Developing Crash Modification Factors for Variable Speed Limits

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FOREWORD

The research documented in this report was conducted as part of the Federal Highway Administration's (FHWA's) Evaluation of Low-Cost Safety Improvements Pooled Fund Study (ELCSI-PFS). FHWA established this PFS in 2005 to research the effectiveness of the safety improvements identified by the National Cooperative Highway Research Program's Report 500 series as part of the implementation of the American Association of State Highway and Transportation Officials' *Strategic Highway Safety Plan* (AASHTO 2005). The ELCSI-PFS research studies provide crash-modification factors and benefit–cost economic analysis for each targeted safety strategy identified as a priority by the PFS member States.

This research study evaluated safety effectiveness of variable speed limit (VSL) implementation at freeway corridors, evaluating its performance for total, fatal, injury, and property damage only crashes. This study used safety data from Virginia, Wyoming, and Georgia. All three States' safety evaluations involved interrupted time series, logistic regression, and negative binomial generalized estimation models. The Wyoming and Georgia results showed significant reductions in several types of crashes and total crash reductions. Results from Virginia were inconclusive for change in overall safety due to the sample size in the after period, the small proportion of time the system was known to be active, and the way the VSL was used in the corridor for enhancing safety during adverse weather conditions. The economic evaluation for Wyoming and Georgia showed larger benefits than costs for VSL implementation. The results of this study will be of interest to State and local engineers and planners responsible for roadway design, operation, and safety. Additionally, highway safety practitioners will find the results useful in making decisions regarding VSL implementation in their jurisdictions.

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16. Abstract
The objective of this study was to perform rigorous safety effectiveness evaluations of variable speed limit (VSL) implementation on freeway corridors. To accomplish this objective, the research team compiled safety data from Virginia, Wyoming, and Georgia and used an interrupted time series study design (with a comparison group for Georgia). The team analyzed data using logistic and negative binomial generalized estimating equations models. The results from Wyoming and Georgia produced evidence of significant reductions in several types of crashes. The research team found total crash reductions of 34.4 and 29.2 percent associated with VSL installations in Wyoming and Georgia, respectively. The economic evaluation for these two States generally indicated larger benefits than costs. For Georgia, the estimated benefit–cost (B/C) ratio was 40.38. The economic analysis for Wyoming yielded a more modest B/C ratio of 9.05, though still indicating benefits outweighing VSL installation costs. Results from Virginia were inconclusive as the analysis found no statistical evidence of a change in overall safety. The inconclusiveness of these results is possibly due to the sample size of the after period, the small amount of time the system was active, and the manner in which the VSL was used in the corridor for enhancing safety during adverse weather conditions.

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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 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 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 (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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

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LIST OF ACRONYMS

AADT	annual average daily traffic
ATM	active traffic management
B/C	benefit–cost
CBA	cost-benefit analysis
CMF	crash modification factor
DCMF	Development of Crash Modification Factors
DOT	department of transportation
EB	empirical Bayes
ELCSI-PFS	Evaluation of Low-Cost Safety Improvements Pooled Fund Study
FHWA	Federal Highway Administration
GDOT	Georgia Department of Transportation
GEE	generalized estimating equation
ITS	interrupted time series
ITS-CG	interrupted time series with comparison group
KABCO	injury-severity scale where K is fatal injury, A is major injury, B is minor injury, C is possible injury, and O is no injury
PDO	property damage only
VDOT	Virginia Department of Transportation
VSL	variable speed limit
VSLIFE	value of a statistical life
WYDOT	Wyoming Department of Transportation

EXECUTIVE SUMMARY

The Federal Highway Administration (FHWA) established the Development of Crash Modification Factors (DCMF) program in 2012 to address highway safety research needs for evaluating new and innovative safety strategies (improvements) by developing reliable quantitative estimates of their effectiveness in reducing crashes.

The ultimate goal of the FHWA DCMF program is to save lives by identifying new safety strategies that effectively reduce crashes and promoting these strategies for nationwide installation by providing measures of their safety effectiveness and benefit–cost (B/C) ratios through research. State departments of transportation (DOTs) and other transportation agencies need to have objective measures for safety effectiveness and B/C ratios before investing in new strategies for statewide safety improvements.

There are 40 State DOTs that provide technical feedback on safety improvements to the DCMF program and implement new safety improvements to facilitate evaluations. These States are members of the Evaluation of Low-Cost Safety Improvements Pooled Fund Study (ELCSI-PFS) that functions under the DCMF program.

The research summarized in this report addresses and evaluates variable speed limits (VSLs) as a safety improvement strategy (safety intervention). The ELCSI-PFS Technical Advisory Committee selected VSL treatment as one of their priority treatments of interest.

This evaluation assessed the potential to reduce crashes in the format of crash modification factors (CMFs) associated with the safety improvement strategy in terms of total, fatal and injury, and property damage only (PDO) crash frequencies. An additional product resulting from this research was the development of B/C ratios for this safety improvement. Practitioners can jointly use the resulting CMFs and B/C ratios for decisionmaking during project development and safety planning processes.

This research focused on freeway corridors in multiple States. The research team obtained geometric, traffic, and crash data at treated and control locations in Virginia, Wyoming, and Georgia. The research team implemented an interrupted time series (ITS) study design for Virginia and Wyoming. The team further used the ITS design with a control group for Georgia.

The Virginia results did not indicate statistically significant crash reductions were associated with VSL installations in the corridor analyzed (this result reflects that, 5 percent of the time, VSLs are known to reduce the speed limit for adverse visibility conditions). In contrast, the Georgia and Wyoming results indicated safety benefits associated with VSL installation in those corridors for various crash types. In Georgia, the estimated CMFs for urban freeways were 0.708, 0.728, and 0.648, corresponding to reductions of 29.2, 27.2, and 35.2 percent in total, day, and rear-end crashes, respectively. Similarly, the Wyoming corridor safety analysis estimated the safety impacts of VSLs on rural freeways were 0.66, 0.49, 0.71, 0.35, and 0.59, corresponding to reductions of 34.4, 50.8, 28.8, 65.2, and 41.0 percent in total, fatal and injury, PDO, rear-end, and fixed-object crashes, respectively. The economic analysis indicated larger benefits than costs for evaluations with statistically significant results. For Georgia, the analysis estimated a B/C ratio of 40.38. The economic analysis for Wyoming yielded a more modest B/C ratio of 9.05, though still indicating benefits outweighing the costs of VSL installations.

