SAFETY PERFORMANCE ANALYSIS OF TSMO: A PRACTICAL APPROACH FOR ASSESSING SAFETY SERVICE PATROL EFFECTS ON SECONDARY CRASHES

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U.S. Department of Transportation
Federal Highway Administration

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TECHNICAL DOCUMENTATION PAGE

1. Report No. FHWA-SA-19-042	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Safety Performance Analysis of TSMO: A Practical Approach for Assessing Safety Service Patrol Effects on Secondary Crashes	5. Report Date November 2019	
	6. Performing Organization Code	
7.Author(s) Porter, R.J., Gooch, J., and Dunn, M.	8. Performing Organization Report No.	
9. Performing Organization Name and Address Vanasse Hangen Brustlin, Inc (VHB) 940 Main Campus Driver, Suite 500 Raleigh, NC 27606	10. Work Unit No.	
	11. Contract or Grant No. DTFH61-05-D-00024 (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 – November 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
The Federal Highway Administration (FHWA) Office of Safety, in cooperation with the Highway Safety Manual (HSM) Implementation Pooled Fund Study, recently completed a safety analysis needs assessment for TSMO. The safety analysis needs assessment characterized the current state of practice, knowledge, and skills for quantifying the safety performance effects of TSMO. It also identified gaps in the existing body of knowledge and corresponding needs, which will provide the foundation for future research activities and advancements in practice. One group of needs focused on exploring sub-annual safety data collection and analysis methods to more effectively address the dynamic conditions under which TSMO strategies operate. This document presents one such sub-annual analysis method: a probabilistic model of crash occurrence to estimate the extent to which strategies that reduce primary incident clearance times affect the potential for secondary crashes. The analysis method is presented in the context of evaluating the secondary crash effects of safety service patrols (SSPs). The result of the analysis is a benefit/cost (B/C) ratio based on the expected change in secondary crash costs and the anticipated costs of SSP operation. The document also contains an example application of the 10-step approach based on a previously published analysis of an SSP program in Indiana. Because the SSP effects on secondary crashes are derived from reductions in traffic incident clearance times, the method can also be extended to other TIM tactics or functions that are aimed at reducing incident clearance times.

17. Key Words: traffic incident management; safety performance; secondary crashes, safety service patrols	18. Distribution Statement No restrictions.		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 39	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

AASHTO	American Association of State Highway and Transportation Officials
B/C	benefit/cost
CMF	crash modification factors
FHWA	Federal Highway Administration
HSM	Highway Safety Manual
MAP-21	Moving Ahead for Progress in the 21st Century
SSP	safety service patrols
TSMO	Transportation Systems Management and Operations

INTRODUCTION

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." 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 will enable a region to track progress towards their objectives. TSMO plans also identify potential policies, services, and projects to make progress towards the performance 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. An agency could monetize these changes 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 other performance measures (e.g., travel times, vehicle emissions). The Federal Highway Administration (FHWA) Office of Safety, in cooperation with the Highway Safety Manual (HSM) Implementation Pooled Fund Study, recently completed a safety analysis needs assessment for TSMO. While safety and TSMO have clear interrelationships, the needs assessment concluded there is incompatibility between many existing safety performance analysis methods and tools and the characteristics of TSMO. For example, few TSMO strategies have robust crash modification factors (CMFs). In addition, the predictive analysis methods in the American Association of State Highway and Transportation Officials (AASHTO) HSM do not consider daily, hourly, or sub-hourly variations in traffic characteristics and the road environment that are a key part of fully assessing the safety performance of TSMO. The safety analysis needs assessment characterized the current state of practice, knowledge, and skills for quantifying the safety performance effects of TSMO. It also identified gaps in the existing body of knowledge and corresponding needs, which will provide the foundation for future research activities and advancements in practice.

 One group of needs focused on exploring sub-annual safety data collection and analysis methods to more effectively address the dynamic conditions under which TSMO strategies operate. This document presents one such sub-annual analysis method: a probabilistic model of crash occurrence to estimate the extent to which strategies that reduce primary incident clearance time affect the potential for secondary crashes. The analysis method is presented in the context of evaluating the secondary crash effects of safety service patrols (SSPs). The result of the analysis is a benefit/cost (B/C) ratio based on the expected change in secondary crash costs and the anticipated costs of SSP operation. The document also contains an example application of the 10-step approach based on a previously published analysis of an SSP program in Indiana.[3] In addition to Indiana's SSP evaluation, other examples that relate secondary crash potential to primary traffic incident clearance time are also available in the published literature.[4,5,6]

Because the SSP effects on secondary crashes are derived from reductions in traffic incident clearance time, the method can also be extended to other TIM tactics or functions that are aimed at reducing incident clearance times. Following an overview of SSPs and the analysis question, the content covers the data definitions and requirements, analysis steps, supporting tools, and effective practices for reporting the results and documenting assumptions and limitations.

SAFETY PERFORMANCE ANALYSIS QUESTION

Safety service patrols (SSPs) have been a key part of traffic incident management since the 1960s.[1] SSPs exist in many forms, all of which seek to reduce the duration of traffic incidents and improve the safety of incident victims, responders, and the traveling public by performing one or more of the following duties:[1]

- Provide the initial report, response, or verification of an event.
- Provide initial traffic control and scene safety for responders and victims.
- Support the incident commander as needed to manage the lane closure.
- Communicate resource needs to their agencies.
- Assist in clearance of debris, disabled vehicles, or crashes in or along the travel portion of the roadway.

Along with decreasing travel time delays caused by incident-related capacity reductions, reducing incident duration is expected to lower the potential for secondary crashes. Secondary crashes are generally identified as those crashes that occur within the scene of a primary incident, or within a queue resulting from a primary incident.[2] As part of performance-based planning and programming, agencies seeking to reduce the number and severity of secondary crashes may want to determine whether the secondary crash reduction benefits of SSPs outweigh the costs of operation and to what degree.

