe crashes were defined as crashes resulting in any fatality or injury (K, A, B, or C).(212) One exception to the decrease in fatal crashes in the presence of winter precipitation may be those involving vulnerable road users such as pedestrians, cyclists, and motorcyclists.(213) Li & Fernie identified significant reductions in pedestrian signal compliance in cold and snowy weather, a potential safety issue that is exacerbated by decreased visibility (of both pedestrians and drivers) and increased vehicle stop distances due to icy and slick roads.(219) However, these groups may travel less in the presence of adverse weather, similar to those noted above for other motorized traffic.

Furthermore, Eisenberg & Warner noted in their study that the first snowy day of the year exhibited substantially worse safety performance in terms of fatal crashes, with a tapering effect on the second, third, and fourth days.(209) They found that the effect of the first snow day was significantly higher for drivers over the age of 65, as shown in figure 36. Maze et al. found that crash risk was 3.5 times higher at the beginning of the winter season than at the end (as reported in Pisano et al., standard error and confidence level not reported).(223) El-Basyouny et al. investigated sudden extreme snow and rain events in Edmonton, Canada and found that major precipitation events which followed dry periods were highly significant for predicting increases in follow-too-close, stop-sign-violation, and run-off-road crashes.(208) These findings indicate that there may be some amount of driver adjustment involved in weather-related crash patterns. Interestingly, Andrey et al. concluded that elevated crash potential due to rainfall stemmed from reduced visibility, not reduced road friction, since crash rates quickly returned to normal following precipitation, even though the ground was still wet.(199) This phenomenon was not identified for snowfall events.

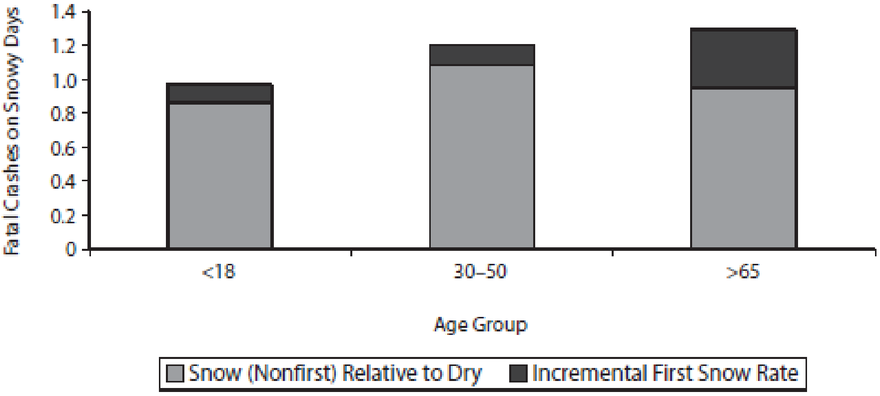

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Figure 36. Graphic. Rates of fatal crashes on snowy days and the first snowy day compared with dry days, by age group.(209)

Andrey also noted that while high winds and fog account for a very small proportion of total weather-related crashes, they can represent conditions for increased risk when they occur in combination with precipitation (for instance, blowing snow or fog and wet pavement).(199) Wind can have a variety of effects on traveler safety, including directly pushing or overturning vehicles, obstructing visibility (blowing sand/snow/etc.), causing buildup of snow, or damaging bridges and other infrastructure. The stability of vehicles in motion is complex and is influenced by many factors, but strong crosswinds have the ability to overturn vehicles or push them out of their lanes or off the road. Edwards studied wind-related road incidents in England and Wales and discovered that the percent of total crashes that occurred in high winds was almost twice the percentage of time during which high winds were present.(221) Kumar & Strong studied the effect of high winds on two sections of roadway in coastal Oregon in relation to the implementation of automated wind warning systems.(222) This study found that there was a consistent difference in crash rates between the high wind season and non-high wind season. It also found that most wind-related crashes are single-vehicle or run-off-road crashes, reportedly involving drivers caught unexpectedly in high-wind situations. This is supported by the finding that drivers mostly rely on personal experience and observations in making decisions about travel.(199) Crash data from California and Minnesota indicate that wind affects single vehicle crashes more than multiple vehicle crashes. The data revealed that the average number of vehicles per crash was lower for wind-related crashes than for non-wind-related crashes: 1.69 vs. 1.99 for California and 1.36 vs. 1.86 for Minnesota (confidence levels were not reported by the authors).(222) Additionally, the data showed that wind-related crashes were more likely to result in fatalities or injuries than non-wind-related crashes. This is because crash types that are more common in wind-related crashes (e.g., overturning, road departure) are also more likely to have severely harmful outcomes. Due to their size and profile, commercial trucks are particularly prone to overturning or lane departure due to high winds (this is especially true of lightly loaded trucks). According to Pisano et al., commercial trucks make up only 7 percent of vehicle miles traveled but are involved in 11 percent of fatal crashes.(223) They represent a potential hazard to other drivers given their larger size and heavier loads, which result in a more extreme impact in the case of a crash. Their size and weight also make them more vulnerable to icy and slick road surfaces, in addition to high winds. The physical and operational characteristics of trucks can also affect the behavior of the drivers of passenger vehicles that may share the roadway, and this can be exacerbated by adverse weather conditions.(224) Furthermore, Maze et al. found that commercial vehicles are much less likely to divert, delay, or cancel trips due to inclement weather conditions.(220) This means that during adverse weather, the proportion of these vehicles is likely to increase.

The issue of single- vs. multiple-vehicle crash characteristics can also be studied for weather conditions other than high winds. Yu et al. examined safety performance in terms of weather on mountainous freeways and concluded that single-vehicle crashes have decidedly different characteristics than multiple-vehicle crashes.(207) In modeling the effect of weather on mountainous freeway crashes, it was determined that some variables were significant for both types of crashes, such as precipitation and average vehicle speed. However, weather parameters were more significant for single-vehicle crashes and traffic characteristics were more significant for multiple-vehicle crashes. Wang et al. analyzed crashes on expressway ramps with real-time traffic and weather data and found that curved ramp geometry and a wet roadway surface increased the probability of single-vehicle crashes, while off-ramps and high variance of speeds increased the probability of multiple-vehicle crashes.(214)

Assessments of Mitigation Strategies

Highway system managers and operators believe that keeping roadways clear of ice and snow significantly increases traveler safety, but technological limitations in weather forecasting often lead to reactionary treatment of adverse road weather conditions. This aspect is generally improving with modern meteorological technology and increasingly reliable forecasting. Additionally, technological advancements have increased the speed and effectiveness with which agencies are able to deliver mitigation strategies, from advisory to control to treatment.

As stated previously, the overwhelming emphasis in safety- and weather-related literature is on strategies intended to mitigate winter weather. Usman et al. examined winter weather maintenance and snowplow operations and found that reducing the time it takes to expose at least 80 percent of the road surface from snow and ice (known as the bare pavement regain time) from eight hours to four hours would produce a 50-percent reduction in crashes.(225) Additionally, Usman et al. found that a 1-percent improvement in road surface condition (as measured by the Road Surface Index) led to a 2- to 3-percent reduction in the expected number of crashes (the result was significant at a 95-percent confidence level but standard errors were not reported by the authors).(210) The California DOT (Caltrans) installed an icy curve warning system on a five-mile segment of highway in northeastern California that was known for fatal crashes in icy conditions. A before-after EB study found an 18 percent reduction in crash rate following the implementation of the icy curve warning system (standard error and confidence level were not reported by the authors).(226) Saha & Young studied the use of weather-related VSL systems in Wyoming.(227) The study found that winter weather VSL implementation resulted in 17.42 fewer crashes per 100 miles of VSL per winter season along the 143 miles of VSL corridors in the study.

Al-Kaisy et al. performed a synthesis of VSL use in adverse weather conditions. The following were among their findings:(228)

- In 2005, South Australia deployed a 45-sign VSL system to address weather and observed a reduction in crash rates of 20 to 40 percent (standard errors and confidence levels were not reported by the authors).
- In the early 2000s, Finland reported a 13 percent decrease in winter crashes (and 2 percent decrease in summer crashes) following deployment of a weather-focused VSL system (standard error and confidence level were not reported by the authors).
- Germany began installing weather-based VSL systems in the 1970s and has reported crash rate reductions of 20 to 30 percent (standard errors and confidence levels were not reported by the authors).
- Various fog-related VSL systems in the U.S. (Alabama, New Jersey, South Carolina, Tennessee, and Utah) have reported various safety improvements, though none presented reliable, quantitative safety performance results.

Source: FHWA

Figure 37. Photo. Example of variable speed limit sign with additional variable message sign for warning drivers of weather-related road conditions in Washington.(229)

Veneziano et al. explored the use of FAST.(200) FAST is designed for anti-icing at specific target locations, particularly bridges, ramps, and other elevated road surfaces. The study determined that, on average, FAST installation resulted in safety improvements, but the results varied widely. Crash reductions were computed to be from 16 to 70 percent on urban highways (standard errors ranged from 31 to 57 percent on rural interstates and from 19 to 40 percent on interstate interchanges). Some locations experienced crash increases, which the authors hypothesized may have been due to other factors such as increased traffic. The major weakness of this study was the lack of data detailing when the FAST system was in action during the study period. This is a common issue in studies examining mitigation strategies that operate dynamically but problematic because it includes time periods when the strategy is not operational. Standard errors and confidence levels for the results were not reported by the authors.

An emerging field of research has begun exploring the implications of climate change on transportation safety and operations. Milder winters caused by climate change have the potential to reduce crashes due to slick pavement by up to 50 percent in some regions.(230) However, other regions may experience increases in winter precipitation.(231)

KEY TAKEAWAYS

Adverse weather can negatively affect road safety performance in a variety of ways. There is a moderate body of research which seeks to explore the effects of weather on safety performance, though many specific aspects of the issue are still not widely understood or agreed upon, such as the reason for decreased crash severity in winter weather conditions and the precise effects of weather on traffic exposure. This is due to several factors, including the varying characteristics of weather and driver behavior both spatially and temporally. Additionally, there are fewer studies which have performed reliable safety performance analyses of weather mitigation strategies. This is because crash studies generally require many years of data to produce statistically significant results. However, more countermeasures are beginning to be implemented long enough that they can be robustly analyzed given appropriate data availability.

There is no shortage of weather data available. One of the most common transportation-related sources is data from RWIS, regional networks of weather sensors geared specifically to road weather and primarily used for road maintenance. RWIS can collect a wide variety of different atmospheric and pavement weather data, and this data is widely available in almost every U.S. State. Another common source of weather data is crash records themselves. Most enforcement agencies record the prevailing weather and/or road surface condition when reporting a crash. This data can be extremely valuable, as it can reveal the conditions at the time and location of a specific incident. However, there is a certain amount of subjectivity involved in crash record data, and this can make it unreliable in some cases. Many studies use data from various sources, including weather data, crash data, and traffic operations data, among others, so it is crucial to be able to integrate these data sources smoothly. The FHWA has developed multiple initiatives to advance the cause of data integration, most notably the ongoing establishment of the WxDE platform.