CHAPTER 1. VARIABLE SPEED LIMITS AND SAFETY

INTRODUCTION

Variable speed limit (VSL) deployments vary speed limits based on real-time traffic, roadway, or weather conditions (FHWA 2014). VSLs are also known as dynamic speed limits, variable advisory speeds, and speed harmonization. They are used for three primary functions that improve safety and operations: reducing congestion, reducing speeds during inclement weather, and managing speeds during traffic events, such as work zones or incidents. The speed limits can either be regulatory (enforceable) or advisory, and they can be applied to an entire roadway segment or individual lanes (FHWA 2017). Figure 1 shows an example of VSLs deployed in Seattle, WA.

Figure 1. Photograph. VSLs on I–5 in Seattle, WA.

In the application shown in figure 1, the Washington State Department of Transportation (DOT) installed an active traffic management (ATM) system on I–5, SR 520, and I–90 that included dynamic lane-use control, dynamic message signs, and enforceable VSL signage to alert drivers of delays and direct drivers out of incident-blocked lanes (FHWA 2012).

LITERATURE REVIEW ON VSLs

Pu et al. evaluated crashes on I–5 in Washington for a 72-mo period using observational empirical Bayes (EB) before–after analysis. The results indicated VSL system implementation associates with a crash reduction of 29 percent, with a standard error of 5 percent. Researchers found the reduction in no-injury and possible-injury crashes higher than severe-injury crashes (Pu et al. 2017).

Sohrab and Al-Kaisy investigated the safety effects of an advisory VSL system deployed in Portland, OR. The researchers utilized surrogate safety measures like speed and speed variability in combination with crash data. This research found a reduced mean speed and speed variability within the same lane associated with the VSL system as well as in the lanes located between the median and shoulder lanes. The researchers estimated reductions of 14.81 and 10.51 percent in total and rear-end crashes, respectively. However, intermittent activation of the VSL system for short periods negatively impacted speed variation (Sohrab and Al-Kaisy 2017).

Downey evaluated a set of 10 locations fitted with VSLs on Oregon Route 217. He reported a 25-percent reduction in speed variation and estimated a 12.47-percent increase in the overall crash rate per million vehicle miles traveled. This analysis utilized naïve before and after comparisons. However, Downey also estimated a decrease between 9 and 35 percent in the frequency of crashes in the immediate vicinity of the VSL signs (Downey 2015).

Chambers et al. concluded that VSLs led to a slightly higher number of overall crashes but a lower number of more severe crashes within the first 2 yr. This study relied on an EB before–after evaluation of a 7-mi, lane-specific, speed sign installation in both northbound and southbound directions on OR 217 (23 segments) in the Portland area. The researchers obtained records obtained from the Washington County Consolidated Communications Agency documenting the complete after period. Analysis of those records suggested fatal and injury crashes declined slightly, whereas property damage only (PDO) crashes increased. The Traffic Operations Center data showed an increase in lower severity crashes. Records showed that more rear-end crashes (about 20 percent) occurred but tended to be less severe. Data results from Transportation Data Section, which contains the official statewide crash data, showed a 20-percent increase in number of crashes. Chambers et al. recommended acquiring more after data as overall crashes and severe crashes may reduce as drivers become more familiar with VSLs (Chambers et al. 2017).

Texas implemented a variety of VSL pilot programs for the following operational conditions: urban congestion (westbound loop 1604 in San Antonio, TX), construction work zone (southbound I–35 in Temple, TX), and weather-related conditions (both directions of I–20 in Eastland County). The researchers collected data for 400 activations (i.e., instances when the VSL was actively managing speeds) over a 3-mo period. Most activations lasted less than 1 hr, but some lasted up to 10 hr. Speed limits changed multiple times per activation. The total number of crashes and crash severity reduced for all sites. The pilot sites did not experience fatal or incapacitating crashes during the test period (Randolph 2015).

Mudgal and Hourdos evaluated the impact of VSLs on freeway rear-end crashes on I–94 in Minneapolis, MN. The crashes typically occurred due to traffic breakdowns leading to shockwaves in the traffic stream that took upstream drivers by surprise. Before–after comparison showed that the crash rate did not decrease significantly even though traffic became smoother. Drivers received an advisory speed warning before the incident in only 32 percent of the cases. Drivers stated that only 60 percent of advisory speed warnings received might have been useful for avoiding crashes (Mudgal and Hourdos 2017).

Bham et al. obtained a crash modification factor (CMF) of 0.92 for VSL installation based on before–after analysis using the EB method. The researchers analyzed crash data from 2007–2009 along the I–270 and I–255 corridor in St. Louis, MO. The driving public and law enforcement were not satisfied with the VSL system based on how they perceived benefits to congestion relief, compliance with posted speed limits, and overall visibility of the current sign configuration (FHWA 2010). The authors argue that homogeneous speeds caused the observed reduction in rear-end or passing crashes, resulting in an overall crash rate reduction of 4 to 8.5 percent.

A microsimulation study of VSLs on I–4 in Orlando, FL, by Abdel-Aty et al. showed safety and travel-time benefits. The research team, however, did not observe any substantial safety benefit in congested conditions (Abdel-Aty, Dilmore, and Hsia 20016; Abdel-Aty, Dilmore, and Dhindsa 2006; Abdel-Aty et al. 2008). When speed differences between upstream and downstream vehicles were high, the researchers used several VSL strategies network-wide for different loading scenarios to reduce rear-end and lane-change crash risks. VSLs reduce crash risk and prevent crash occurrence when the freeway is operating in uncongested conditions (Abdel-Aty et al. 2008). The following are final recommendations for enhancing safety benefits of VSLs (Abdel-Aty, Dilmore, and Dhindsa 2006):

- Introduce speed changes in time gradually (5 mph every 10 min).
- Introduce speed changes in space abruptly, with the amount of change limited to 10 or 15 mph both upstream and downstream at the same amount.
- Use upstream reductions in speed and downstream increases in speed.
- Change speed limit by significant values (15 mph).
- Use short up- and downstream distances, as they are sufficient (2 mi each).