The following sections of this document outline a method for estimating the effects of SSPs on the potential for secondary crashes. The result of the analysis is a benefit/cost (B/C) ratio based on the expected change in secondary crash costs and the anticipated costs of SSP operation.

DATA NEEDS

Incident data, including data on crashes, are the key data required for this analysis. The incidents of interest are those that will be the focus of SSPs, including, for example, traffic crashes, disabled vehicles, and/or spilled cargo. Crash and other incident-level data of interest should include, at a minimum, location, location characteristics (e.g., cross section, alignment, ramp presence and location) severity (for crashes), prevailing operational conditions, and incident clearance time. Incident clearance time is the time between the first recordable awareness of an incident by a responsible agency and the time at which the last responder has left the scene. Incident clearance time is one part of the overall incident duration, which is the time from when the incident first occurs to the time when any queue resulting from that incident dissipates. The timing of the events that bound incident clearance time can be clearly identified, and therefore incident clearance time is more directly measurable than the overall incident duration. Incident duration is typically estimated using a variety of information sources (e.g., crash reports, analysis of traffic data from stationary and mobile sensor data).

Parameters are also needed for distinguishing primary incidents (including primary crashes) from secondary crashes. Goodall et al. identified three primary methods for detecting and classifying secondary crashes: 1) crashes that occur within a defined distance or time period of a primary crash, 2) crashes that occur within the modeled queue of a primary crash as determined using cumulative arrival and departure curve models, and 3) crashes that occur within an observed queue from empirical measurements during the primary incident.[5] As an example, one analysis in the literature identified a crash as secondary if it occurred within three miles upstream of the primary crash and from the time the incident occurred to 15 minutes after the incident was cleared.[4] Another study also included crashes occurring in the opposite direction of travel under the definition of secondary crashes, if the opposite direction crash occurred within the hour following the primary incident, within a half-mile upstream of the primary incident, and in a queue.[6] Some states now include a "primary crash" or "secondary crash" variable on their crash report forms. Secondary crash identification is an area of ongoing work, and ultimately the reliability of the analysis results will be dependent on the accuracy of the available data, including the primary and secondary crash distinctions.

If an incident prediction model is used for predicting primary incidents expected to occur in the future, traffic and geometric data for the patrolled facilities and other similar facilities to serve as potential predictor variables will be necessary in addition to the incident data. Data on the specific routes and operational times intended for the SSPs, the proportions of primary incidents within the coverage areas and times expected to receive SSP assistance, the associated costs of implementing and operating the SSP program, and agency crash costs to monetize the reduction in secondary crash potential are also needed. FHWA's *Crash Costs for Highway Safety Analysis* proposes national crash costs and provides guidance on establishing State-specific crash

costs.[7] If an agency does not have experience with SSPs, peer exchange (either formal or informal) with other agencies with existing SSP programs may help to gather data or identify assumptions with respect to factors such as patrol response rate, expected reduction in primary incident clearance time, and program costs.

Table 1 through table 3 contains the notation and definitions of the variables referenced in the safety analysis.

Table 1. Variables, notation, and definitions for probabilities.

Variable	Description
P_{SC}	The probability of a secondary crash occurring
$P_{SC,SSP}$	The probability of a secondary crash occurring with SSP
$P_{SC,NoSSP}$	The probability of a secondary crash occurring without SSP
$P_{SC,Winter}$	The probability of a secondary crash occurring in Winter, per Latoski et al.[3]
$P_{SC,NotWinter}$	The probability of a secondary crash occurring not in Winter, per Latoski et al.[3]
$P_{SSP,Resp}$	The proportion of the predicted average primary incident frequency within the SSP coverage areas and times that will receive service from SSPs

Table 2. Variables, notation, and definitions for crash prediction.

Variable	Description (Units)
x_i	Covariate i describing the primary incident, can include primary incident clearance time, vehicle type, etc. (units vary)
a, b_i	Regression constant (a) and coefficients corresponding to each covariate (b_i) (unitless)
N_{PI}	The predicted average primary incident frequency for study sites within the study area (primary incidents per year)
N_{PC}	The predicted average primary crash frequency for study sites within the study area (primary crashes per year)
N_{OI}	The predicted average primary other incident frequency for study sites within the study area (other primary incidents per year)
p_{OI}	The ratio of predicted average primary other incident frequency to predicted average primary crash frequency (unitless)
$N_{SC,NoSSP}$	Predicted average secondary crash frequency without SSPs (secondary crashes per year)
$N_{SC,SSP}$	Predicted average secondary crash frequency with SSPs (secondary crashes per year)
$N_{SC,Difference}$	The difference in predicted average secondary crash frequency with and without an SSP program (secondary crashes per year)

Table 3. Variables, notation, and definitions for economic analysis.

Variable	Description (Units)
$\$_{SC,Avg}$	The average, comprehensive costs of a secondary crash (dollars)
$\$_{SC,Difference}$	The predicted comprehensive cost of the difference in average secondary crash frequency with and without an SSP program (dollars)
$\$_i$	The comprehensive cost for a secondary crash of severity i, where i can be any severity level on the KABCO scale (dollars)
N_x	The observed number of secondary crashes of severity x, where x can be any severity level on the KABCO scale (secondary crashes)
B/C	Benefit-cost ratio for the SSP program (unitless)
$\$_{CapitalCost}$	Estimated capital cost of the SSP program (dollars)
$\$_{AnnualCost}$	Estimated annual costs of the SSP program (dollars)
P/A	Uniform-series present worth factor – converts the annual cost of secondary crash reduction and maintenance costs to a present value (unitless)
i	Discount factor for monetary growth (unitless)
t	Estimated service life of the SSP program (years)

Table 4 shows an example database structure for estimating the models described in this document. In this example, one row of the database represents one primary incident. Each entry provides information about the primary incident, including the roadway characteristics at the location of the primary incident and whether a secondary crash occurred. Analysts applying this method may choose to include other variables that are available or of interest to their agencies.