Researchers have used a variety of analysis tools to explore the effect of weather on safety performance. The fundamental safety performance metrics are crash frequency, which was more commonly used in the studies reviewed here, and crash rate. As noted in Chapter 3, crash rates assume a linear relationship between crash frequency and traffic volumes. Research has shown that this assumption is false in many cases. Crash rates are therefore being phased out as a reliable metric for safety performance. The most common technique for identifying the effect of a parameter or mitigation strategy is the before-after EB method. Another common technique is the matched-pair framework, which multiple studies have used to compare crash occurrence on days with inclement weather with that of normal days. Many different statistical modeling techniques have been applied to various aspects of weather and safety performance to determine which factors have the most significant effect on safety performance and the aggregate effect of certain weather conditions or mitigation strategies. The method most commonly used is the negative binomial regression family of models.

These different analysis approaches have resulted in a wide range of different findings. Eisenberg & Warner studied the entire continental U.S. and concluded that while crashes increased in snowy and icy conditions compared to dry conditions, fatal crashes decreased.(209) This could be caused by heightened driver caution and/or decreased vehicle volumes during conditions of inclement winter weather.(203) Furthermore, fatal and serious injury crashes tend to be more likely during the first snow event of the season compared to the second, third, and fourth storm events, and the early part of the winter season represents higher crash potential than the latter part.(209,220) El-Basyouny revealed a similar result for major rain and snow events following dry periods.(208) Kumar & Strong found a high number of crashes occurring in high-wind conditions in some regions,(222) which can particularly affect commercial trucks.(223) Additionally, different weather conditions can have different effects on the occurrence of single-vehicle crashes versus multiple-vehicle crashes. In terms of the effect of weather mitigation strategies, most studies reviewed in this chapter indicate improvements in safety performance. However, studies frequently suffered from incomplete data and small sample sizes of crashes. It is also important to note that studies finding increases in crash frequency or severity are often less likely to be published or reported.

There are several challenges that remain in coming to a full understanding of the effect of weather and weather-related road conditions on safety performance. Identifying a balance between macroscopic and microscopic study approaches continues to be a need for producing reliable-but-useful results. As Strong et al. identified, macroscopic studies are preferred when dealing with crash data because of the nature of traffic crashes and the presence of noise in the data.(198) However, these large-scale studies often produce results that inform the “bird’s eye view” of the issue but leave many questions as to the specifics. Developing techniques for reliable, actionable studies at the local and regional level represents a key area of advancement. Additionally, defining common, accepted approaches in data collection, aggregation, and definition will increase the transferability of methods and the translatability of results.(198) Finally, the effect of climate change on transportation safety, especially regarding winter and extreme weather, is a field that is growing in importance.

CHAPTER 5 — MODELING TRAVELER BEHAVIOR AND SAFETY INTERACTIONS

INTRODUCTION

Some TSMO strategies are expected to affect performance at a corridor, area, or system level. For some strategies, this might occur because the strategy regularly increases capacity or more effectively utilizes capacity on a facility during the peak period and in the peak direction of travel. This additional capacity and the resulting changes in travel time or travel time reliability, may attract drivers from parallel facilities. For other strategies, this might occur because the strategies increase the attractiveness of non-automobile modes or incorporate the use of traveler information, specifically to influence traveler behavior, including whether to make a trip, trip timing, mode choice, route choice, and destination.

A previous FHWA Office of Planning effort, *An Open Source Dynamic Traffic Assignment Tool for Assessing the Effects of Roadway Pricing and Crash Reduction Strategies on Recurring and Non-Recurring Congestion*, attempted to integrate crash prediction models with DTALite, an open-source dynamic traffic assignment (DTA) package. The effort ran into multiple challenges related to the temporal and network detail compatibility of the crash prediction and DTA models. Other than this effort, there are no known efforts related to the integration of safety performance modeling and analysis with transportation demand modeling and analysis for strategies that are expected to affect performance at a corridor, area, or system level. There are, however, some high-level estimates in the literature of safety performance benefits of travel demand management strategies, some of which are related to the demand management category of TSMO in figure 1.The purpose of this chapter is to provide an overview of ways in which travel demand patterns and safety performance might interact within a corridor, area, or system. The chapter also includes considerations for future research aimed at modeling these interactions and quantifying their safety performance outcomes.

To model the possible operational and safety effects of TSMO strategies that influence traveler behavior, including whether to make a trip, trip timing, mode choice, route choice, and destination, practitioners must grapple with the systemic effects of induced demand and the spectrum of complications implied within *triple convergence*.(232) Downs defines triple convergence as the self-regulating relationship inherent to traffic in a transportation network.(233) For instance, if vehicle capacity were hypothetically expanded along a corridor to alleviate peak period congestion, travelers that had otherwise 1) taken an alternate route, 2) used the corridor at an alternate time, or 3) taken an alternative mode during the peak travel periods would migrate back to the newly expanded corridor to take advantage of the improved performance. This would likely lead to a return to congestion during the peak periods. Travel demand is a fluid and interrelated phenomenon, and operational changes on one facility will have follow-on and spillover effects for much of the adjacent transportation system. These effects can be distilled into four categories:

1. **Trip Generation:** How many trips are made?
2. **Temporal Shift:** When are trips made?
3. **Route Shift:** Where are trips made?
4. **Modal Shift:** By what mode are trips made?

Selected TSMO and other demand management policies and strategies influence the fundamental costs and trade-offs associated with transportation choices, usually during the peak periods of travel, to optimize the performance for a given corridor or region. For instance, agencies may apply tolls and fees to price out demand for a given roadway and attempt to provide reliable service for those individuals who are willing to pay. Likewise, operational improvements to alternative transportation modes may reduce existing barriers or travel time costs and encourage additional usage of those modes. While some TSMO strategies attempt to influence the factors that govern individual travel demand decisions, like any other transportation policy, they are not immune to spillover effects.

These complex interrelationships underscore the difficulty in determining the potential safety outcomes of a given strategy. The safety effects of any TSMO strategy are likely dependent on the geographic constraints of the strategy, as well as the systemic network outcomes on adjacent facilities that result from the implementation of that strategy. Three examples of TSMO programs demonstrate thinking about these outcomes in practice: PTSU, HOT lanes, and TSP.

Each of the aforementioned strategies will likely have a tangible, but significantly different influence on the four components of travel demand. Each strategy influences trip generation, but PTSU and TSP temporarily expand and optimize existing capacity to accommodate additional trips while HOT lanes attempt to curtail demand of a particular facility to improve travel time reliability. In response, travelers may be attracted to the new capacity along a given corridor provided by PTSU and TSP, while strategies that convert existing general-purpose lanes into HOT lanes may push away drivers unwilling to pay for travel time benefits onto parallel facilities or an alternative mode, or they may choose to travel during less congested times when tolls are reduced or not present. Finally, PTSU may encourage additional motor vehicle travel by adding vehicular capacity, while TSP may encourage transit ridership by optimizing travel time. The specific performance of any TSMO strategy is highly context-dependent, but these four measures of travel demand (trip generation, route shift, temporal shift, and modal shift) are the foundation for discussing changes in outcomes.

Because of these complex and interrelated travel demand results, practitioners and researchers attempting to quantify the safety performance of TSMO strategies must apply a modeling process that can address all four components of the strategy to arrive at estimates of exposure on affected facilities, which are key to analyzing safety performance. The following will affect exposure because of a TSMO policy aimed at demand management and/or better utilization of capacity:

1. Change in traffic volumes on the treated facility(ies) during period of active operation.
2. Change in traffic volumes on the treated facility(ies) during period of inactivity.
3. Change in traffic volumes on parallel/alternate/competing routes.
4. Change in traffic volumes on alternate/competing modes.

The following sections of this chapter will survey the literature surrounding travel demand responses to TSMO and some other demand management strategies, provide a taxonomy of likely outcomes for certain strategies, and outline potential methods for future research to consider when modeling changes in exposure that may lead to changes in safety performance.

PREVIOUS RESEARCH

This section outlines some of the literature describing the relationship between strategies aimed at managing travel demand and/or more effectively utilizing existing capacity and travel demand. These strategies vary in scope and application; they range from more traditional programs, such as telework and transit service improvements, to more complex operations, such as managed lanes and congestion pricing schemes. Much of the related literature focuses on an economic approach that defines demand with respect to price elasticity. This review outlines the behavioral expectations associated with the four dimensions of travel demand: trip generation, temporal shift, route shift, and modal shift.

Trip Generation

Transportation responds to the forces of supply and demand like any other market; however, there are numerous confounding factors that make it difficult to quantify exact relationships between available capacity on a given corridor and the number of trips taken. Burris succinctly summarized this challenge in describing the effect of flat rate tolls and variable rate tolls (i.e., congestion pricing and dynamic lane tolling) on travel demand, “empirical estimates of both $E_{T\text{-}variable}$ and $E_{T\text{-}flat}$ range from (almost) perfectly inelastic (-0.02) to unit elastic (-1.0)” (p. 55).(234)

Essentially, similarly-designed strategies will have wide ranging effects based on the exact context. To this point, surveys of elasticity of demand for select strategies, including parking price, transit price and service, fuel price, and dynamic HOT lane pricing, provide wide ranges of empirical estimates for the effect of these strategies on willingness to travel (i.e., trip generation).(234,235,236,237,238) This research suggests that the relationship between the cost of travel, in direct and indirect price, time, reliability, and transportation demand, is non-linear and highly dependent on an individual’s transportation options.

Changes to travel behavior may not necessarily be the difference between a trip made or deferred. More nuanced solutions, such as car-pooling, alternative routes, altering trip timing, or shifting modes, may satisfy traveler demand. As Lee notes, vehicular travel demand is not synonymous with person travel demand.(236) Vehicle travel demand might be more elastic than personal travel demand, as the former implies the consumer can replace a vehicle trip with alternatives (i.e., alternative times, car-pooling, and alternative modes), while the latter suggests that a trip deferred entirely is the least likely outcome.

Lee illustrates demand for transportation is the product of a bundle of cost inputs (fuel cost, vehicle maintenance, insurance, tolls, parking, etc.) that can translate into a variety of travel choices (route choice, trip timing, modal shifts, occupancy shifts, etc.).(236) Furthermore, these constituent costs may not factor equally in an individual's decision. Ephemeral component costs, like parking and toll fees, may be significantly less important than more direct personal costs, such as travel time savings and the cost of fuel, in the decision to drive a personal motor vehicle. The balance between these individual costs and the resulting trade-offs incentivize individuals to seek transportation alternatives.

Alternatives: Route Shift, Temporal Shift, and Modal Shift

Like trip generation, individual decisions to seek alternatives is a product of costs relative to the viable options. As Burris concludes, a significant determining factor in the outcome of a strategy aimed at managing travel demand and/or more effectively utilizing existing capacity is the diversity and viability of legitimate alternatives.(234) Travel demand will tend to be highly inelastic in communities with fewer alternatives available to consumers (i.e., travel modes, alternate routes, flexibility of trip timing). For example, drivers may be more willing to pay a toll if they believe that there are no viable alternatives to evade the toll. An example of this balance in practice relates to the performance of HOT lanes.