The Wyoming DOT (WYDOT) implemented VSL systems on four stretches along the I–80 Elk Mountain corridor in Wyoming to improve safety and reduce closure frequency and duration. A naïve safety evaluation indicated fewer crashes after deployment compared to any of the 10 yr prior. However, the number of fatal crashes remained consistent. The evaluation found crashes reduced by 0.67 crashes per week per 100 mi of VSL corridor. This observation equates to 50.1 crashes per year avoided using the VSL system on the 143 mi of VSL corridors on I–80 (WYDOT 2012). Total crashes reduced from 237 (2004) to 197 (2010), and closures reduced as well.

Nezamuddin et al. conducted simulation studies on a section of the Missouri-Pacific expressway (northbound) in Austin, TX, and considered VSL as an ATM strategy. VSLs associated with a reduced crash likelihood by increasing the time-to-crash and post-encroachment time between vehicles. This technology also decreased crash severity by reducing the vehicle's maximum speed, speed differential between two vehicles involved in a crash, and maximum change in speed pre- and postcrash. The research team found VSLs stimulated an overall safer driving condition by decreasing the number of total crashes, rear-end crashes, and lane-change crashes (Nezamuddin et al. 2011).

Variable advisory speed limits seem to yield benefits comparable to those from VSLs. Edara et al. tested variable advisory speed limit systems in work zones on a dangerous stretch of I–270 in St. Louis, MO, and observed a 39- to 53-percent reduction in average queue length. The risk of rear-end crashes and lane-changing crashes decreased by 30 and 20 percent, respectively (Edara et al. 2016). A microscopic traffic simulation model created by Lee et al. examined VSL automated control strategies. Results indicated the variable advisory speed limit systems could reduce crash potential by 5 to 17 percent (Lee et al. 2006).

BENEFIT–COST STUDIES ON VSLs

VSL implementations generate preferential system benefits of traffic efficiency and safety (FHWA 2017). Reported benefits of VSL systems include the following (USDOT 2016):

- Reduced crashes and crash severity.
- Smoother traffic flow and less delay.
- Safer speeds in work zones.
- Reduced travel times.
- Reduced bottlenecks.
- Ability to tie into road weather information system data.

WYDOT estimated VSL systems generate $4.7 million in safety benefits per year on high volume routes (WYDOT 2012). This 2008 estimation was based on the values for crash costs and crash severity distributions in the *Highway Safety Manual* (AASHTO 2010). Maintenance expense (infrastructure repair and replacement) is a considerable cost of VSL systems. Operations, staffing, evaluation, and end-of-life replacement costs should be considered along with installation cost when deploying VSLs.

CHAPTER SUMMARY

This chapter introduced the project background and outlined the characteristics of VSL installations in freeway corridors. The chapter presented a brief literature review covering past research on the topic and similar safety effectiveness evaluations.

CHAPTER 2. STUDY DESIGN AND STATISTICAL METHODOLOGY

This chapter outlines the study design and analytical methods implemented for the safety effectiveness evaluation in this project. The research team evaluated multiple experimental design factors to address the need to account for features of available data and how to most effectively incorporate this information as part of the VSL assessment. Safety studies are often limited to evaluating observational data, since randomization is not possible and true experiments like randomized control group experiments are not feasible. This study initially targeted quasi-experimental designs to the extent possible, such as the nonequivalent control (or comparison) group design or a control series design (e.g., Campbell and Stanley (1966); Campbell and Ross (1968)) because it is important to select control (or comparison) group sites with similar characteristics as the sites with VSLs to strengthen the before–after study designs.

STUDY DESIGN

Team members identified available sources of before–after data suitable for evaluating VSL safety. The research team initially identified potential data sources to build before–after evaluations. The team then reached out to agencies with known VSL projects in which the periods of installation were known and complete, or nearly complete. The research team also determined whether historical safety data were available for multiple years. The team approached multiple agencies and requested safety data both on VSL installations and potential control locations. Most agencies indicated they could provide data for the VSLs (with various degrees of completeness). The research team requested crash data extending over a long period, if available, to construct a database for interrupted time series analysis for which historic crash variation at study sites establishes a "baseline" crash trend for the sites. When comparison site data are limited, this baseline can play the role of a control group, and the effectiveness of the treatment is established as disrupting changes (either a jump or a drop) to the baseline trend at the time of intervention. Considering the final data characteristics, as described in later chapters, the research team implemented an interrupted time series (ITS) design for Virginia and Wyoming and an ITS with comparison group (ITS-CG) design for Georgia in the safety effectiveness evaluations of VSL systems in those States.

As previously mentioned, the research team added control groups or control series to strengthen the study design whenever possible. The team received safety data elements for both treated segments and untreated segments of the same freeway in Georgia. For this evaluation, the research team selected the untreated segments as the controls in the before–after comparison of the treated segments.

ITS Design

The research team implemented an ITS or ITS-CG design to leverage multiple years of disaggregated safety data. Because freeway crashes are relatively more frequent compared to other facility types (on a per-mile, not per-unit-of-exposure, basis), this approach allows the analysis at a lower level of aggregation (yearly or even monthly) at each study site (Campbell and Stanley 1966; Campbell and Ross 1968; Gillings et al. 1981; Wagner et al. 2002; Friedman et al. 2009; Grundy et al. 2009). The ITS and ITS-CG designs are quasi-experimental methods used to determine the impact of an intervention. Quoting Campbell and Ross (1968, p. 41), "In the Interrupted Time-Series, the 'causal' variable is examined as an event or change occurring at a single time, specified independently of inspection of the data."

In this study, the causal variable (*Intervention*, henceforth referred to as *I*) is VSL deployment. Researchers have applied ITS-CG to before–after data to evaluate the impact of the intervention treatment on the crash frequency (Wagenaar 1986; Wagenaar and Maybee 1986). In ITS-CG, an intervention group is also compared to the comparison group that did not undergo treatment. The comparison group is selected to be as similar as possible to the intervention group to better estimate the true intervention treatment implications.

DATA ANALYSIS METHODS

The research team selected statistical methods to conduct empirical analyses appropriate for the study design and characteristics of the datasets. The analysis method the team selected for this evaluation was segmented regression models with generalized estimating equations (GEEs). For Georgia, the team intended to implement EB methods, but the poor quality of the resulting safety performance functions from the control group prevented this effort.