Table 4. Example data structure for estimating the effect of primary incident clearance time on the probability of a secondary crash.

Primary Incident ID	Primary Incident Type	Date	Day of Week	Hour [Military]	Did a secondary crash occur? [Yes or No]	Incident clearance time [minutes]	Horizontal Geometry [tangent or curve]	Lane Width [feet]	Outside Shoulder width	Number of Lanes in Direction of Travel	Did the primary incident occur in congested flow?
459871	Crash	7/12/15	Monday	16	No	29	Tangent	12	8	3	Yes
459872	Disabled Vehicle	7/13/15	Tuesday	7	No	26	Tangent	12	10	2	Yes
459872	Crash	7/13/15	Tuesday	8	Yes	47	Tangent	11	8	3	Yes
459873	Disabled Vehicle	7/16/15	Friday	13	No	18	Curve	12	8	2	No
459874	Spilled Cargo	7/22/15	Thursday	9	No	82	Tangent	12	10	3	Yes
459875	Crash	7/22/15	Thursday	9	No	34	Curve	12	12	2	Yes
459876	Crash	7/23/15	Friday	6	Yes	40	Curve	12	6	2	No
459877	Disabled Vehicle	7/23/15	Friday	17	No	39	Tangent	11	3	3	Yes
459878	Disabled Vehicle	7/28/15	Wednesday	18	No	23	Tangent	12	4	3	Yes

SAFETY PERFORMANCE ANALYSIS STEPS – ESTIMATING POTENTIAL BENEFITS OF PROGRAM IMPLEMENTATION

This section describes a nine-step procedure for estimating the B/C ratio of SSPs. Figure 1 provides a visual representation of the procedure. Both "simple" and "advanced" approaches are provided for most steps, depending on the agency capabilities for conducting this B/C analysis. Secondary crash frequency is predicted on an annual basis. Where possible, agencies are encouraged to use the advanced approach in each step, as it will provide more detailed and localized information.

1. Estimate the probability of a secondary crash as a function of primary incident clearance time

2. Predict the probability of a secondary crash occurring with and without SSP

3. Predict average primary incident frequency

4. Estimate the number of primary incidents which will receive SSP response

5. Predict average secondary crash frequency without SSP

6. Predict average secondary crash frequency with SSP

7. Calculate the difference in secondary crash frequency with and without SSP

8. Monetize the difference in average secondary crash frequency

9. Estimate capital and annual costs for SSPs

10. Calculate the B/C ratio for SSPs

Source: FHWA.

Figure 1. Graphic. Procedure to estimate the safety benefits of SSP program implementation.

1. **Estimate the probability of a secondary crash as a function of primary incident clearance time.**

   Research suggests the probability of a secondary crash occurring is a function of the primary incident clearance time. [4,5,6] The first step involves determining the relationship between primary incident clearance time and the probability of a secondary crash.

   Outcome

   The probability of a secondary crash occurring given that a primary incident has occurred and given the characteristics of the primary incident.

Simple Approach

The literature indicates that the probability of a secondary crash occurring increases by approximately one percentage point for every additional 2-3 minutes of primary incident clearance time. [4,5,6] In the absence of agency-specific data, the simple approach to predicting the probability of a secondary crash based on primary incident clearance time would be to base the probability on this general relationship.

Advanced Approach

A more advanced approach applies binary logistic regression to a local dataset like the example dataset in table 4. The resulting model predicts the probability that a secondary crash will occur during the primary incident as a function of primary incident characteristics, including incident clearance time.

Binary logistic regression can be used to model dependent variables with two possible outcomes (e.g., a secondary crash occurs, a secondary crash does not occur). The resulting model predicts the probabilities of the binary outcomes occurring as a function of variables that affect the probabilities. In this case, the probability being predicted will be the probability of a secondary crash occurring during the primary incident, while the predictive variables will describe the primary incident (e.g., hour of the day, day of week, clearance time, type of incident, vehicle types involved, number of lanes, shoulder width). The key predictor for implementing the method in this document is the primary incident clearance time; the other variables are considered in an effort to more accurately capture the contribution of clearance time on secondary crash occurrence.

The equation in Figure 2 illustrates the form of the binary logistic regression model describing the probability of a secondary crash (P_{SC}).[8]

$$P_{SC} = \frac{e^{(a+b_1x_1+b_2x_2+\cdots+b_nx_n)}}{1+e^{(a+b_1x_1+b_2x_2+\cdots+b_nx_n)}}$$

Figure 2. Equation. Binary logistic regression model illustrating the probability of a secondary crash.

Where:

P_{SC} = the probability of a secondary crash occurring given the characteristics of the primary incident.

x_i = covariates describing the primary incident (e.g., hour of the day, day of the week, clearance time, type of incident, vehicle types involved, number of lanes, shoulder width).

a, b_i = regression coefficients.

As shown by the example dataset in table 4, the observations building the modeling dataset are primary incidents. In other words, one row of the dataset represents one primary incident.. For each primary incident, the data should indicate whether a secondary crash occurred. This variable is the dependent variable (e.g., 1 = a secondary crash occurred, 0 = a secondary crash did not occur). The incident clearance time, type of incident, vehicle types involved, time of day, and other factors are the independent variables.