Jansen & Levinson (2013) and Liu et al. (2011) both found a positive correlation between HOT lane price and demand: as price increases, demand for HOT lanes increases.(239,240) While this may seem counterintuitive, both studies note that price acts as a signal of future congestion. Drivers might believe increases in toll price reflect more congested conditions and less reliable travel times. At a certain threshold, the travel time savings and reliability outweigh the toll price. However, as Brent & Gross note, the demand for a tolled facility relative to the general purpose lanes is a much better indicator of the elasticity of demand.(232) Demand for the HOT facility will be lower than the general purpose lanes by virtue of the direct cost of using the tolled facilities. Individuals must make the trade-off of sitting in congestion, paying the toll, or identifying an alternative.

Sullivan reported that variably-priced express lanes on SR-91 in southern California seemed to experience route diversion from parallel facilities.(243) After the express lanes opened on SR-91, reduced congestion on the tolled facility drew traffic from adjacent local streets. Conversely, as congestion returned to SR-91 over time, traffic on parallel, local roads also increased indicating that drivers sought alternative routes. To a lesser extent, there were mixed effects on peak period congestion spreading; there was a modest increase in traffic volumes at the shoulders of the peak period, but there were strong directional and AM/PM components to any discernable trip timing diversion.

Like TSMO strategies that improve travel time for motor vehicle travel, several techniques, like TSP and bus-only hard shoulder running, improve the reliability of transit to make this mode more appealing to consumers. To estimate the effect of transit improvements on transit ridership, Litman surveyed existing literature surrounding transit fare and service elasticities and recommended the transit elasticity ranges in table 23.(237)

Table 23. Recommended transit elasticity values.(237)

	Market Segment	Short Term	Long Term
Transit ridership WRT* transit fares	Overall	–0.2 to –0.5	–0.6 to –0.9
Transit ridership WRT* transit fares	Peak	–0.15 to –0.3	–0.4 to –0.6
Transit ridership WRT* transit fares	Off-Peak	–0.3 to –0.6	–0.8 to –1.0
Transit ridership WRT* transit fares	Suburban Commuters	–0.3 to –0.6	–0.8 to –1.0
Transit ridership WRT* transit service	Overall	0.5 to 0.7	0.7 to 1.1
Transit ridership WRT* auto operating costs	Overall	0.05 to 0.15	0.2 to 0.4
Automobile travel WRT* transit costs	Overall	0.03 to 0.1	0.15 to 0.3

Note: * WRT = with respect to.

Price elasticities refer to the proportional response in demand (consumption) to a change in price. For instance, if the estimated price elasticity of transit ridership relative to transit fares is -0.4, then a ten percent increase in the cost of a transit fare is expected to lead to a four percent decline in total ridership. Conversely, a ten percent decline in the price of a fare should lead to a four percent increase in ridership.

Table 23 illustrates two important points: 1) demand is a range of values and tends to be more elastic in the long term, either reducing or encouraging ridership as customers become accustomed to the changes, and 2) the increasing costs of motor vehicle travel are less effective at incentivizing new ridership than direct investments in transit. The first point suggests that the travel demand (and potential safety benefit) of improved transit ridership is not fixed; the same increase in transit service frequency will yield vastly different increases in ridership numbers depending on context (i.e., street connectivity, density of land uses, existing traffic congestion).

To the second point, if rising vehicular costs do not drastically increase transit ridership, then the inverse is likely true. Improvements to transit may have a slight effect on modal shift to transit, but ultimately, the direct costs of motor vehicle travel will govern the demand for personal motor vehicle travel. If the strategy does not produce a sustained decline in the number of vehicles on a given corridor, then the net effect on traffic volumes may be negligible. If new transit trips are eventually replaced by new vehicle trips due to available capacity, either through individuals shifting routes or travel times, then it does not seem intuitive to expect a corresponding change in traffic volumes.

Challenges to Quantifying Strategy Effectiveness

Many strategies aimed at managing travel demand and/or more effectively utilizing existing capacity have a temporal dimension, in addition to a geographic element. While this narrowly applies to time-specific policies, such as peak-period tolling or congestion pricing, there is short- and long-run effectiveness to every policy.(236,237) In addition to this temporal dimension, strategies often affect traffic characteristics which vary over time. Both factors complicate analysis of strategy effectiveness. Travel demand tends to be more elastic over the long term, as individuals adapt, identify alternatives, and make trade-offs that suit their individual needs. While this initially supports the longevity of effective TSMO management, empirical evidence tends to suggest that the limited scope of some TSMO strategies can produce mixed effects. For instance, if a toll only applies to single-occupancy vehicles and a congestion charge only applies to certain classes of vehicles, then travelers may choose to car-pool or drive non-charged vehicles to escape or minimize the toll, or they may simply decide that the additional costs are an acceptable trade-off for time savings and reliability. In these circumstances, the policy may have effectively targeted a specific component of demand, but the net effect on congestion may not be as strong as anticipated.(241)

TSMO strategies have mixed long-run effects as travelers adjust to the shifting transportation costs. Long-range housing and work location decisions may further distort the effects of TSMO strategies on traffic volumes, as well as safety. Land use and transportation's reciprocal relationship suggest that over time, individuals may make permanent housing and work decisions that conform to transportation conditions. As an example, housing within London's congestion charge cordon appears to command a price premium over non-cordoned areas of central London.(242) Individuals may decide that the housing premium is worth the latent transportation benefits, as well as to take advantage of a residential discount in the policy. The response to the strategies may be mixed and uneven over time–from a few months to several years–but it is clear from the literature that these tactics do not produce linear, easily transferable results that can be evenly applied to a range of contexts. The effects of the strategies are highly network-specific.

Connections to Safety

While studies of the empirical effects of strategies aimed at managing travel demand and/or more effectively utilizing existing capacity have typically focused on operations or price sensitivity, researchers and DOTs have only recently investigated the influence of these programs on safety. Approaches have varied between more macro-level trends, such as the cost of fuel,(243) and more local trends like London's peak-period congestion charge.(245) Intuitively, these studies note a negative correlation between travel costs and the number of crashes (i.e., higher travel costs are associated with having fewer crashes). If travel costs decrease overall travel, particularly single-occupant vehicles, then one might expect a similar decline in the number of crashes as well. However, the direct effects of these policies may be just as nebulous as the empirical measures of travel demand elasticity.

Grabowski & Morrisey found that decreasing retail gasoline prices appear to yield proportionally smaller increases in traffic fatalities.(246) This suggests that travel demand increases as the general cost of motor vehicle travel decreases, resulting in increased fatalities. Likewise, Green et al. noted that although traffic crashes within London's congestion cordon decreased faster than the rest of the country, it is also true that the general trend in the rate and frequency of roadway crashes in the United Kingdom was still declining.(245) Additionally, the study observed that the number of crashes occurring outside of the charged time period decreased, as well. While one may conclude that temporal shifts in vehicle travel did not contribute to additional spillover crashes outside of the charged period, it may also suggest that the congestion charge itself had a limited influence on safety outcomes. The effect of policies that reduce motor vehicle travel are likely beneficial for safety, but the direct, quantifiable effect is difficult to ascertain.

Litman attempted to provide preliminary estimates of travel demand management and TSMO's effects on safety by providing safety benefits in a manageable format, similar to one that might be provided in a traditional CMF format.(247) Table 24 and table 25 provide a summary of Litman's conclusions.

Table 24. Ten new shorter-term paradigm safety strategies (less than three years).(247)

Strategy	Traffic Safety Effects	Crash Rate Reductions
Transit service improvements (more routes, frequency, etc.).	Reduces vehicle travel directly, and often leverages additional reductions.	Each 1% transit ridership gains typically reduces traffic casualties by 1% or more.
HOV and bus traffic priority.	Reduces automobile travel and encourages transit and ridesharing.	Can reduce affected traveler's crash rates 10-30%, and total rates 1-5%.
Active transport improvements (better sidewalks, crosswalks, bike lane, etc.).	Reduces walking and bicycling crash rates, and total per capita crash rates.	Comprehensive active transport improvements can reduce resident's total crash casualty rates 5-10%.
Expanded carsharing services.	Reduces crashes by reducing car ownership.	Reduce total crashes 0.3-3%, with larger reductions in denser areas.
Raise fuel taxes to fully finance roadway costs, or as a carbon tax.	Reduces total vehicle travel and traffic speeds.	A 50¢ per gallon tax should reduce crash casualty rates 4-12%.
Efficient parking pricing (motorists pay directly for using parking spaces).	Charging motorists directly for parking typically reduces affected trips 10-30% and may reduce vehicle ownership.	Each 10% increase in the portion of parking that is efficiently priced reduces crash casualties 1-3%.
Congestion pricing (road tolls that increase under congested conditions).	Reduces crashes by reducing automobile use, particularly in large cities.	Reduces affected areas crash casualty rates 15-30%, with smaller reductions in nearby areas.
Distance-based vehicle insurance and registration fees.	Reduces vehicle use, especially higher risk driving.	Reduces affected vehicles' crashes by 10-20%.
Commute trip reduction programs.	Typically reduces affected commute trips 5-30% and may cause some vehicle ownership reductions.	Can reduce affected commuters' crashes casualty rates 5-30% and total crashes 0.5-3%.
Mobility management marketing.	Encourages travelers to use non-auto modes.	Can reduce affected households' crashes 5-10% and total crashes 3-6%.

Table 25. Five new longer-term paradigm safety strategies (more than three years)(247)

Strategy	Traffic Safety Effects	Crash Rate Reductions
More comprehensive and multi-modal planning.	Supports more multi-modal transport planning and considers safety effects.	Can lead to large vehicle travel and crash reductions.
More connected and complete streets.	Reduces crash frequency and severity by reducing vehicle travel, improving non-auto modes and reducing traffic speeds.	Can reduce local crash casualty rates 10-30%.
Reduced parking requirements (for zoning and development).	Reduces crashes by reducing vehicle ownership and use.	Can reduce affected area's crash casualty rates 5-15%.
Urban rail and Bus Rapid Transit.	Reduces crashes by reducing vehicle ownership and use, and traffic speeds.	Can reduce crash rates 30-60% in affected areas and 10-30% region-wide.
Smart Growth and Transit Oriented Development.	Reduces crash frequency and severity by reducing vehicle travel, improving non-auto modes and reducing traffic speeds.	Can reduce crash casualty rates 30-60% in affected areas and 10-30% region-wide.

These point estimates typically reflect individual studies or the author's own work, and they may not reflect a wide range of contexts, scenarios, and potential outcomes. As previous literature on travel demand strategies has indicated, unique circumstances often dictate the effectiveness of individual programs. However useful these estimates may be as a starting point, they likely suffer from many of the same issues that affect estimates of elasticity of travel demand. Actual effects to safety outcomes likely vary widely according to geographic context, availability of alternatives, personal preferences, and long-range temporal effects.