Segment Regression Analysis for Virginia and Wyoming Corridors

The datasets for Virginia and Wyoming consist of crash, traffic, and roadway data obtained from multiple segments in a common corridor. The research team assessed the safety impacts of VSL implementations on multiple crash types and severities. Crash types varied slightly by State because of different available variables for filtering crash data and different purposes for the VSL implementation. Chapter 3 and chapter 4 describe specific crash types for each evaluation. At a minimum, the research team assessed total, fatal and injury, and rear-end crashes in each evaluation. The team aggregated data monthly to implement the ITS analysis using segmented regression. Because outcomes (monthly crash counts) were mostly zero or one (more than 90 percent for total and other crash types), the research team used the logistic regression estimation approach. This analysis approach also incorporated time as a variable to control for overall trend and intervention (VSL installation). The research team also utilized an indicator variable for estimating VSL effect in the analysis. The team used the dichotomous outcome variable, *Y* (crash occurrence), as the response variable:

- $Y = 0$ if the crash count is 0.
- $Y = 1$ if the crash count is greater than 0.

For *I*, the months corresponding to the after period (postintervention period) are coded as 1, and the years corresponding to the before period (preintervention period) are coded as 0. Then, at segment *i,* the logit ($g(x)$) of the expected value of *Y* given the value *x* ($E(Y|x)$) in a given month can be expressed as the equation shown in figure 2.

$$g(x) = \ln\left[\frac{E(Y|x)}{1 - E(Y|x)}\right] = \beta_0 + \beta_1 \cdot Time_t + \beta_2 \cdot I_t + \left(\beta_3 \cdot X_{i,3t} + \cdots + \beta_k \cdot X_{i,kt}\right)$$

Figure 2. Equation. Logit of conditional expectation of yearly crashes at site *i*.

Where:

$Time_t$ = variable indicating the month in the study period (t = 1, 2, ..., T).

I_t = indicator variable indicating the presence of intervention.

X = value of the additional independent variables in the study period t (up to k additional independent variables).

β_0 = baseline level of $g(x)$.

β_1 = baseline trend corresponding to the change in $g(x)$ occurring in each month before the intervention.

β_2 = possible jump or drop in VSL effect on Y.

β_3 = effect of $Xi_{,3t}$ on Y.

β_k = effect of $Xi_{,kt}$ on Y.

The underlying assumption for the model shown in figure 2 is the relationship between $g(x)$ and *Time* (a numeric variable indicating study period) is linear within each segment of time (i.e., for the preintervention period and independently for the postintervention period).

In addition to *Time* and *I*, the research team included other key variables (detailed in chapters 3 and 4 for each evaluation) as predictors in the logistic regression models. The team applied the GEE method to account for possible correlation in the outcome variable obtained for multiple months from the same segment. From each model, the research team estimated the corresponding odds ratio for the change of crash risk at the time of the intervention. The odds ratio is a direct estimate of the CMF and is expressed as the expected increase or decrease in the crash risk due to the presence of the VSL. An odds ratio greater than 1.0 suggests the presence of the VSL increases risk, while a value less than 1.0 suggests it decreases risk.

Segment Regression Analysis for Georgia Corridors

The research team conducted a safety evaluation of VSLs in Georgia by utilizing a segmented regression analysis including indicator variables for the intervention and control series as well as their interactions. Specifically, they employed a negative binomial regression model with the log of the expected number of monthly crashes in month t at site i (μ_{it}) as shown in figure 3. It should be noted that the variable definitions for figure 3 differ from those given for figure 2 because of differences among the structures of each of the datasets analyzed.

$$\log \mu_{it} = \beta_0 + \beta_1 Time_t + \beta_2 I_t + \beta_3 Trt_i + \beta_4\, Trt_i I_t + \beta_5 X_{5\,it} + \cdots + \beta_k X_{k\,it}$$

Figure 3. Equation. Poisson conditional distribution of monthly crashes at site *i*.

Where:

I_t = intervention variable which takes a value of 1 if t belongs to the after period and 0 otherwise.

Trt_i = group indicator (1 if the ith site is a treatment site and 0 otherwise).

$X_{5\,it}$, …, $X_{k\,it}$ = segment characteristic variables, where k may vary from model to model.

k = number of variables.

β_0 = baseline level of the log mean monthly crash frequency.

β_1 = baseline trend corresponding to the change in logμ_{it} occurring in each month before the intervention.
β_2 = level change following the intervention.
β_3 = difference in intercept between the control group and the treatment group (at t = 0).
β_4 = difference between the change in level in the control group and treatment group associated with the intervention.
β_5 = effect of $X_{5\,it}$ on Y.
β_k = effect of $X_{k\,it}$ on Y.

The underlying assumption for the model shown in figure 3 is the relationship between logμ_{it} and t is linear within each segment of time (i.e., for the preintervention period and independently for the postintervention period) and the underlying trend is the same for the control and treatment group.

CHAPTER SUMMARY

This chapter described the study design, statistical methodology, analysis methods, and tools the research team utilized to perform the analysis in this project. Early in the chapter, the research team presented and discussed how the features of ITS designs they implemented in this research minimized the risk of regression to the mean bias when safety data on comparison sites are limited or unavailable. Then, the chapter presented rationale for a before–after study evaluation using these designs. Finally, this chapter outlined statistical analysis methods for developing statistical models of crashes to use in estimating the CMFs of interest.

CHAPTER 3. DATA COLLECTION AND INTEGRATION

This chapter outlines the data preparation effort prior to a detailed review of the analysis to follow in chapter 4.

VSLs

Initially, the research team reached out to multiple agencies requesting recommendations for potential data sources and locations for evaluation. Based on email responses from nine different DOTs (Alabama, Florida, Georgia, Minneapolis, New Hampshire, Oregon, Virginia, Washington, and Wyoming) and partial VSL implementation data obtained from these sources, the research team identified potential traffic and crash data sources for 26 different corridors from the 9 States.

The initial data collection efforts narrowed down the evaluation sites to five corridors from five different States. The major criteria for corridor selection were availability of before–after crash data and immediate availability of multiple periods of traffic data. The initial set of corridors are shown in table 1.

Table 1. List of States included in VSL data collection project.