Binary logistic regression is a relatively robust and informative method for modeling dependent variables with two possible outcomes. Model results are straight forward to interpret and incorporate into a benefit-cost analysis. Researchers have applied binary logistic regression in multiple contexts in the TSMO-related literature, including evaluations of traffic signal coordination and models that relate measures of traffic operational performance to crash probability over short time intervals.[9,10,11,12]

As with any statistical method, analysts should be aware of how to assess the dataset for accuracy and sample size. This includes whether the dataset contains an adequate number of cases for each binary outcome (e.g., an adequate number of cases with a secondary crash and without a secondary crash for different combinations of traffic volume and roadway cross section). Analysts should also be familiar with how to specify models, assess the model goodness of fit, and validate the model by testing its predictive performance on different datasets than that used to develop the model. Binary logistic regression is one of several approaches available to analyze binary outcomes. Other alternatives include probit regression, classification and regression trees, and rare event logistic regression.

2. **Predict the probability of a secondary crash occurring with and without SSP.**

   Using the binary logistic regression model estimated in Step 1, estimate the proportion of primary crashes expected to produce a secondary crash with and without SSPs based on differences in average incident clearance times with and without SSPs (see figure 3 and figure 4).

$$P_{SC,SSP} = f(Clearance\ time\ with\ patrol, volume, etc.)$$

Figure 3. Equation. Proportion of primary crashes with SSPs expected to result in a secondary crash.

$$P_{SC,No\ SSP} = f(Clearance\ time\ without\ patrol, volume, etc.)$$

Figure 4. Equation. Proportion of primary crashes without SSPs expected to result in a secondary crash.

This step requires estimating the average incident clearance times with and without SSPs. Incident clearance times can be estimated using existing traffic monitoring systems, police incident reports, and other types of field observations. If the agency has already implemented an SSP program and is evaluating its effectiveness, it can use observed average primary incident clearance times with and without SSP assistance. If the agency is considering an SSP program, they can use their own data to observe existing primary incident clearance times (without SSP assistance) and use information from other SSP programs to estimate expected clearance times with SSP assistance.

Average values for the other primary incident characteristics can be used for the remainder of the variables in the model.

Outcome

The probabilities of secondary crashes given average primary incident conditions with and without SSPs.

Example – Steps 1 and 2

To demonstrate application of the method outlined in this document, this example adopts the binary logistic regression model reported by Latoski et al. to evaluate the effectiveness of the Hoosier Helper program in Indiana.[3] In applying this model as an example, the key model coefficients will be those that relate the incident clearance times to the probability of a secondary crash. Agencies wishing to test this method are encouraged to estimate binary logistic regression models as outlined in Step 1 using their own data, as these key model coefficients may change across locations and time periods. This model and other similar models in the literature indicate that the probability of a secondary crash occurring increases by approximately one percentage point for every additional 2-3 minutes of primary incident clearance time. [4,5,6]

Table 5 displays the binary logistic regression model reported by Latoski et al. Positive coefficients indicate that the presence of a variable, or an increase in the magnitude of the variable, increases the probability of a secondary crash. For example, the sixth variable in table 5 references whether the incident occurs on a weekday. If so, the probability of a secondary crash is higher than if the primary incident is on a weekend. The first and second variables in table 5 show that the probability of a secondary crash increases as the clearance time increases, regardless of the season. However, the rate of increase in secondary crash probability with clearance time was higher during spring, summer, and fall (coefficient of 0.031) than it was during winter (coefficient of 0.017) in this data. Possible explanations include differences in traffic volumes (i.e., lower volumes on average during winter) and differences in speeds approaching the incident location (i.e., lower speeds on average during winter). Alternatively, negative coefficients indicate a decrease in secondary crash probability in the presence of a variable, or an increase in the magnitude of the variable. The model in table 5 shows that if the primary incident occurred near a ramp or median, the probability of a secondary crash is lower than if the primary incident did not occur near a ramp or median.

The following represents an example application of the model in table 5 from Latoski et al in the context of analyzing SSPs.[3] Average inputs for the example are provided in table 6. To account for average incident conditions, most indicator variables in the probability function are treated as averages. For instance, 80 percent of primary incidents are passenger car incidents, so in place of entering the typical binary inputs of 0 or 1 for the indicator variable of "primary incident vehicle is a passenger car," analysts can use the proportion of incidents involving a passenger car, 0.80.

The binary logistic regression model is used to calculate the probability of a secondary crash with and without SSP. However, because the relationship between primary incident clearance time and secondary crash probability is different in the winter compared to the

remainder of the year in the Latoski et al. model, this process is executed twice, for both winter and non-winter seasons. Figure 5 and figure 6 show the probability models for secondary crashes during winter and other seasons. The calculated probabilities for winter, non-winter, with, and without SSP are provided in table 7.

Table 5. Binary logistic regression model reported by Latoski et al. to determine how primary incident clearance time affects the probability of a secondary crash.

Variable (x_i)	Coefficient (b_i)	t-statistic	p-value
Primary incident clearance time (if the season is winter)	0.017	3.26	< 0.001
Primary incident clearance time (if the season is not winter)	0.031	6.69	< 0.001
Primary incident vehicle is a passenger car	0.964	2.34	0.019
Primary incident vehicle is a single-unit truck	0.415	0.67	0.506
Primary incident vehicle is a combination truck	0.731	1.67	0.096
Primary incident occurs on a weekday	0.353	1.83	0.071
Primary incident occurs on a ramp or in the median	-0.248	1.21	0.232
Constant	-2.440	5.61	< 0.001

Table 6. Average primary incident conditions with and without SSP for the example.