TAXONOMY OF DEMAND MANAGEMENT STRATEGIES

Demand management strategies, depending on the individual policy design, will vary in their influence on the four dimensions of travel demand: trip generation, route shift, temporal shift, and modal shift. Furthermore, these strategies typically take two general approaches, either through directly pricing transportation or by optimizing the existing capacity of the system. Table 26 and table 27 outline a conceptual taxonomy for demand management strategies, including some that fall under the umbrella of TSMO, according to their design and potential effects on the transportation demand modeling process. It is important to note that terms such as high, medium, and low are subjective and can be interpreted differently even within the traffic operations industry.

Table 26. Example taxonomy for considering transportation demand effects of pricing strategies.

Demand Management Strategy	Trip Generation	Route Assignment	Temporal Shift	Modal Shift
Congestion Pricing	High	Medium	High	Medium
VMT Tax	High	High	Low	High
HOT Lanes/Tolls	High	High	Medium	Low
Rideshare	High	Medium	Low	Low
Fuel Tax	High	Low	Low	Medium
Parking Fees	Medium	Low	Medium	Medium
Parking Cash Out	Medium	Medium	Low	Medium
Transit Fare Subsidies	Medium	Low	Low	High

Table 27. Example taxonomy for considering transportation demand effects of capacity optimization strategies.

TSMO Strategy	Trip Generation	Route Assignment	Temporal Shift	Modal Shift
PTSU	Medium	Medium	Medium	Low
Transit Improvements	Medium	Low	Low	High
Text/Mobile Alerts	Medium	High	High	Medium
Bike/Scooter-share	Low	Low	Low	High
Dynamic Message Boards	Low	High	Medium	Low
HOV/ Carpooling	Low	Low	Medium	Low
Tele-commuting	Low	Low	Low	Low
Flexible Work Schedules	Low	Low	Low	Low

Trip Generation

Strategies with a strong to moderate effect on trip generation tend to either induce trips that may not otherwise have been taken or discourage trips from happening at all. They typically achieve this by either freeing capacity for additional trips or pricing more discretionary travelers off a given corridor (i.e., through a toll). To evaluate the potential trip-generating effects of such policies, the practitioner must determine if the policy encourages additional trips through additional capacity, or if the policy discourages use of a facility to improve travel time reliability for those who are willing to pay. Every strategy has a magnitude of effect between these two poles on the spectrum. If the policy improves capacity, then the practitioner must identify the source of any additional trips (i.e., other routes, other times of the day, or trips that would have been forgone entirely). Conversely, if a strategy tends to restrict trips, typically through direct pricing like congestion tolling or a fuel tax, then the practitioner must identify the potential alternatives to the affected network. Travelers will usually exhaust all potential alternatives before abandoning a trip, and the willingness for people to pursue those alternatives is directly related to the viability of the alternatives.(234,236)

Route Shift

The available road network within a community strongly influences route choice. Lee's insight, that a trip deferred entirely is the most inelastic travel decision, suggests that individuals will almost always exhaust all opportunities to make a trip before abandoning a trip altogether.(236) While the nature of the trip (commuting as opposed to shopping, for instance) certainly affects an individual's willingness to make a trip, most individuals will seek to optimize their transportation before deferring it. To this point, Lee also notes that travel time is typically one of the strongest perceived costs of making a trip, usually overshadowing other direct costs like tolls or parking. Individual travelers, particularly those making necessary trips, could be expected to consider an optimized route for travel time before considering other alternatives.

Street network connectivity, as well as the real and perceived congestion along this network, is typically the first set of trade-offs for a potential traveler. Limitations to connectivity could include the lack of parallel road facilities, natural barriers (e.g., a single bridge over a water feature), or strongly nodal community development (e.g., desert or mountain communities). In limited connectivity environments, demand for transportation along the few available facilities will likely be highly inelastic. Burris notes that price-based TSMO strategies on these facilities would likely yield weak changes in traffic volumes; users are willing to pay higher fees to use the road.(234) This flexibility to choose alternate routes should be a critical factor in modeling projected traffic volumes.

Temporal Shift

In addition to choosing alternative routes, travelers may choose to travel during off-peak periods when congestion has abated and a demand management or operational strategy may not be in operation. This behavioral choice has a strong relationship with trip generation, as individuals choose to travel during, or at the edges of, the peak travel period. Strategies with the strongest effect on trip timing (e.g., congestion pricing) are those that either narrow or expand the peak travel period. Certain time-independent strategies, like a fuel tax or VMT tax, would influence travel at any time of day and not during a limited window; these policies would have a very weak influence on the temporal shift in travel demand.

Modal Shift

Strategies that target modal shift attempt to reduce the perceived costs associated with alternative transportation modes. These costs may be direct or indirect, and include improved travel time reliability of transit, perceptions of safety, or, in dense urban environments, the cost of personal vehicle ownership. These improvements may or may not increase the cost of driving. In fact, if ultimately successful, strategies that encourage shifts to alternative travel modes may even reduce the actual perceived costs of driving, particularly in terms of travel time and reliability, to those that do not change modes. Unless a strategy is formulated as a direct cost to personal driving (e.g., a fuel tax), it is unlikely that the policy would directly result in a significant decline in VMT. Nevertheless, strategies that improve alternative modes, regardless of their effect on driving, may facilitate many more individual trips across all modes where they are applied, ultimately making the entire system more efficient.

MODELING THE SAFETY EFFECTS OF TSMO STRATEGIES

This section builds on the preceding taxonomy by outlining a framework of practices that may allow practitioners to model the safety outcomes of strategies that influence trip-making behavior. This begins with a brief discussion of some simplifying assumptions that modelers will likely have to make in order to define the scope of analysis and concludes with a discussion of possible methods for assessing potential outcomes. Many of the recommended methods are already common practices for modeling travel demand and the operational results. To bridge the gap between changes in exposure and possible safety performance analysis applications, the framework must allow practitioners to parse the operational, and ultimately safety effects of the strategies into the four modeling components listed in the introduction of this chapter:

1. Change in traffic volumes on the treated facility(ies) during time of implementation.
2. Change in traffic volumes on the treated facility(ies) outside of time of implementation.
3. Change in traffic volumes on parallel/alternate/competing routes.
4. Change in traffic volumes on alternate/competing modes.

Assumptions

The simplifying assumptions below provide a manageable construct for implementing a modeling framework.

The Framework Only Applies to Peak Period Conditions

Many of the strategies focus on peak period conditions, as they are intended to offset peak period congestion. This conceptual model considers only peak period performance, rather than disaggregating these strategies from more systemic trends. As previously noted, future advancements to this work would consider coordinated strategies that could address recurring and non-recurring congestion in real-time, regardless of the time of day.

The Framework Does Not Consider the Influence of Land Use Planning or Smart Growth

Dense urban environments with a variety of transportation options appear to yield better safety performance outcomes (on a per capita basis) than suburban or rural contexts.(247) While land use patterns and Smart Growth strategies certainly influence transportation demand and safety performance, their effect on a specific program is likely highly dependent on context. Safety performance predictive tools should not compare diverse contexts with highly distinct travel patterns; they should compare the performance of a specific location with the strategy in place to the performance of that location without the strategy in place.

Methods to Model Trip Generation

The traditional Four-Step Model consists of four sequential steps closely related to the four previously outlined dimensions of travel demand: trip generation, trip distribution, modal split, and route assignment. The initial two steps, trip generation and trip distribution, define the demand within a transportation network by assigning magnitudes to trip generators and trip attractors within a network (trip generation) and applying a traditional gravity model to distribute trips within the system according to a quantified friction or cost (trip distribution). While this method has strong applicability for modeling macro-level movements within a transportation network, it may not provide an adequate means for assessing most strategies aimed at managing travel demand and/or more effectively utilizing existing capacity. The linear, sequential process of trip-based modeling may struggle with factoring induced demand and distinguishing more necessary travel (e.g., commute trips) from more discretionary travel (e.g., recreation and shopping). Both elements are likely necessary to determine the effects of a given policy, especially since the policies may directly incentivize or discourage additional trips on a portion of a network.

Activity-based models provide a useful enhancement that considers detailed land use and personal behavior in the modeling process. These models attempt to mimic the personal travel decisions (when, where, how long, and why) that individuals make throughout the day. As some TSMO strategies clearly produce responses in travel demand and the willingness to pay for that travel or destination, trip-based models alone would likely miss many of the system constraints and trade-offs incentivized by these policies. Ferdous et al. found that activity-based models performed better than traditional trip-based models in estimating inter-county commuter flows, and at least as well as trip-based models in modeling project-level effects to traffic volumes in metropolitan Columbus, Ohio.(248) As the research recognized, this comparison is only a first step in testing and validating activity-based models. Further refinements promise to capture a wider range of the transportation utility and the sensitivities to price and travel time reliability noted in the literature.

Methods to Model When a Trip is Made

Like trip generation, trip-based models have limitations associated with allocating trips by time of day. The lack of sensitivity to individual traveler behaviors and temporal variation in trips throughout the day (i.e., considering all hours of the day individually rather than peak period vs. off-peak period) translates into travel time predictions that are not effective in traditional safety analyses. By contrast, Ferdous et al. found that activity-based models outperformed traditional trip-based models in modeling peak and off-peak commuter flows, trip time, and travel duration in the same Ohio study. For evaluating the detailed changes in behavior, activity-based models promise to provide the granular detail necessary to evaluate operational and safety effects at a specific site, as well as its parallel facilities.(249)

Methods to Model Mode Choice

Activity and utility-based models also provide a better framework for modeling individual modal choices for certain trips. As Bhat observed, traditional trip-based modeling tends to overestimate modal shifts to alternative modes during commute trips, particularly because it struggles to capture trip-chaining and other travel behaviors that incentivize mode choice.(250) Multivariate utility models allow for many of the individual preferences and economic costs of transportation decisions to be weighted and factored into discrete choices (as shown in figure 38).

$$\begin{aligned}\text{Utility}_{\text{Transit}} = {} & a * \text{in-vehicle time} \\ & + b * \text{fare} \\ & + c * (\text{access time} + \text{egress time}) \\ & + d * \text{wait time} \\ & + \text{mode-specific constant}\end{aligned}$$

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Figure 38. Equation. Example utility function for mode choice.(251)

While there are limitations to this method, such as the consideration personal and cultural preferences, it does improve on traditional trip-based modeling by considering individual changes to the unit costs outlined in the travel demand literature and translates each cost into a modellable trade-off.(251)

Methods to Model Network Assignment

The last step in the traditional Four-Step Model is route assignment. After travel demand, system constraints, and mode choice have been defined, the model must allocate trips to specific routes based on the cumulative results of the preceding three steps. Route assignment generally assumes that all users will maximize their utility by selecting the shortest route, in terms of travel time, relative to the decisions of all other users. However, as previous sections have detailed, there are significant limitations with this method. Traditional models are ill-equipped to handle fine-grain temporal variations in traffic, and, therefore, travel times along every route are static across the network. In other words, while traditional models assume that each user will seek their shortest path, these models also struggle to determine the shortest path based on the flow of traffic over precise time periods.(252) Naturally, this static model of the transportation system may be ill-suited to quantify the nuanced network effects of some TSMO strategies.