State	Site	Installation Date	Miles
Florida	SR 25/US 27	Fall of 2011; deployed in June 2012	4.25
Georgia	I–285	Deployed in October 2014	35
Virginia	I–77	Deployed in October 2016	12
Washington	I–5	Fall 2010 (software enhancement from 2009–2011)	6
Wyoming	I–80 Elk Mountain corridor	Deployed in February 2009	52

The research team eliminated two of the States during a second round of data collection efforts. Washington provided numerous disaggregated files offering great potential for an analysis focusing on short periods. The deciding factors for not pursuing the analysis of those data were VSL implementation in only one direction and potential database field limitations that would allow assigning crashes directionally. The other eliminated State was Florida, as it was the shortest and only corridor on highway segments rather than freeway. As such, it had the complication of dealing with signalized intersections between segments. Therefore, the research team proceeded with preparing the data obtained from the three remaining States: Georgia, Virginia, and Wyoming. The team created separate databases for each corridor since the variables available for filtering were different per State and had different properties regarding the implemented VSL systems and segment characteristics. However, all variables considered for analysis can be broadly classified in four major categories as shown in the left column of table 2.

Table 2. List of variables collected for each VSL corridor.

Variable Category	Variable Name	Variable Description
TCD	ID	Unique segment number
TCD	Name	Unique segment name
TCD	Period	Indicating data collected before (Bf), during (Du), and after (Af) the installation year
TCD	Pre_VSL	Indicates whether VSL sign board is present in the segment (yes or no)
TCD	B_PSL	Speed limit before VSL installation (mph)
TCD	A_VSL	Speed limits after VSL installation (mph)
RDE	Rightshoul	Width of right shoulder (ft)
RDE	Leftshoul	Width of left shoulder (ft)
RDE	Widetotal	Total width of lanes in one direction (ft)
RDE	Location	Indicates whether a ramp is present (ramp) or not in the segment
RDE	Pre_ramp	Indicates whether a ramp is present in the given segment (yes or no)
RDE	Num_ramps	Number of ramps present in a segment
RDE	Length	Segment length (mi)
RDE	Pre_curve	Indicates whether a curve is present in the given segment (yes or no)
RDE	Num_curves	Number of curves present in a segment
RDE	Median	Median type for the segment: raised, flush, depressed, barrier, and no median
RDE	Pre_connector	Whether connecters for only authorized vehicles are present in the segment (yes or no)
RDE	Num_connector	Number of connectors present in a segment
RDE	Lane_width	Width of a lane (ft)
RDE	Rum_E_with	Period for which rumble strips are present
RDE	Rum_L_out	Period for which rumble strips are not present
Volume	AADT_year	Average AADT for the segment (year represents the year when traffic volume was collected)
Crashes	Crash	Total number of crashes
Crashes	K	Fatal crashes
Crashes	A	Major injury
Crashes	B	Minor injury
Crashes	C	Possible injury
Crashes	O	PDO
Crashes	Weather	Weather at the time of crash: rain, fog, dry, wet, and snow
Crashes	Lighting condition	Type of lighting present: daylight, darkness, dawn, and dusk
Crashes	Crash manner	Manner of crash: rear-end or fixed-object

AADT = annual average daily traffic; RDE = roadway design element; TCD = traffic control device.

The four variable categories in table 2 are defined as follows:

- Traffic control device VSL-related variables**.** This category contains variables describing when and where VSLs are installed and their associated speed limits.
- Roadway design elements. This category contains road-related variables for characterizing road segments where VSLs are installed.
- Traffic volume. This category contains annual average daily traffic (AADT) values for each segment throughout the analysis period.
- Crash data. This category contains multiple variables showing the crash counts for each study segment based on injury severity (using the KABCO scale where K is fatal injury, A is major injury, B is minor injury, C is possible injury, and O is no injury or PDO) crash type, and weather conditions.

The following sections provide more details about the data collected from each of the three datasets.

Virginia

VSL and Roadway Design Data

The research team used Google Earth satellite imagery to collect data on roadway design elements from a 12-mi section of I–77 (Google Earth 2018). The team segmented the entire corridor into 22 parts (11 in each direction), with the minimum length of a segment being 0.4 mi and maximum length being 1.75 mi. VSLs on the corridor were located within the segments. VDOT deployed VSL technology in October 2016, with the upper speed limit bound set to 65 mph. The displayed speed limits were 35, 45, 55, and 65 mph depending on the logic programmed into the system. The signs displayed speed limits lower than 65 mph primarily in response to reduced visibility conditions, estimated at 5 percent of the time or less.

The research team made assumptions about the rumble strips variable. As observed from the Google Earth images, the last day without rumble strips in the northbound direction was June 2011 and the earliest day with rumble strips in the southbound direction was October 2011. The team confirmed that this was consistent throughout the corridor. Therefore, the team assumed rumble strips were present between June and October of 2011 (provided that both directions were treated during the same period).

Crash Data

The research team obtained 8 yr of crash data (2010–2017) from the Virginia DOT (VDOT) (VDOT 2019). The team assigned crashes to segments based on the geolocation coded in the crash. They then conducted a quality control check to ensure the crash's reported direction matched the segment's direction. Out of the total 697 crashes, 538 occurred during the before period (January 2010–May 2016), 65 occurred during the intervention period (June 2016–January 2017), and 94 occurred during the after period (February 2017–December 2017). VDOT reported a total of 14 K crashes, 40 A crashes, 92 B crashes, 33 C crashes, and 518 O crashes within the 22 segments considered by the research team.

In addition to the variables in the previous paragraph, the dataset contained binary variables for the presence of VSLs, ramps, curves, and connectors. For these variables, 81 percent of segments had VSLs, 23 percent had ramps, 72 percent had curves, and 76 percent had connectors. The dataset also contained a variable indicating median type (27 percent had barrier medians, 36.5 percent had depressed medians, and 36.5 percent had raised medians).