Variable (x_i)	Without SSP	With SSP
Primary incident clearance time (if the season is winter) ($X_{1,Winter}$)	20 Minutes	15 Minutes
Primary incident clearance time (if the season is not winter) ($X_{1,NotWinter}$)	20 Minutes	15 Minutes
Primary incident vehicle is a passenger car (X_2)	80% of incidents	80% of incidents
Primary incident vehicle is a single-unit truck (X_3)	10% of incidents	10% of incidents
Primary incident vehicle is a combination truck (X_4)	10% of incidents	10% of incidents
Primary incident occurs on a weekday (X_5)	90% of incidents	90% of incidents
Primary incident occurs on a ramp or in the median (X_6)	10% of incidents	10% of incidents

$$P_{SC,Winter} = \frac{e^{(-2.440+0.017*x_{1,winter}+0.964*x_2+0.415*x_3+0.731*x_4+0.353*x_5-0.248*x_6)}}{1+e^{(-2.440+0.017*x_{1,winter}+0.964*x_2+0.415*x_3+0.731*x_4+0.353*x_5-0.248*x_6)}}$$

Figure 5. Equation. Probability model for crashes during winter.

$$P_{SC,NotWinter} = \frac{e^{(-2.440+0.031*x_{1,not\ winter}+0.964*x_2+0.415*x_3+0.731*x_4+0.353*x_5)}}{1+e^{(-2.440+0.031*x_{1,not\ winte\ r}+0.964*x_2+0.415*x_3+0.731*x_4+0.353*x_5)}}$$

Figure 6. Equation. Probability model for crashes not during winter.

Table 7. Estimated probability of a secondary crash given average primary incident conditions.

	Without SSP ($P_{SC,NoSSP}$)	SSP ($P_{SC,SSP}$)
Winter	0.285	0.268
Not Winter	0.345	0.311

As expected, the calculated probabilities in table 7 show the probability of a secondary crash is lower when the primary incident clearance time is shorter.

3. **Predict average primary incident frequency within the SSP coverage areas and times.**

   This step provides a prediction of the number of primary incidents (N_{PI}) that have the potential to lead to secondary crashes. The number of primary incidents is the sum of primary crashes (N_{PC}) and the number of other incidents (N_{OI}), such as vehicle breakdowns (as shown in figure 7).

$$N_{PI} = N_{PC} + N_{OI}$$

Figure 7. Equation. Number of primary incidents.

   For analyzing the potential impacts of SSPs, this prediction of primary incident frequency should be limited to anticipated patrol times (e.g., peak hours, AM peak only, PM peak only, 24 hours) and facilities on which the patrols will occur (e.g., all freeways, selected freeways and arterials, tunnels).

   Figure 8 shows that the predicted number of primary crashes (N_{PC}) is typically a function of exposure variables such as the traffic volume, duration of the evaluation period and segment length. Primary crash frequency is also expected to be a function of other characteristics, including horizontal and vertical alignment; lane, shoulder, and median widths; number of lanes; barrier presence and offset; and location and type of access. Detailed guidance for estimating crash prediction models is available through FHWA.[13]

$$N_{PC} = f(volume, duration\ of\ evaluation\ period, segment\ length, geometrics)$$

Figure 8. Equation. Predicted number of primary crashes as a function of traffic volume, duration of the evaluation period, segment length, and site geometrics.

   Models that predict the number of other incidents (N_{OI}) are not typically available. One option is to predict the number of other incidents using a ratio adjustment to the predicted number of primary crashes. Figure 9 provides an example of this calculation. Agencies can review police incident reports along the subject facilities and find the proportional ratio (p_{OI}) between primary crashes and other incidents. Assuming this ratio is fixed, agencies can use their primary crash prediction model to predict average primary crash frequency then apply the ratio of other incidents to determine the predicted average frequency of other incidents.

$$N_{OI} = N_{PC} p_{OI}$$

Figure 9. Equation. Example calculation for a ratio adjustment to the predicted number of primary crashes.

In general, p_{OI} ranges from 0.053 to 0.111, which means that crashes are expected to make up 90 to 95 percent of primary incidents. [14]

Outcome

The predicted average primary incident frequency on the patrolled facilities during the patrolled times.

Simple Approach

Estimate an average primary incident frequency for patrol facilities during anticipated patrol times using historical incident and crash data.

Advanced Approach

Develop a primary incident prediction model for facilities like those to be patrolled. Use the prediction model to predict annual average incident frequency for patrolled roadways during anticipated patrol times.

4. **Estimate the predicted average number of primary incidents within the coverage areas and times that will receive assistance from the SSPs.**

It is unlikely the SSPs will be able to respond to all primary incidents occurring on the targeted facilities and during the targeted times. As a result, this step incorporates the proportion of primary incidents where the patrols will provide assistance ($P_{SSP,Resp}$) and, by default, the remaining proportion of primary incidents where patrols will not provide assistance ($1 - P_{SSP,Resp}$). Agencies implementing these programs should reach out to agencies with similar programs to determine the coverage their programs achieve. As one example, Maryland's Coordinated Highways Action Response Team (CHART) was able to assist with 95% of eligible reported incidents in 2017.[15] The method should predict the number of secondary crashes that occur for both treated and untreated primary incidents when predicting secondary crash frequency with an SSP program. This will occur in Step 6.

Outcome

The predicted average annual number of primary incidents that will receive assistance from SSPs.

5. **Predict average secondary crash frequency without SSP.**

Combine the probability of a secondary crash occurring without SSPs from Step 2 and the predicted average primary incident frequency from Step 3 to predict the average secondary crash frequency without SSP, as shown in figure 10.

$$N_{SC,No\ SSP} = N_{PI} * P_{SC,NoSSP}$$

Figure 10. Equation. Prediction of the average secondary crash frequency without SSP.

Outcome

The predicted average secondary crash frequency without an SSP program.