By contrast, dynamic traffic assignment (DTA) is a potential solution to this critical shortcoming. DTA assigns traffic to routes with a similar goal of dynamic equilibrium but does so with the ability to model detailed temporal changes across the network. Therefore, modeled travelers seek equilibrium more intuitively than traditional trip-based models. To this end, DTA has already been applied to TSMO scenario testing. Shelton et al. used DTA to model congestion along I-35 in central Texas.(253) The study noticed that DTA modeling efforts were able to discern the phenomena of induced demand as expanded capacity encouraged additional drivers and managed lanes produced lane changing and weaving by drivers attempting to access the facility. The modeled scenarios also tested the effectiveness of additional factors, such as truck and heavy vehicle tolls and dedicated express lanes for traffic bypassing the city of Austin entirely. While these are still preliminary efforts for applying DTA to TSMO strategies, it is a promising indication for the ability of DTA models to handle the complex and interdependent relationships implicit in behavioral responses to travel demand.

LIMITATIONS & FUTURE DIRECTIONS

While this methodology poses a useful guide for conceptual modeling, actual safety outcomes will vary in relation to several confounding circumstances. In addition to the previously mentioned assumptions, the following issues should be carefully considered while conducting travel demand modeling and safety analyses for TSMO strategies. Furthermore, these limitations also present opportunities for future research into modeling TSMO and transportation safety.

Non-Linear Relationship between Travel Demand and TSMO

Safety analyses are highly dependent on the defined confluence of roadway facility infrastructure and traffic volumes (motorized and non-motorized). As the literature notes, TSMO strategies have highly variable effects on travel demand based on specific circumstances. The emergence of real-time traffic information and predictive tools for personal and shared mobility modes only increases the complexity of modeling changes in demand and road user behavior. Consequently, it is unlikely that standardized SPFs could be reliably applied across different contexts except in highly similar situations. However, the ability to model the effects of TSMO strategies on travel demand may prove to be more transferable, and future research should explore the applicability of future modeling practices.

Spillover Effects

TSMO strategies will cause spillover effects across a wider geographic and temporal window than most planning and engineering studies could reasonably expect to capture. It may prove difficult to disentangle the total safety effects of a TSMO strategy from other background noise in the transportation system.

Autonomous and Connected Technologies

While the planning horizon for most TSMO strategies does not yet extend far enough into the future to consider the effect of widespread adoption of connected and autonomous vehicle technologies, most preconceived notions of operational and safety performance may be challenged by these technologies. Future research and discussion surrounding all dimensions of TSMO performance should include evaluations of the effects of these technologies.

Need for Additional Empirical Safety Analyses and Modeling

While this chapter proposes a guide for modeling potential safety effects of TSMO strategies, this is not a substitute for empirical research on the observed effects. Future research should attempt to discern the practical responses to trade-offs presented by each individual context and transportation system. While responses to TSMO strategies may vary widely, each individual study presents an opportunity to refine modeling techniques for both traffic operations and resulting safety outcomes.

CHAPTER 6 — SAFETY PERFORMANCE ANALYSIS NEEDS

This chapter outlines safety performance analysis needs for TSMO. The development of these needs was informed by the syntheses of strategy-specific safety performance knowledge and capabilities documented in Chapter 2, as well as the syntheses of crosscutting topics contained in Chapters 3, 4, and 5. The safety performance analysis needs are organized into two general sections: 1) strategy-specific evaluation needs and 2) methodological needs. Strategy-specific evaluation needs focus on developing knowledge on the safety performance effects of specific strategies to inform agency decisions regarding implementation of those strategies. Methodological needs are not specific to any one strategy. They represent needed advancements in safety data collection and analysis approaches to more accurately and reliably capture safety performance effects of TSMO strategies and to more broadly advance the practice of safety performance evaluation and prediction.

STRATEGY-SPECIFIC EVALUATION NEEDS

The strategy-specific syntheses in Chapter 2 show that the literature contains various types of safety performance evaluations for some TSMO strategies. However, there are only a limited number of published safety performance evaluations that are robust enough to inform future evaluations or the development of quantitative safety performance predictions. There is a need for safety and operations staff from local, State, and Federal agencies, as well as researchers and other stakeholders, to engage in regular dialogue on safety performance evaluation needs and priorities specific to TSMO strategies. TRB activities, AASHTO meetings, and pooled-fund efforts are logical forums for such communications. The following represent an overview of potential near-term needs for consideration by these groups.

HOV/HOT Lanes

Fuhs & Obenberger found that there were about 1,200 route-miles of HOV facilities and 50 route-miles of HOT facilities as of 2001.(262) By 2015, Fitzpatrick et al. indicated that these numbers increased to 1,800 route-miles of HOV facilities and 500 route-miles of HOT facilities.(264) While the strategy-specific synthesis for managed lanes uncovered some safety performance analyses of HOV/HOT facilities, a stand-alone predictive methodology for freeway facilities with HOV/HOT lanes (and associated ramps) is needed. At the time of this report, work was initiated on Phase 2 of the NCHRP project 17-89A, *HOV/HOT Freeway Crash Prediction Method for the Highway Safety Manual*. It makes sense to monitor the scope and review the results of this effort (once results become available) prior to detailing future research needs regarding safety performance effects of HOV/HOT lanes. One consideration for detailing future needs will be the extent to which NCHRP 17-89A covers the range of applications, including exclusive lanes (with two-way or reversible operations), concurrent flow lanes, and contraflow lanes.

Part-Time Shoulder Use

Published safety research on part-time shoulder use focused primarily on the overall effect that implementation has on safety performance. Results vary significantly and are generally inconclusive, with previous studies illustrating that this is likely because safety performance effects are dependent on the number of lanes present, the level of congestion, and any changes that may have occurred upstream of the part-time shoulder use location. No previous studies looked at the specific safety performance effects of the geometric considerations, including remaining shoulder widths, lateral clearance to roadside objects, shoulder cross-slopes, stopping sight distances on curves, and design characteristics at entrance and exit ramp locations. With over 30 part-time shoulder use installations in operation covering 16 States as of 2016, quantitative safety performance knowledge on part-time shoulder use represents a significant safety analysis need.(50) At the time of this report, the team of NCHRP project 17-89, *Safety of Part-Time Shoulder Use on Freeways*, initiated work on the second phase of the project. It makes sense to monitor the scope and review the results of this effort (once results become available) prior to detailing future research needs. One consideration for detailing future needs will be the extent to which NCHRP 17-89A covers the range of operating characteristics (e.g., bus-only, all vehicles) as well as application contexts in figure 1 (e.g., incident/event management applications, traffic management applications).

Bus Facilities and Preferential Treatments

Safety performance research related to exclusive bus facilities and preferential treatments was limited and inconclusive. Given the existence of safety performance predictive methodologies for urban and suburban streets, a near term opportunity exists to enhance those methodologies by incorporating the effects of bus routes, bus stops, BRT presence and design, queue jump lanes, and TSP. Future research needs to consider safety performance impacts on all users and consider effects of other urban and suburban street features likely to interact with the presence and design of bus facilities and preferential treatments (e.g., presence, extent, and design of pedestrian and bicyclist infrastructure in the vicinity of bus facilities).

Traffic Signal Technology and Timing Practices

The results of safety performance research on traffic signal coordination, transit signal priority, and truck signal priority were mixed, inconclusive, or non-existent. Given the extent of applications in the U.S., a near-term opportunity exists to enhance capabilities to estimate the safety performance effects of traffic signal technology and timing practices, with an initial focus on traffic signal coordination, transit signal priority, and truck signal priority.

The literature did contain a limited number of defensible before-after crash-based evaluations of adaptive signal control technology, which helped set the stage for an ongoing (at the time of this report) FHWA Office of Safety R&D safety evaluation of adaptive signal control technologies under *Evaluation of Safety Improvements, Phase X*. The results of this "Phase X" effort should be reviewed (once they become available) prior to detailing future research needs with respect to adaptive signal control technology.

Ramp Metering

The synthesis of ramp metering safety research uncovered several safety evaluations based on an analysis of crash data. All indicated improvements in safety performance, but all used what is generally thought to be the least reliable type of observational study design: a naïve before-after study comparing observed crash frequencies or rates (Chapter 1 contains additional detail on the limitations of this approach). There is a need for a more robust and defensible safety performance evaluation to build on these previous results. The research should consider the type of meter operation (e.g., static, dynamic) and application (e.g., incident/event management, traffic management); the effects of surrounding key geometrics (e.g., distance from the crossroad to the ramp meter for queue storage and the distance from the ramp meter to the freeway entrance terminal to provide for vehicle acceleration); and the group of crashes (type and location) influenced by ramp metering.

Variable Speed Limits

The literature contained a limited number of defensible before-after crash-based evaluations of variable speed limits as well as several surrogate-based evaluations, all of which indicate safety benefits. A need exists to build on this research, distinguishing the safety performance effects of variable speed limits across the applicable tactical program areas in figure 1. Variable speed limits are used as strategies for road weather management, traffic incident and emergency transportation operations, work zone management, planned special event management, freeway management, and active transportation management. A safety evaluation of variable speed limits is occurring as part of an ongoing (at the time of this report) FHWA Office of Safety R&D effort, *Evaluation of Safety Improvements, Phase X*. The results of this "Phase X" effort should be reviewed (once they become available) prior to detailing remaining gaps and future research needs with respect to variable speed limits.

Dynamic Lane Assignment

The review of strategies did not uncover any safety evaluations of dynamic lane assignment strategies (other than dynamic part-time shoulder use), including dynamic junction control, dynamic lane reversal, or other applications of dynamic lane use control (e.g., as part of incident management). This is possibly due to relatively limited applications throughout the U.S. and variations in methods used for communicating dynamic lane use control to drivers. With transportation agency interest in these strategies continuing to increase, NCHRP 3-123, *Proposed Practices for the Application of Dynamic Lane Use Control*, is underway and is expected to develop recommendations for the application of dynamic lane use based on human factors implications. The results of this NCHRP 3-123 effort should be reviewed prior to detailing future research needs with respect to dynamic lane assignment.

Strategy Combinations

This needs assessment has covered the safety performance evaluations of TSMO strategies and strategy groupings in isolation. It may be common to see the strategies discussed in this report implemented in combination, particularly those with operational synergies (e.g., dynamic part-time shoulder use with dynamic lane assignment, or VSL with ramp metering). In these cases, it may not be possible or useful to try to disaggregate the individual contributions to safety performance made by each strategy that is part of the combination. Future safety performance findings will need to be clearly tied to the strategy combinations and operational conditions for which they apply.