AADT Traffic Volume Data

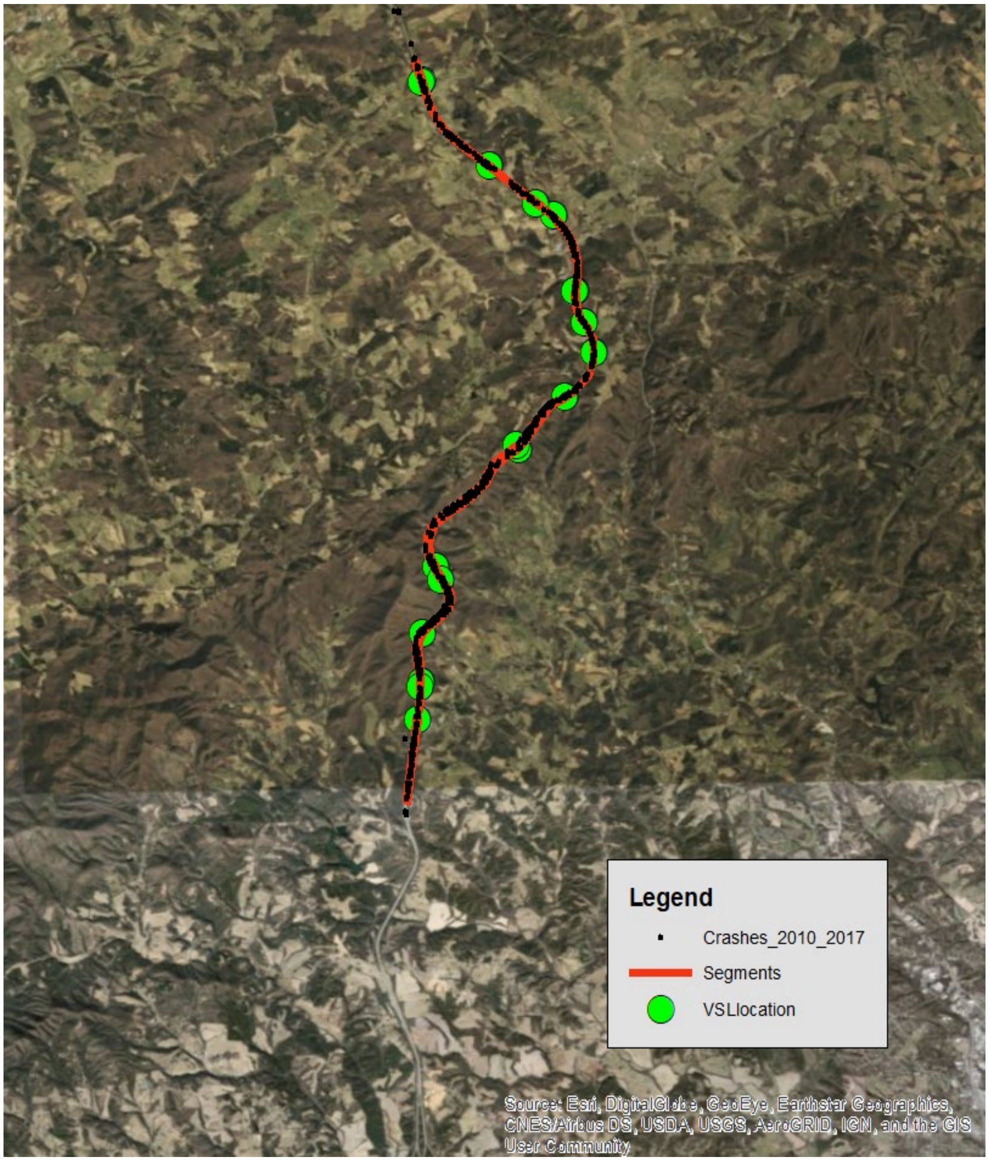
The research team also obtained AADT data for the segments from VDOT for 2010–2016 (VDOT 2019). The data were based on 3-mi points on the corridor. The research team assigned the data to corresponding segments. The team obtained the 2017 AADT data from the VDOT website, which gave countywide roadway specific traffic information in the form of reports. The corridor under consideration passes through Carroll County, and the research team extracted relevant data from the online VDOT report (VDOT 2019).

Table 3 details the descriptive statistics for the resulting database for Virginia.

Table 3. Descriptive statistics of VSL corridor in Virginia (22 segments).

Variable Name	Minimum	Maximum	Mean	Standard Deviation
Number of lanes in one direction	2	3	2	0.4
Lane width (ft)	11.4	13.4	12.1	0.4
Right shoulder width (ft)	9.6	14.3	11.8	1.3
Left shoulder width (ft)	3.8	9.9	5.7	1.7
Length (mi)	0.38	1.7	1.1	0.39
AADT	16,048	20,463	17,914	1,118
Number of ramps	0	2	0.4	0.80
Total crashes (per segment)	10	59	31.7	12.8
K crashes (per segment)	0	2	0.64	0.68
A crashes (per segment)	0	4	1.8	1.6
B crashes (per segment)	1	9	4.2	2.2
C crashes (per segment)	0	4	1.5	1.4
O crashes (per segment)	7	52	23.5	10.8

Figure 4 depicts the I–77 corridor the research team evaluated in Virginia.



Screen capture by Texas A&M Transportation Institute using ArcGIS software. © 2019 Esri and its licensors. All rights reserved. Service Layer Sources: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

Figure 4. Map. I–77 corridor with VSL and crash data.

Wyoming

VSL and Roadway Design Data

The Elk Mountain corridor is located in southeastern Wyoming on I–80 between Laramie, WY, and Rawlins, WY. Prior to VSL implementation, this corridor had an existing posted speed limit of 75 mph. The research team divided the 52-mi I–80 Elk Mountain corridor into 64 segments (32 segments in each direction). This is a rural, four-lane freeway with no major highways joining the stretch. WYDOT deployed VSLs in February 2009 displayed speed limit values of 35, 40, 45, 50, 55, 60, 65, 70, and 75 mph. The VSL system included 20 VSL signs at

10 locations (5 each in the eastbound and westbound directions) and 10 speed sensors. WYDOT expanded the VSL system in the 2009–2010 winter season to include eight additional VSL signs in four new locations (two each in the eastbound and westbound directions).

The details collected using Google Earth satellite imagery included lane width, shoulder width, median type, curve presence, ramp connectors, and rumble strips.