6. Predict average secondary crash frequency with SSP.

Combine the probability of a secondary crash occurring with and without SSPs from Step 2, the predicted average primary incident frequency from Step 3, and the proportion of primary incidents which will receive a response from SSPs from Step 4. The total predicted average secondary crash frequency with SSPs is the sum of predicted average secondary crash frequency for primary incidents assisted by SSPs and primary incidents not assisted by SSPs, as shown in figure 11.

$$N_{SC,SSP} = N_{PI} * P_{SSP,Resp} * P_{SC,SSP} + N_{PI} * (1 - P_{SSP,Resp}) * P_{SC,NoSSP}$$

Figure 11. Equation. Sum of predicted average secondary crash frequency.

Outcome

The predicted average secondary crash frequency with an SSP program.

Example – Steps 3 through 6

An agency is considering implementing an SSP program along 10 miles of freeway during all hours. Using a calibrated version of the safety performance functions (SPF) for freeways in the Highway Safety Manual (HSM), the agency predicts 400 primary crashes per year (N_{PC}) on this segment of freeway. Additionally, the agency reviewed police incident reports along this section of freeway and determined the ratio (p_{OI}) of other primary incidents to primary crashes is 0.07. Using the equation in figure 9, they predict an additional 28 primary other incidents per year (N_{OI}) on the freeway section, leaving the total predicted average primary incident frequency (N_{PI}) at 428 primary incidents per year as calculated using the equation in figure 7. In total, the agency expects 25 percent of these incidents to occur in winter (107 primary incidents) and the rest during non-winter (321 primary incidents).

Using the probabilities calculated in table 7 and the equation in figure 10, the agency calculated the predicted average secondary crash frequency without SSP. This calculation is provided below in figure 12. If the agency does not implement SSPs, they predicted 141 secondary crashes per year on this 10-mile section of freeway.

$$N_{SC,No\ SSP} = N_{PI,Winter} * P_{SC,NoSSP,Winter} + N_{PI,NotWinter} * P_{SC,NoSSP,NotWinter}$$
$$= 107 * 0.285 + 321 * 0.345 = 141\ secondary\ crashes\ per\ year$$

Figure 12. Equation. Predicted average secondary crash frequency without SSP.

The agency must now calculate the predicted average secondary crash frequency with SSPs. Based on consultations with neighboring agencies, the agency assumes their SSPs will address 95 percent of primary incidents ($P_{SSP,Resp}$) within the SSP coverage area. As such, the agency uses the equation in figure 11 to predict average secondary crash frequency. This calculation is performed below in figure 13, which combines the prediction for winter and non-winter. If the agency implements the SSP program, they predict an average secondary crash frequency of 129 secondary crashes per year.

$$N_{SC,SSP} = N_{PI,Winter} * P_{SSP,Resp} * P_{SC,SSP,Winter} + N_{PI,Winter} * (1 - P_{SSP,Resp})$$
$$* P_{SC,NoSSP,Winter} + N_{PI,NotWinter} * P_{SSP,Resp} * P_{SC,SSP,NotWinter}$$
$$+ N_{PI,NotWin\ ter} * (1 - P_{SSP,Resp}) * P_{SC,NoSSP,NotWinter}$$
$$= 107 * 0.95 * 0.268 + 107 * (1 - 0.95) * 0.285 + 321 * 0.95 * 0.311$$
$$+ 321 * (1 - 0.95) * 0.345 = 129\ secondary\ crashes\ per\ year$$

Figure 13. Equation. Combination of the prediction for winter and non-winter.

7. **Calculate the difference in average secondary crash frequency with and without SSP.**

The difference in average secondary crash frequency with and without SSPs represents the annual safety effects of the SSP program. This annual difference is calculated in figure 14.

$$N_{SC,Difference} = N_{SC,NoSSP} - N_{SC,SSP}$$

Figure 14. Equation. Calculation for annual difference.

Outcome

The predicted difference in average secondary crash frequency with and without an SSP program.

8. **Monetize the difference in predicted average secondary crash frequency.**

Using the equation in figure 15, estimate the monetary benefit due to the reduction in secondary crashes.

$$\$_{SC,Difference} = \$_{SC,Avg} * N_{SC,Difference}$$

Figure 15. Equation. Estimation of monetary benefit.

The average cost of a secondary crash can be estimated by computing a weighted average of observed secondary crash severity. Comprehensive KABCO-level severity crash costs were recently updated to 2016 dollars by FHWA.[7] Additionally, Harmon et al. describe procedures for adjusting these costs to specific states and future years.

The weighted average cost of secondary crashes ($\$_{SC,Avg}$) is based on their observed severity distribution. Figure 16 represents the procedure for calculating this average crash cost. This cost is commonly based on three to five years of secondary crash data.

$$\$_{SC,Avg} = \frac{\$_K * N_K + \$_A C + \$_B N_B + \$_C N_C + \$_O N_O}{N_K + N_A + N_B + N_C + N_O}$$

Figure 16. Equation. Calculation for average crash cost.

$\$_X$ = average cost of a secondary crash for severity X, where X can be K (fatal crash), A (suspected serious injury crash), B (suspected minor injury crash), C (possible injury crash), and O (property damage only crash). The average cost at each severity level is obtained from Harmon et al.[7]

N_X = the number of secondary crashes for severity X during the evaluation period, where X can be K, A, B, C, or O.

Arizona is one state which collects data on secondary crashes. Table 8 shows the distribution of these secondary crashes by severity, as well as the associated costs by severity proposed by Harmon et al.[7] Combining these crash costs and severity distribution, the average comprehensive crash cost of a secondary crash would be $125,209. Agencies wishing to apply this method are encouraged to collected their own data on the severity of secondary crashes.

Table 8. Severity distribution of secondary crashes on Arizona roads from 2014-2016.