METHODOLOGICAL NEEDS

The syntheses of strategy-specific safety performance knowledge and capabilities documented in Chapter 2, as well as the syntheses of crosscutting topics contained in Chapters 3, 4, and 5 also resulted in insights on methodological (i.e., study design and analysis) issues and related lessons learned with respect to analyzing safety performance effects of TSMO. These issues and lessons learned led to a set of methodological safety performance analysis needs for TSMO. This section describes these methodological needs, which fall into five categories:

1. “Sub-annual” safety data collection and analysis.
2. Safety performance effects beyond the site level.
3. Safety performance effects of traffic operational conditions.
4. Study design and statistical analysis.
5. Mechanistic approaches to safety performance analysis of TSMO.

1. Need to Conduct “Sub-Annual” Safety Data Collection and Analysis

A significant number of TSMO strategies operate (or have the potential to operate) dynamically, based on changing traffic or environmental conditions. Most safety performance evaluations of TSMO strategies in the literature ignored these operational aspects, instead analyzing annual crash frequencies (i.e., crash frequencies across all days, all times) and using an annual average number of vehicles as a measure of exposure (i.e., numbers of vehicles across all days, all times). Two examples include the two reviewed safety evaluations of road weather management strategies that used an annual analysis, even though the strategies were only “on” during specific weather and road conditions.(200,226) Conducting such an annual analysis without regard for when a strategy is operational makes it challenging to distinguish what portion of the reported safety performance change was due to the strategy during the times it was operational.

There is a need to distinguish between the following measures of crash frequency and exposure as part of safety performance evaluations of TSMO:

- Average crash frequency (all days, all times) and actual or average number of vehicles (all days, all times): most relevant to TSMO features and strategies that operate permanently ("on" 24/7).
- Average crash frequency (during specific statically defined days or times, such as daytime, weekday, weekday peak-period) and actual or average number of vehicles (during the same specific statically defined days or times, such as annual weekday volume, annual weekday peak-period volume): most relevant to features and strategies that operate on a set time-of-day schedule.
- Average crash frequency (during dynamically defined days or times) and actual or average number of vehicles (during dynamically defined days or times, such as during certain operational conditions or weather conditions): most relevant to features and strategies that operate dynamically.

In addition to the overall schedule that characterizes when a strategy is "on" or "off," a given strategy may have characteristics that vary dynamically during times when the strategy is "on." One example is ASCT, where the specifics of the traffic signal timing change dynamically in response to traffic conditions when the strategy is "on." Ma et al. performed a before-after study of ASCT in which they analyzed annual crash frequencies (all days, all times) and used annual measures of exposure.(99) The CMF in this case is for "install adaptive traffic signal" (CMF Clearinghouse IDs 6856 – 6861). However, the differences in the signal timing parameters of the adaptive traffic signals across sites (which are changing dynamically as a function of traffic demand) are likely to add "noise" to the CMF estimate. This proved to be the case for Ma et al., who were unable to achieve a statistically significant CMF for fatal and injury crashes and noted that safety performance benefits appeared to vary by facility and by the traffic volume.(99)

Given that the current practice of statistical road safety analysis is largely based on statistical analyses of crash data and related hypothesis testing, "sub-annual" analyses during specific statically or dynamically defined days or times could result in sample size-related challenges. This was demonstrated in Lee et al., who attempted to develop an SPF that predicted crash frequency for a peak hour time period.(51) The objective of the analysis was to analyze the freeway safety performance effects of HOV operations on the inner (left) lane and part-time shoulder use, but the authors struggled to identify any statistically significant variables for the SPF because of the sub-annual analysis period.

Several solutions are possible and will need additional study:

- Utilizing longer periods of data than the typical 3-5 years since only crashes on specific days and during specific times of day are counted. Collecting data over longer periods of time should be done as part of longer-term performance monitoring but may cause practical challenges when needing to know as soon as possible how strategies are affecting safety performance. Including longer time periods can also introduce bias or noise in the results because of changes in vehicle fleet characteristics, enforcement funding and deployment levels, investments in maintenance, crash reporting thresholds, and other factors that influence safety but change over these longer periods of time.
- Using probabilistic models of crash occurrence, such as those used to evaluate arterial signal coordination and incident management.(93,165,166,168,169,170)
- Using traffic operational measures as safety surrogates if links between those operational measures and crash frequency or severity exist (see methodological need 3: Need to Analyze Safety Performance Effects of Traffic Operational Conditions).

Safety performance analyses that incorporate all three of these techniques could strengthen evaluations of TSMO strategies. For example, a surrogate analysis or probabilistic model of crash occurrence at a shorter time interval (e.g., 15-minutes) could reinforce an analysis of longer time periods such as weekday peak-period, which could finally reinforce the more macro-level average crash frequency (all days, all times).

Needs for evaluating road weather management strategies offer additional challenges within this sub-annual data collection and analysis context.

Sub-Annual Data and Analysis Needs for Road Weather Management Strategies

As the synthesis in Chapter 4 showed, road weather management strategies have operational schedules that are dynamic and operational characteristics that are dynamic, sensitive to prevailing weather and road conditions. To determine safety effectiveness of these strategies, one needs to be able to compare safety performance with the strategy operational to what safety performance would have been under those same prevailing conditions without the strategy operational.

SPFs used in safety studies explicitly account for traffic and road geometrics and implicitly account for "other unmeasured things" that change in systematic ways over time or space (e.g., weather and road conditions). This approach can be problematic for evaluating the safety performance effectiveness of road weather management strategies. In implicitly addressing unmeasured factors such as weather and road conditions in SPFs, the assumption is made that the unmeasured factors are present in the same way, change in the same way, and influence safety in the same way, at both treatment locations (i.e., locations that receive the road weather management strategy) and reference locations (i.e., locations that do not receive the road weather management strategy). This assumption may not hold when it comes to weather and road conditions, which can vary significantly across time and space.

There is a need to explore and develop alternatives for explicitly incorporating weather and road conditions into safety performance analysis so that road weather management strategies can be more effectively evaluated from a safety performance perspective by agencies investing in them. This could include, for example, incorporating aggregate measures of weather and road conditions into predictions of annual crash frequency or incorporating more time-specific weather and road conditions into probabilistic models of crash occurrence during much shorter timeframes. The methodologies will be influenced by current and foreseeable weather data collection and management infrastructure.

2. Need to Analyze Safety Performance Effects Beyond the Site Level

This methodological need deals with capturing safety performance effects of TSMO strategies beyond a site level to get a more complete picture of their "total" safety performance effects. Many of the TSMO strategies reviewed in Chapter 2 can be expected to affect performance beyond an individual segment, intersection, or interchange. The needs assessment identified at least four different mechanisms by which this could occur. The first is that application of the strategy itself extends beyond an individual intersection or segment and therefore has an effect on performance at that level. Examples include arterial signal coordination, part-time shoulder use, and managed lanes.

The other three mechanisms that lead to a strategy affecting performance beyond a site level are more complicated and range from the migration of crashes to changes in traveler behavior. The next three sections describe these mechanisms.

Crash Frequencies Increasing Downstream of Bottleneck Removal Projects and Other Crash Migration Effects

In two different safety performance evaluations of part-time shoulder use, results indicated an increase in crash frequency downstream of where a bottleneck was removed.(55,254) In the case of Margiotta et al., a significant bottleneck was removed upstream of the location with part-time shoulder use at about the same time part-time shoulder use began.(254) As a result of the upstream bottleneck removal, crashes increased significantly at the location with part-time shoulder use, making it challenging to determine the safety effects attributable to part-time shoulder use. In the case of Aron et al., part-time shoulder use contributed to removal of a bottleneck.(55) While the authors did observe a reduction in crash frequency at the location with part-time shoulder use, it was accompanied by an increase in crashes downstream of the location. In addition to these cases, Bauer et al. noted the possibility of crash migration leading to an increase in crashes at managed lane conversion sites,(30) and Gayah used simulation techniques to show that ramp metering introduced the potential for crash migration upstream or downstream of the ramp meter under some conditions.(74) Additional work is needed to understand and quantify the crash migration effects of permanent or temporary increases in capacity or changes in traffic flow characteristics.

Crashes Occurring Due to Non-Recurring Congestion Resulting from a Primary Incident

Published safety performance evaluations of traffic incident clearance programs were typically related to effects of these programs on secondary crashes. Secondary crashes are crashes that occur in the timeframe beginning with the primary incident and within the boundaries of the incident scene or the queue that results from the primary incident, including the opposite direction of travel. Analyzing secondary crashes involves defining the boundaries of the primary incident scene and queue. Goodall noted that there are three different approaches to doing this: 1) using a predefined distance from a primary incident, 2) estimating the distance based on an estimated deterministic queue, and 3) observing the queue with empirical measurements.(169) The spatial boundary at which safety performance is affected by non-recurring congestion resulting from an incident as well as the spatial boundary at which safety performance is affected by incident management strategies changes with the characteristics of each incident. The amount of existing work in this area is significant and could inform future efforts to develop a predictive method that captures interrelationships between road geometry, primary crashes, incident management, and secondary crashes.

Corridor, Area, and System Safety Performance Effects of Strategies that Change Traveler Decisions

A significant number of TSMO strategies are expected to affect performance at a corridor, area, or system level. For some strategies, this occurs because the strategy regularly increases capacity or more effectively utilizes capacity on a facility during the peak period and in the peak direction of travel. This additional capacity, and the resulting changes in travel time, may attract drivers from parallel facilities. If this occurs, the safety performance effects of the strategy at the location where it is implemented may be different than it would have been if no additional traffic was attracted by the increase in available capacity. Examples where this is most likely to occur include deployments of dynamic lane reversal, part-time shoulder use, and managed lanes.

For other strategies, corridor-, area-, and system-level effects may occur because the strategies increase the attractiveness of non-automobile modes and/or incorporate the use of traveler information, specifically to influence traveler behavior, including whether to make a trip, trip timing, mode choice, route choice, and destination. Examples include providing traveler information on alternative modes as part of integrated corridor management, deploying dynamically-priced parking, implementing dynamic parking wayfinding, disseminating weather information to travelers, and implementing transit-only lanes. The spatial extent of the influence of traveler information and/or increasing the attractiveness of non-automobile modes on traveler behavior that are part of these strategies varies, ranging from parallel corridors to an entire network. It is unclear whether these changes in traveler behavior can be accurately measured and, furthermore, whether the changes have a significant effect on safety performance. The synthesis of related literature in Chapter 5 showed that the effects on traveler behavior and resulting traffic patterns were very context-specific and may not lend themselves to CMF-type characterizations. Answering these types of questions will likely require the integration of safety performance analysis with dynamic traffic assignment methodologies and tools. The integration of travel demand and safety performance modeling would likely occur at a system level and be able to incorporate dynamic changes in travel demand resulting from integrated sets of TSMO strategies that target recurring and non-recurring congestion during any time of day.