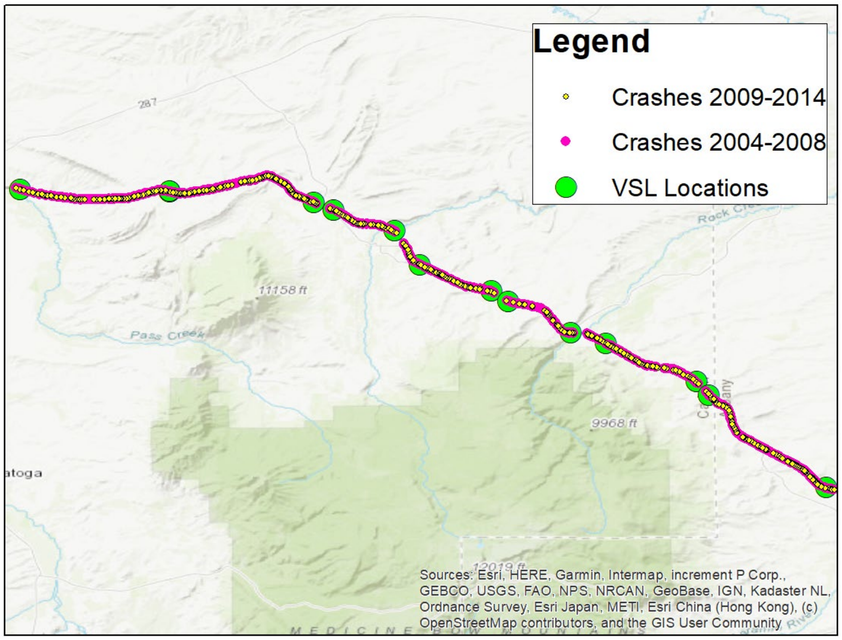
Crash Data

The research team obtained crash data from 2004–2014 directly from WYDOT (WYDOT 2019). The team first spatially assigned crashes to each segment based on their location. They then conducted a quality control check to match the crashes' direction with their assigned segments and eliminate records with no information on the date of occurrence. The team also excluded crashes occurring at three minor interchanges from the analysis.

Out of the 3,699 crash records the research team obtained after excluding anomalous records, 1,433 occurred during the before period (February 2004–October 2008), 313 occurred during the intervention period (November 2008–May 2009), and 1,943 occurred during the after period (June 2009–February 2014).

AADT Data

The research team collected 10 yr of AADT data (2004–2014) from the WYDOT website (WYDOT 2019). The team used AADT values at permanent traffic recorder station 106 on I–80 west of Laramie for this analysis. These AADT values are inconsistent with the values Buddemeyer et al. adopted for the Elk Mountain corridor crash analysis performed in 2010. Since this section of road is a straight corridor without major interchanges, the research team assumed the AADT values remained similar throughout the entire road segment. Figure 5 shows the corridor, crashes, and VSL locations analyzed by the research team.



Screen capture by Texas A&M Transportation Institute using ArcGIS software. © 2019 Esri and its licensors. All rights reserved. Service Layer Sources: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

Figure 5. Map. I–80 Elk Mountain corridor in Wyoming.

Table 4 details the descriptive statistics of the resulting database for Wyoming.

Table 4. Descriptive statistics of VSL corridor in Wyoming (64 segments).

Variable Name	Minimum	Maximum	Mean	Standard Deviation
Number of lanes in one direction	2	3	2	0.20
Lane width (ft)	11.4	12.7	12	0.30
Right shoulder width (ft)	7.1	11.4	9.5	0.80
Left shoulder width (ft)	3.4	6.3	4.6	0.60
Length (mi)	0.60	1.9	1.5	0.40
AADT	10,194	11,090	10,605	284.7
Number of curves	0	2	0.84	0.62
Number of connectors	0	2	0.81	0.59
Total crashes (per segment)	33	1,056	273.4	181.9
K crashes (per segment)	0	3	0.48	0.75
A crashes (per segment)	0	18	4.5	3.8
B crashes (per segment)	0	78	19.4	14.6
C crashes (per segment)	0	84	16.5	16.3
O crashes (per segment)	25	840	221.6	153.9
Total rear-end crashes (per segment)	0	37	7.6	6.7
Total fixed-object crashes (per segment)	1	152	31.2	26.4

In addition to the variables in table 4, the dataset contained binary variables for the presence of VSLs, curves, connectors, and rumble strips. For these variables, 22 percent of segments had VSLs, 72 percent had curves, 75 percent had connectors, and all segments had rumble strips at different points in time. Lastly, the dataset contained a variable indicating median type (98.5 percent had depressed medians and 1.5 percent had raised medians with fences).

Georgia

VSL and Roadway Design Data

The Georgia DOT (GDOT) installed VSLs along the I–285 loop between I–20 on the west side and I–20 on the east side in Atlanta in October 2014. These VSLs are regulatory and always active, with intent to harmonize and level out the flow of traffic, allowing for greater throughput. However, there are no timestamps for when the system activated and deactivated. The system includes 94 sets of VSL signs, for a total of 188 signs. The signs are mounted on the left and right sides of the freeway. The left-side sign is mounted on the concrete barrier wall, and the right-side sign is a ground mount sign. The communications to the right-side and left-side signs are fiber and wireless radio communication, respectively. The right-side signs use direct electric power, and the left-side signs use solar power. All signs connected back to the traffic management center and were controlled by advanced traffic management system software during the evaluation period. The total cost of the contract to install the VSL system was $5.1 million.

The speed limit prior to VSL implementation was 55 mph. After the project, GDOT increased the maximum speed limit to 65 mph. Possible displays on the VSL signs are 65, 55, 45, and 35 mph. The southern side of the I–285 loop (below I–20) did not undergo VSL treatment. However, GDOT raised speed limits for this section from 55 to 65 mph during the VSL treatment period for the northern part of the loop. The research team then treated the segments in the northern section as the treatment group and the segments in the southern section as the control group. The VSL system contained a total of 108 segments (54 in each direction)—34 control segments and 74 treatment segments.

The details the research team collected using Google Earth satellite imagery included lane width, shoulder width, median type, and presence and number of curves and ramps. Rumble strips were present throughout the two section for before, during, and after periods, thus the research team eliminated the rumble strips from the analysis. Figure 6 shows the complete loop, evaluation and comparison sections, and AADT and VSL locations.