Severity	2014-2016 Crashes	Percent of Secondary Crashes	Comprehensive Crash Cost, 2016 Dollars
Fatal (K)	19	0.4%	$11,295,400
Suspected Serious Injury (A)	124	2.9%	$655,000
Suspected Minor Injury (B)	590	13.7%	$198,500
Possible Injury (C)	735	17.1%	$125,600
Property Damage Only (O)	2,837	65.9%	$11,900

Outcome

The monetary value of the expected annual reduction in secondary crashes.

9. **Estimate capital and annual costs for the SSP program.**

The costs can be generated internally and can be adjusted based on findings from similar patrol programs.

Outcome

Costs for the SSP program which will serve as the denominator for the B/C calculation.

10. Calculate the B/C ratio for SSPs.

Using the annual benefit calculated in Step 5 and the costs calculated in Step 6, determine the B/C ratio with the equation in figure 17. Annual costs and benefits can be amortized over the lifetime of the program using the Uniform Series Present Worth Factor (figure 18); discount factor and project lifetime should be assumed based on present economic conditions and anticipated operation of the program. A B/C ratio greater than one shows the program is expected to be economically efficient based on the reduction in secondary crashes. The analysis could also be extended to monetize and include other potential effects (e.g., reduced delay from non-recurring congestion, safety of occupants involved in primary incident, or other potential benefits).

$$ B/C = \frac{\$_{SC,Difference} \ast P/A}{\$_{CapitalCost} + \$_{AnnualCost} \ast P/A} $$

Figure 17. Equation. Calculation for the B/C ratio.

$$ P/A = \frac{(1+i)^t - 1}{i(1+i)^t} $$

Figure 18. Equation. Calculation for the Uniform Series Worth Factor.

Outcome

B/C ratio to assess the potential economic efficiency of an SSP program from a safety perspective.

Example – Steps 7 through 10

The agency predicted an average secondary crash frequency of 141 secondary crashes per year without the SSP program and 129 secondary crashes per year with the SSP program. The difference in predicted average secondary crash frequency, calculated using the equation in figure 14, is 12 secondary crashes per year.

In order to monetize this benefit, the agency uses observed secondary crash data to calculate an average secondary crash cost. This average cost is calculated using the equation in figure 16 and the comprehensive crash costs proposed by Harmon et al.[7]

Table 9. Secondary crashes by severity for the example agency.

Severity	Secondary Crashes	Percent of Secondary Crashes
Fatal (K)	30	0.4%
Suspected Serious Injury (A)	265	2.9%
Suspected Minor Injury (B)	483	13.7%
Possible Injury (C)	801	17.1%
Property Damage Only (O)	4,132	65.9%

The comprehensive average crash cost is calculated in figure 19.

$$\$_{SC,Avg} = \frac{\$_K * N_K + \$_A N_A + \$_B N_B + \$_C N_C + \$_O N_O}{N_K + N_A + N_B + N_C + N_O}$$

$$= \frac{\$11,295,400 * 30 + \$655,000 * 265 + \$198,500 * 483 + \$125,600 * 801 + \$11,900 * 4,132}{30 + 265 + 483 + 801 + 4,132}$$

$$= \$132,742$$

Figure 19. Equation. Comprehensive crash cost calculation.

Given an annual reduction of 12 secondary crashes per year and an average cost of $132,742 per secondary crashes, the annual benefit calculated using the equation in figure 15 is $1,592,903. The agency estimates a capital cost of $500,000 to start the program ($CapitalCost) and an additional $400,000 per year to maintain the program ($AnnualCost), which is intended to operate for ten years. Over those ten years, the agency estimates an average monetary discount rate of 4 percent. Given a 4 percent discount rate and a ten-year project lifetime, the Uniform Series Present Net Worth factor (*P/A*) calculated using the equation in figure 18 is 8.11. The equation in figure 17 is used to combine these components and

calculate a B/C ratio, the example calculation is shown in figure 20.

$$\frac{B}{C} = \frac{\$_{SC,Difference} * P/A}{\$_{CapitalCost} + \$_{AnnualCost} * P/A} = \frac{\$1,592,903 * 8.11}{\$500,000 + \$400,000 * 8.11} = 3.45$$

Figure 20. Equation. Example calculation for B/C ratio.

This analysis by the agency in this example estimates a B/C ratio of 3.45 for the proposed incident management program.

SUPPORTING TOOLS

Statistical software is required for estimating the binary logistic regression models. It is also required for agencies to develop incident prediction models. Statistical software with regression models can be found for free or at a cost. As previously mentioned, analysts developing the models should have experience in how to assess the analysis dataset for accuracy and sample size, specify models, assess the model goodness of fit, and validate the model by testing its predictive performance on different datasets than that used to develop the model. The rest of the analysis steps can be executed using Microsoft Excel or another spreadsheet software.

DOCUMENTING ANALYSIS AND REPORTING RESULTS

Consistent documentation of analyses that inform investment decisions improves the transparency and defensibility of those decisions. It helps future officials, planners, and engineers know why and how certain decisions were made and provides data and contexts for those decisions. Consistent documentation also provides a valuable record in the event of public or legal challenges to a decision. Documentation of the analysis described in this document should generally include:

- A description of the anticipated program;
- A summary of similar programs (if identified);
- Descriptive statistics for each model developed;
- A list of justified assumptions (listed below);
- The estimated incident frequency model;
- The estimated secondary crash probability model;
- Crash costs, project costs, and economic data; and
- A summary of the results.

The following assumptions are necessary for this analysis and should form part of the analysis documentation:

- The proportion of primary crashes which will be serviced by the SSPs;
- The average primary incident clearance times with and without SSPs;
- The crash cost(s) used;
- The estimated initial and annual costs for the patrol program; and
- The discount rate and service life of the patrol program.