3. Need to Analyze Safety Performance Effects of Traffic Operational Conditions

TSMO strategies affect traffic operational and safety performance. The safety performance effects of TSMO strategies will depend on the traffic operational conditions with a strategy in place and what would have been the traffic operational conditions without the strategy. The review of strategies and related safety literature in Chapter 2 uncovered evidence of this interrelationship between traffic operational conditions and safety performance effects. In an evaluation of ASCT, Ma et al. noted that safety performance effects varied by facility and by traffic volume, concluding that this could be due to the differences in traffic operational changes that resulted from implementation of ASCT on the corridors.(99) Li & Tarko demonstrated that the safety performance of a coordinated traffic signal system will depend on the proportion of vehicle arrivals during different parts of the traffic signal indications.(93) The MnDOT safety performance evaluation of part-time shoulder use showed that safety performance was influenced by the presence (and subsequent removal) of upstream and downstream bottlenecks.(12) Jang et al. demonstrated that the potential for crashes associated with HOV facility design varies by lane, and is therefore a function of lane-specific volumes.(34) Fitzpatrick and Avelar recommended that future research related to safety performance analyses of HOV/HOT lanes consider freeway operational characteristics.(37) It is well known that crash severity increases with speed, but what is not known is how an increase in operating speed interacts with changes in other operational measures (e.g., density, speed variance) and in turn influences safety performance after implementing a TSMO strategy. Chapter 3 explored the relationship between traffic operational and safety performance in detail, including an overview of both annual and real-time measures and the associated data needs, methods, and findings.

There is a need to develop methodologies and tools that incorporate traffic operational conditions into the safety performance analysis of TSMO. Depending on the strategy, examples of addressing this methodological need include:

- Incorporating macroscopic measures of traffic operations throughout the year into an analysis of average annual crash frequency. This might include, for example, effects of annual average hourly flow, density, and V/C ratio during a defined hour on average annual crash frequency during that same hour (e.g., midnight – 1 a.m., 1 a.m. – 2 a.m., 2 a.m. – 3 a.m.).

- Incorporating macroscopic measures of traffic operations during defined time intervals into an analysis of crash frequency or crash probability during those time periods and future time periods. This might include, for example, effects of average volume, average speed, standard deviation of volume, and standard deviation of speed on crash probability during the next 5, 10, 15, 20, 25, and 30 minutes from the time of the macroscopic traffic operations measurement.

Quantifying relationships between traffic operations and safety performance would also inform how to operate TSMO strategies from a safety performance perspective. This could include, for example, the most desirable operational conditions from a safety performance perspective under which to dynamically open (or close) a shoulder as a travel lane. This could also lead to methods to achieve desirable operational conditions from a safety performance perspective using dynamic lane assignment by increasing or decreasing the number of open travel lanes during different times of day.

The synthesis in Chapter 3 covered a growing body of work that has started to address the interaction between operations and safety performance in some way. The findings of these studies have not made their way into commonly-used safety predictive methods, but they do offer a starting point for addressing this safety performance analysis need.

Linking traffic operational measures to safety performance is also related to the use of alternative measures of safety (i.e., safety surrogates). Alternative measures of safety were identified by researchers more than 30 years ago as quantifiable observations that can be used to supplement analyses of crash data.(262) Example alternative measures include different characteristics of speed (e.g., magnitudes and variations), traffic densities, lane changing behavior, gap acceptance behavior, lane departures and/or encroachments, traffic control compliance, stopping behavior (e.g., hard decelerations), and traffic conflicts. Alternative measures can, in theory, be used to estimate safety performance indirectly, in lieu of using crash data. For example, the use of alternative measures to estimate the safety performance effect of one or more safety countermeasures is identified as one possible study approach in FHWA's *A Guide to Developing Quality Crash Modification Factors.*(6) As noted in the introductory chapter of this report, Tarko et al. recommend that two conditions must be met before an alternative measure of safety can be useful in a transportation safety application:(9)

1. The alternative measure should be based on an observable non-crash event that is related to crashes; and
2. There should be a practical method for converting the changes or differences in non-crash events into corresponding changes or differences in crash frequency and crash severity.

In other words, Tarko et al. argue that the key to the application of alternative measures of safety is the availability of reliable models to relate crash frequency (by crash type and severity) or changes in crash frequency (by crash type and severity) to the alternative measures or changes in the alternative measures. In the context of safety performance analyses of TSMO strategies, such models would likely be an outcome of continuing to address the methodological need of quantifying the level and extent to which traffic operational conditions influence safety performance effects.

The strategy-specific syntheses in Chapter 2 uncovered numerous studies that used surrogate safety measures to assess TSMO strategies. These studies mostly focused on managed lanes strategies, ramp metering, and variable speed limits. Table 28 shows that these studies used a variety of surrogate measures and techniques. FHWA’s Surrogate Safety Assessment Model (SSAM) was a commonly used tool in this context. There is a need for increased research efforts in validating the link between surrogate measures (such as traffic conflicts) and the occurrence and severity of crashes. Of the surrogate-based studies reviewed in this report, only a small portion attempted to validate this link. Validating the relationship between surrogate measures and crash-based safety performance will provide further opportunities for applying these techniques in safety performance assessments of TSMO.

Table 28. Summary of surrogate safety studies of TSMO strategies.

Study Authors and Year	TSMO Strategy	Site type	Surrogate Measures	Method for deriving measure	Link to crashes?	Link validated?
Adelakum, A.A. (2008).(45)	Managed Lanes (Truck lane restriction)	Urban freeway	Rate of lane change maneuvers	Simulation	Previous work (Yang & Reagan, 2007; Cate & Urbanik, 2004)	Not attempted
El-Tantawy, S., Djavadian, S., Roorda, M.J., Abdulhai, B. (2009).(46)	Managed Lanes (Truck lane restriction)	Urban freeway	Lane changing, merging, rear-end conflicts	Simulation	Previous work by Liu & Garber (2007) and FHWA (2003)	Not attempted
Tao, H. (2015). (44)	Managed Lanes	Arterial and urban freeway	Time to collision (TTC), post-encroachment time (PET), conflict angle	Simulation	SSAM	Not attempted
Goh, K.C.K., Currie, G., Sarvi, M., & Logan, D. (2013). (48)	Managed Lanes	Arterial with bus lane	TTC, deceleration rate to avoid a crash (DRAC)	Simulation	SSAM	Not attempted
Lee, C., Hellinga, B., & Ozbay, K. (2006). (72)	Ramp Metering	Urban freeway	Coeff. of variation of speed at a point, difference in speed between upstream/downstream locations, covariance of volume difference between upstream/downstream locations on adjacent lanes	Simulation	Calibrated with 1 year of crash, traffic, and road geometry data from Toronto, CAN (study performed in California)	Not attempted
Abdel-Aty, M., Dhindsa, A., & Gayah, V. (2007). (73)	Ramp Metering	Urban freeway	Speed variation, loop detector occupancy, volume variation	Simulation	Calibrated using 3 years of historical crash data	Not attempted
Gayah, V. (2006). (74)	Ramp Metering	Urban freeway	Speed variation, loop detector occupancy, volume variation	Simulation	Classification trees used to identify factors associated with crashes	Not attempted
Abdel-Aty, M., Dilmore, J., & Dhindsa, A. (2005). (85)	Variable Speed Limits	Urban freeway	High speed regime: occupancy, flow	Simulation	Not attempted	Not attempted

Study Authors and Year	TSMO Strategy	Site type	Surrogate Measures	Method for deriving measure	Link to crashes?	Link validated?
			Low speed regime: volume, occupancy, coeff. of variation of speed			
Lee, C., Hellinga, B., & Saccomanno, F. (2006). (86)	Variable Speed Limits	Urban freeway	Coeff. of variation of speed at a point, difference in speed between upstream/downstream locations, covariance of volume difference between upstream/downstream locations on adjacent lanes	Simulation	Calibrated with 1 year of crash, traffic, and road geometry data	Not attempted
Islam, M.T., Hadiuzzaman, M., Fang, J., Qiu, T.Z., El-Basyouny, K. (2013). (88)	Variable Speed Limits	Urban freeway	Speed variation, loop detector occupancy, volume variation	Simulation	Calibrated using crash data	Not attempted
Habtemichael, F.G. & de Picado Santos, L. (2013). (87)	Variable Speed Limits	Urban freeway	TTC, PET, conflict angle	Simulation	SSAM	Simulated conflicts linked to five years of crash data (293 crashes). Log-quadratic curve showed high correlation (adjusted R^2 = 0.923)
Wang, L., Abdel-Aty, M. & Lee, J. (2017).	Variable Speed Limits and Ramp Metering	Urban freeway	TTC	Simulation	SSAM	Not attempted
Stevanovic, A., Stevanovic, J., & Kergaye, C. (2013). (97)	Arterial Signal Coordination	Signalized arterial corridor	TTC, PET, conflict angle	Simulation	SSAM	Validated using database of 83 urban signalized intersections, accuracy similar to traditional crash-prediction

Study Authors and Year	TSMO Strategy	Site type	Surrogate Measures	Method for deriving measure	Link to crashes?	Link validated?
						models based on traffic volumes.
Stevanovic, A., Kergaye, C., & Haigwood, J. (2011). (103)	Adaptive Signal Control Technology	Signalized arterial corridor	TTC, PET, conflict angle	Simulation	SSAM	Attempted, but unsuccessful
Li, L., Persaud, B., & Shalaby, A. (2017). (113)	Transit Signal Priority	Signalized arterial corridor	Unstated (likely TTC, PET, and conflict angle)	Simulation	SSAM	Referenced Gettman et al. (2008) for "strong positive association" in the regression relationship between simulated conflicts and observed crash frequency.

The availability of data sources and tools to support analysis of alternative measures of safety continues to grow. Examples include SSAM, SHRP2 Naturalistic Driving Study (NDS) data, probe data from sources such as HERE or INRIX, data from community-based navigation applications such as Waze, and data from connected and autonomous vehicles. At the time of this report, NCHRP project 17-86, *Estimating Effectiveness of Safety Treatments in the Absence of Crash Data,* was underway to develop a procedural guide for using alternative measures of safety for developing CMFs and functions and other quantifiable measures in the absence of crash data.(49)

4. Needs Related to Study Design and Statistical Analysis

A significant portion of published safety research on TSMO used naïve before-after or with-without study designs and analyzed measures such as observed crash rates and observed crash frequencies. Methodological issues with these study designs and performance measures are well documented, including in the *Highway Safety Manual*, and they are continuing to be phased out as options for defensible safety analysis and evaluation.

Generalized linear modeling and a limited amount of non-linear modeling, combined with Empirical Bayes approaches to estimated expected crash frequency, form the basis of the current predictive methods in the *Highway Safety Manual*. These approaches represent a significant improvement over safety analysis that relies solely on observed crash rates and observed crash frequencies.

Study design and statistical analysis approaches continue to advance. Examples include approaches to selecting treatment and corresponding comparison/reference sites for both before-after and cross-sectional studies, such as the propensity score-potential outcomes approach as well as statistical analysis approaches that may more appropriately represent uncertainty in safety performance effects estimates, such as random parameters and Bayesian approaches. Such advancements should be incorporated into future safety performance analyses of TSMO.

5. Need to Explore Mechanistic Approaches to Safety Analysis of TSMO

This needs assessment did not identify any studies in the literature that used mechanistic approaches to analyze the safety performance of TSMO. The literature does, however, contain examples of such approaches in contexts that show potential for future application to TSMO, such as Wang et al.'s approach to estimating rear-end crash occurrence at signalized intersections.(12) It could be applied to analyzing strategies such as arterial signal coordination and ASCT and could potentially be modified for analyzing other strategies, such as ramp metering and variable speed limits. The fundamental concept of the approach could also extent to other mechanisms and associated crash types, such as lane keeping, lane changing, and sideswipe crashes. There is a need to advance research on the use and validation of mechanistic approaches to quantify the safety performance effects of TSMO.

CHAPTER 7 — SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

TSMO is an "integrated set of strategies aimed at optimizing the performance of existing infrastructure through the implementation of multimodal and intermodal, cross-jurisdictional systems, services, and projects designed to improve operations and the reliability of the transportation system" (MAP-21, § 1103 (a) (30) (A)). TSMO offers agencies a wide range of potential strategies for addressing system- and project-level performance needs with cost-effective, tailored strategies. State and local agencies are increasingly recognizing TSMO as core business area in support of maximizing the performance of their transportation infrastructure and making better use of resources.

The ability for agencies to quantify the effects of TSMO strategies on the number and severity of traffic crashes is limited when compared to similar abilities for operational performance measures. This report presents a safety performance analysis needs assessment for TSMO. The purpose of this needs assessment was to characterize the current state of safety performance analysis practice, knowledge, and skills with respect to specific TSMO strategies and broader TSMO program areas, and then to identify gaps and associated research needs. Readers of this report will gain an increased understanding of existing knowledge, analysis methods, and research needs in the context of quantifying the safety performance effects of TSMO. This information will be valuable to staff at various Federal, State, and local transportation agencies, as well as universities and other organizations that are involved in safety performance research and working to advance performance-based practices in planning, design, operations, and maintenance.

The objective of a safety performance analysis of a TSMO strategy (or combination of strategies) is to determine how implementing the strategy (or combination of strategies) will affect, or has affected, safety performance. The number, severity, and types of crashes characterize the safety performance of a highway segment, intersection, facility, corridor, subarea, or network. While safety and TSMO have always had visible interrelationships, there is incompatibility between many existing safety performance analysis tools and the characteristics of TSMO. For example, few TSMO strategies have robust CMFs and the AASHTO *Highway HSM* analysis methods do not currently incorporate daily, hourly, or sub-hourly variations in traffic characteristics and the road environment that are key factors in fully assessing the safety performance impacts of TSMO.

The needs assessment characterized the current state of TSMO-related safety performance analysis practice, knowledge, and skills through four sets of activities:

1) Syntheses of TSMO strategy-specific safety performance evaluations and analysis capabilities (Chapter 2).

2) A synthesis of research on interrelationships between measures of traffic operational performance and safety performance (Chapter 3).
3) A synthesis of research relating weather and weather-related road conditions to safety performance (Chapter 4).
4) A synthesis of research, tools, and challenges in estimating safety performance effects of TSMO that result from changes in travel choices and traffic demand patterns (Chapter 5).

The syntheses of strategy-specific safety performance evaluations and analysis capabilities addresses 15 strategies or sets of strategies:

1) Managed lanes.
2) Part-time shoulder use.
3) Reversible lanes.
4) Dynamic lane use control.
5) Dynamic junction control.
6) Ramp metering.
7) Variable speed limits.
8) Traffic signal coordination.
9) Adaptive signal control technology.
10) Transit signal priority.
11) Truck signal priority.
12) Queue jump lanes.
13) Safety warning applications.
14) Work zone management and temporary traffic control applications.
15) Traffic incident management.

The strategy-specific syntheses show that the literature contains various types of safety performance evaluations for some TSMO strategies. However, there are only a limited number of published safety performance evaluations that may be robust enough to inform future evaluations or the development of quantitative safety performance predictions. There is a need for safety and operations staff from local, State, and Federal agencies, as well as researchers and other stakeholders, to engage in regular dialogue on safety performance evaluation needs and priorities specific to TSMO strategies. TRB activities, AASHTO meetings, and pooled-fund efforts are logical forums for such communications. The report presents an overview of potential near-term needs for consideration by these groups that cover HOV/HOT lanes, part-time shoulder use, bus facilities and preferential treatments, traffic signal technology and timing practices, ramp metering, variable speed limits, dynamic lane assignment, and strategy combinations.

The syntheses of strategy-specific safety performance knowledge and capabilities documented in Chapter 2, as well as the syntheses of crosscutting topics contained in Chapters 3, 4, and 5, also resulted in insights on methodological (i.e., study design and analysis) issues and related lessons learned. These issues and lessons learned led to a set of methodological safety performance analysis needs for TSMO, which fell into five categories:

1) "Sub-annual" safety data collection and analysis.
2) Safety performance effects beyond the site level.
3) Safety performance effects of traffic operational conditions.
4) Study design and statistical analysis.
5) Mechanistic approaches to safety performance analysis of TSMO.

The following are offered as next steps in continuing to advance safety performance analysis capabilities of TSMO:

Short-Term Steps

1. Continue to monitor ongoing research related to safety performance analyses of TSMO strategies, including AASHTO-sponsored research on HOV/HOT lanes (NCHRP 17-89A), part-time shoulder use (NCHRP 17-89) and safety surrogates (NCHRP 17-86) and FHWA-sponsored research on VSL and ASCT. These efforts may not only result in valuable strategy-specific information for more commonly-implemented TSMO strategies, but they may also provide new "lessons learned" for data integration and analysis approaches that are related to the five areas of methodological needs described in Chapter 6. Monitoring these projects could involve coordination calls between the FHWA Office of Safety, FHWA Office of Operations, and the sponsor technical or panel leads from the FHWA Office of Safety R&D and NCHRP. Annual and midyear meetings of the following stakeholder groups offer additional opportunities for coordination:
    a. AASHTO: Standing Committee on Safety (formerly SCOHTS) and the *HSM* Steering Group.
    b. TRB: ANB10 (Transportation Safety Management), ANB20 (Safety Data, Analysis and Evaluation), ANB25 (Highway Safety Performance), AHB65 (Operational Effects of Geometrics).
2. Using the CMF Clearinghouse results documented in Chapter 2 of this report, the FHWA Office of Safety could consider modifying the Clearinghouse search algorithms so that strategies that fall under the umbrella of TSMO result from user searches for "TSMO." Similarly, strategies that fall under the three broader categories or 12 tactical program areas of figure 1 could result from searches for those terms (e.g., CMFs for VSL would result from searches for "Traffic Management," "Freeway Management," "Active Traffic Management," and other relevant categories and program areas).
3. The FHWA Office of Safety and the ITS JPO should consider coordinating the TSMO-related safety performance information available in the CMF Clearinghouse and ITS Benefits Database.

4. Prepare research needs statements that hold promise for near-term success given experience with strategy-implementation and data availability in the U.S. These research needs statements could be developed immediately, as they do not overlap with ongoing research and offer an additional set of opportunities to not only provide valuable strategy-specific information but provide additional opportunities to implement data integration and analysis approaches that are related to the five areas of methodological needs described in Chapter 6. Considering or testing the methodological needs should be made part of the project scope in the research needs statements. These research needs statements could cover the following strategies:
    a. Safety performance effects of bus facilities and preferential treatments on surface streets (e.g., bus routes, bus stops, BRT presence and design, queue jump lanes, and TSP). Results could be integrated into the urban and suburban predictive methods chapters of the *HSM* as well as into the CMF Clearinghouse.
    b. Safety performance effects of traffic signal technology and timing practices. Results could also be integrated into the urban and suburban predictive methods chapters of the *HSM* as well as the CMF Clearinghouse.
    c. Safety performance effects of ramp metering. Results could be implemented into the freeway and interchange predictive methods chapters of the *HSM* or integrated with the HOV/HOT predictive methods in development given the fact that HOV/HOT facilities and ramp metering can both be present along an urban freeway facility.
5. Prepare a series of brief "how-to" guides on the use of probabilistic models of crash occurrence, which have been applied in the literature to evaluate some TSMO strategies that necessitate shorter analysis periods than traditional crash-based safety performance analysis. Researchers have also applied these methods to link safety performance and traffic metrics in real-time by developing models that predict the probability of a crash occurring for a given set of traffic conditions. The "how-to" guides should describe the analysis process as well as data needs and supporting tools required.

Long-Term Steps

1. The FHWA Office of Safety should consider a TSMO-specific section of the CMF Clearinghouse and advance related approaches by which the results of new analysis methods that will be more common to TSMO (e.g., probabilistic models of crash occurrence, safety surrogates) can be presented and rated for use by the practitioner community. This activity could build on the results of two ongoing and planned NCHRP projects that may provide insights to the reliability of different analysis methods and therefore inform the star-rating: NCHRP 17-86, *Estimating Effectiveness of Safety Treatments in the Absence of Crash Data,* (ongoing) and NCHRP 22-48, *Methods for Short-Term Crash Prediction,* (anticipated).

2. Consider a program of strategically identified sets of research projects and project sequences for TSMO tactical program areas that target broadly defined system-, area-, and corridor-level management and seek to influence traveler behavior, including trip timing, mode choice, route choice, and destination. Such tactical program areas include congestion pricing, parking management, and integrated corridor management. Development of a strategic research program in these and other related areas could begin with a one- or two-day workshop that invites leading experts across transportation demand modeling, operations, safety, data systems, statistical and econometric analysis, and innovative simulations to present key developments in each field and outline a prioritized research program surrounding safety analysis of TSMO. The proceedings of the workshop, along with research needs statements, could be documented in an FHWA or TRB publication. Examples of processes in other areas of research include Transportation Research Circular E-C179, Theory, Explanation, and Prediction in Road Safety and Transportation Research Circular E-C110, Geometric Design Strategic Research.(11,265)

ACKNOWLEDGEMENTS

This research report is a product of FHWA Office of Safety Task Order DTFH6116D00005/0013, *Safety Analysis Needs Assessment for Performance-Based Practical Design and Transportation Systems Management and Operations*. The Task Order was funded through Transportation Pooled Fund Study TPF-5(255), Highway Safety Manual Implementation. This report was prepared by Dr. Richard J. (R.J.) Porter, Mr. Michael Dunn, Mr. Ian Hamilton, Mr. Jeff Gooch, and Dr. Vikash Gayah of VHB. Other members of the project team included Mr. Pete Jenior, Mr. Joe Toole, and Dr. Anusha Musunuru of Kittelson & Associates, Inc. and Dr. Hugh McGee.

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FHWA-SA-19-041