In addition, the procedure in this document has the following methodological assumptions:

- The method considers the probability of one secondary crash as a result of a primary incident. Multiple secondary crashes to the same primary incident are not considered.
- The method considers the primary indirect effect of an SSP program on secondary crashes, where SSPs reduce primary incident clearance time, which in turn reduces the probability of a secondary crash. Other direct and indirect effects of SSPs on secondary crash frequency are not considered.
- The method assumes that the crash prediction model applied in Step 3 predicts the frequency of primary crashes. To meet this assumption, analysts would use only primary crashes when estimating or calibrating a primary crash prediction model.
- The example in this document assumed no traffic growth, and thus no increase in the average annual number of crashes as a result of traffic growth. An analyst wishing to account for traffic growth would do so in the prediction of primary crashes in Step 3. The analyst would predict primary crash frequency for each year in the analysis period

separately (accounting for changes in volume), then sum the predictions and divide by the number of years in the analysis period for an average primary crash frequency.

BROADER APPLICATIONS

This document outlines a method for estimating the effects of SSPs on the number of secondary crashes. The result of the analysis is a B/C ratio based on the expected change in secondary crash costs and the anticipated costs of SSP operation. Because the SSP effects on secondary crashes are derived from reductions in primary traffic incident clearance times, the method can also be extended to other TIM tactics or functions that are aimed at reducing primary incident clearance times. Examples include integrating computer-aided dispatch into transportation management centers, establishing towing service agreements, and integrating transportation management centers with law enforcement dispatch centers and emergency operations centers.

When extended to other contexts, analysts should tailor the same general steps of this method to the strategy of interest. For example, the probability of a secondary crash for a given primary incident will depend on the specific strategy's expected impact on primary incident clearance time. When predicting average primary incident frequency in Step 3, the prediction should be limited to the times and facilities to which the strategy of interest will have an impact. The proportion of primary incidents where the strategy will impact incident clearance time (Step 4) and the strategy implementation costs (Step 9) will also be strategy specific.

In addition to applications for safety analyses of TIM, the use of binary logistic regression for short-term crash prediction has other potential applications to safety performance analyses of TSMO. A companion noteworthy practice report shows its application to estimating changes in the occurrence and severity of crashes due to implementing traffic signal coordination. [16] A final report documenting a safety analysis needs assessment for TSMO synthesizes research that used binary logistic regression to relate traffic operational performance to safety performance.[17]

REFERENCES

1. Marquess, A., P. Desai, G. Havinoviski, & C. Heise (2017). *Safety Service Patrol Priorities and Best Practices*. Report No. FHWA-HOP-16-047. Federal Highway Administration, Washington, D.C..
2. NCHRP (n.d.). Secondary Crashes. *Guidance for Implementation of Traffic Incident Management Performance Measurement.*
3. Latoski, S. P., Pal, R., & Sinha, K. C. (1999). Cost-effectiveness evaluation of Hoosier Helper freeway service patrol. *Journal of Transportation Engineering 125(5)*, 429-438.
4. Khattak, A., X. Wang, & H. Zhang (2012). Incident management integration tool: dynamically predicting incident durations, secondary incident occurrence and incident delays. *IET Intelligent Transport Systems, 6(2)*, 204-214.
5. Goodall, N. J. (2017). Probability of Secondary Crash Occurrence on Freeways with the Use of Private-Sector Speed Data. *Transportation Research Record: Journal of the Transportation Research Board, 2635*, 11-18.
6. Yang, H., Ozbay, K., & Xie, K. (2014). Assessing the risk of secondary crashes on highways. *Journal of Safety Research, 49*, 143-149.
7. Harmon, T., G. Bahar, & F. Gross (2018). *Crash Costs for Highway Safety Analysis*. Report No. FHWA-SA-17-071. Federal Highway Administration, Washington, D.C.
8. Kennedy, P. (2003). *A Guide to Econometrics*. MIT press.
9. Li, W. & Tarko, A.P (2011). Effect of Arterial Signal Coordination on Safety. *Transportation Research Record: The Journal of the Transportation Research Board, 2237,* 51-59.
10. Lee, C., Saccomanno, F., & Hellinga, B. (2002). Analysis of Crash Precursors on Instrumented Freeways. *Transportation Research Record: Journal of the Transportation Research Board, 1784*, 1-8.
11. Abdel-Aty, M., Uddin, N., Pande, A., Abdalla, F., & Hsia, L. (2004). Predicting Freeway Crashes From Loop Detector Data by Matched Case-Control Logistic Regression. *Transportation Research Record: Journal of the Transportation Research Board, 1897*, 88-95.
12. Golob, T. F., Recker, W., & Pavlis, Y. (2008). Probabilistic Models of Freeway Safety Performance Using Traffic Flow Data as Predictors. *Safety Science, 46*(9), 1306-1333.
13. Srinivisan, R., & K. Bauer (2013). *Safety Performance Function Development Guide: Developing Jurisdiction-Specific SPFs*. Report No. FHWA-SA-14-005. Federal Highway Administration, Washington, D.C.
14. Ahrens, M., & B. Evarts (2017). "Fire Department Roadway and Vehicle Incidents". National Fire Protection Association, Quincy, MA.
15. Maryland Department of Transportation, State Highway Administration (2018). *Performance Evaluation and Benefit Analysis for CHART in Year 2017*. Maryland Department of Transportation, State Highway Administration, Baltimore, MD.
16. Porter, R.J., Gooch, J., & Dunn, M. (2019). *Safety Performance Analysis of TSMO: A Practical Application for Assessing Traffic Signal Coordination*. Report No. FHWA-SA-19-043. Federal Highway Administration, Washington, D.C.

17. Porter, R.J., Dunn, M., Hamilton, I., Gooch, J., & Gayah, V. (2019). *Safety Analysis Needs Assessment for Transportation Systems Management and Operations.* Report No. FHWA-SA-19-041. Federal Highway Administration, Washington, D.C.