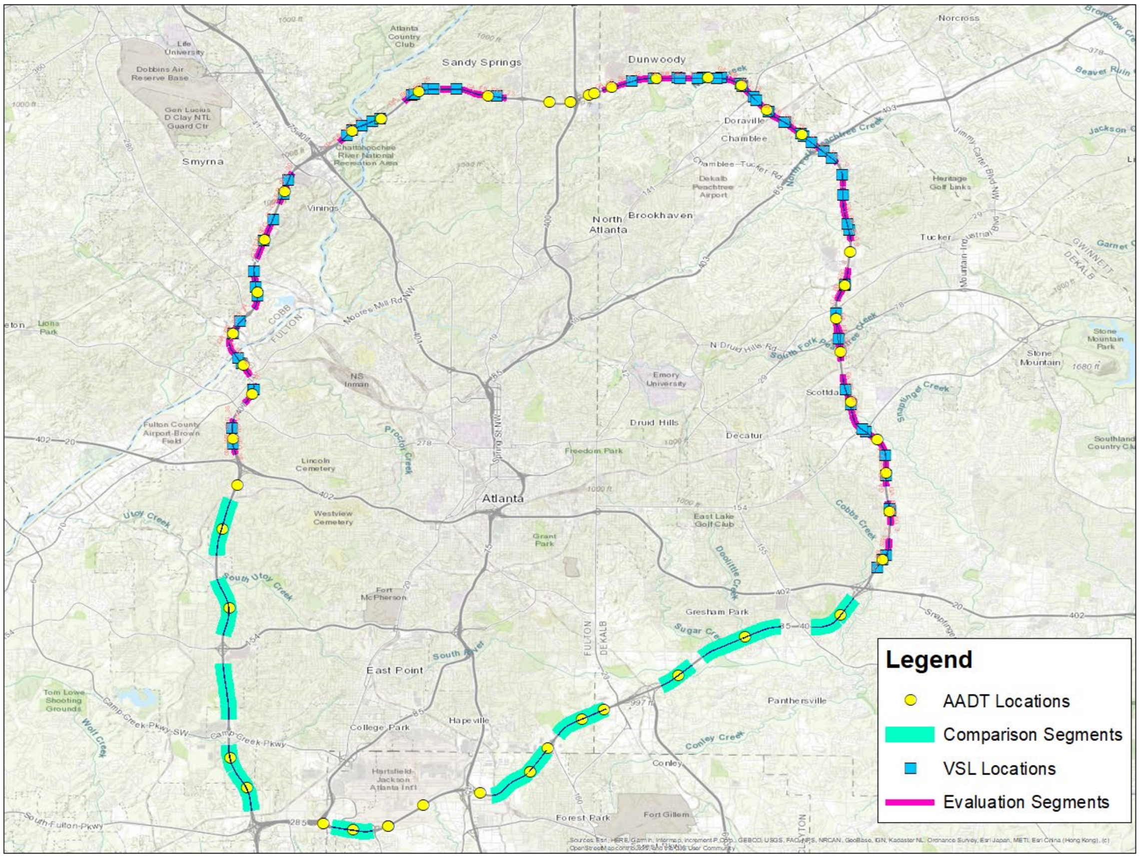


Figure 6. Map. I–285 loop in Atlanta, GA.

Crash Data

In response to the research team's request, GDOT representatives provided crash data for 2012–2014 and 2015–2017, with a total of 16,898 and 30,694 crash records, respectively. The research team applied several filtering criteria to the spreadsheet containing the data to narrow down the data to only show crashes that occurred specifically on the segments (not on the ramps or any other connecting roads). A second round of this process involved a selection-by-location function with a geographic information system buffer distance of 100 ft.

A total of 3,096 crashes occurred during the before period (January 2012–June 2014), 1,143 occurred during the intervention period (July 2014–January 2015), and 4,289 occurred during the after period (February 2015–December 2017) for both treatment and comparison sites. The research team removed four control group segments from the final analysis since the available crash data for those sections were limited. Table 5 provides descriptive statistics for the Georgia dataset.

Table 5. Descriptive statistics for I–285 loop segments without ramps (63 segments: 4,451 crashes).

Variable Name	Minimum	Maximum	Mean	Standard Deviation
Number of lanes in one direction	4	7	4.5	0.75
Lane width (ft)	10.8	12.6	11.8	0.23
Right shoulder width (ft)	7.6	13.9	11.0	1.19
Left shoulder width (ft)	5	8.8	6.4	0.77
Length (mi)	0.24	1.63	0.77	0.37
AADT	120,000	242,000	172,107	33,104
Total crashes (per segment)	1	302	56.78	54.69
Fatal and Injury (KABC) crashes (per segment)	1	71	14.88	14.05

In addition to the variables in table 5, the dataset contained binary variables for VSL and curve presence. For these variables, 61.9 percent of segments had VSLs and 54 percent had curves. The entire loop had concrete-barrier medians, and rumble strips were present in all segments for all periods. The dataset also contained a variable indicating median type (27 percent had barrier medians, 36.5 percent had depressed medians, and 36.5 percent had raised medians). Additionally, the research team aggregated crashes by type (rear-end or not), light conditions (day or night), and weather conditions. 74.0 percent of all crashes occurred during the day, 68.4 percent were rear-end crashes, and 19.9 percent were nondry (snow, wet, etc.) crashes.

Unfortunately, after quality checks, the research team deemed 45 of the originally defined segments (31 treatment and 14 control) not usable because the segments had ramps, and GDOT provided limited fields in the crash data to identify ramp-related crashes. Despite the team's efforts to utilize text-based fields to identify those crashes, the research team remained cautious because they could not confirm they had filtered out all ramp-related crashes from the analysis.

AADT Data

GDOT maintains AADT collection stations every ⅓ mi, or about 210 stations total in this project area, each collecting data in 20-s increments. The research team used GDOT's interactive online tool (GDOT 2020) to collect AADT values along the I–285 loop. Data were available from 52 locations. The team ensured the values they obtained were for the loop but not for ramps or other roads in the proximity. The research team then assigned the obtained values to each segment using their location details. I–285 24-hr volumes range from approximately 140,000 vehicles on the east and west sides of I–285 to 230,000 on the north side—both directions of traffic combined (clockwise and counterclockwise).

CHAPTER SUMMARY

This chapter described data acquisition, dataset selection, supplemental data collection, data reduction, and characteristics of the final databases for analysis. The research team considered an initial pool of nine States for evaluation but narrowed the pool down to three States for analysis: Georgia, Virginia, and Wyoming. The chapter described specific data collection and key variables for each of these States.

CHAPTER 4. SAFETY EFFECTIVENESS EVALUATION

This chapter documents the statistical evaluations and analyses performed to develop CMFs based on databases for Virginia, Wyoming, and Georgia. The research team assessed VSL safety benefits for the following severities: total, fatal, and injury (obtained as the sum of K, A, B, and C crashes). The research team typified crashes when further disaggregation of the crash data was feasible, mainly when appropriate variables to filter were available and when enough crashes could be obtained after the team applied filters. This effort considered the following categories: rear-end, fixed-object, night, nondry conditions, and low visibility. Due to non-negligible differences in corridor characteristics across three States—mainly the purposes of initial installation and different VSL-activation protocols—the research team performed crash analyses separately for each State.

VIRGINIA CRASH ANALYSIS

The Virginia crash data consisted of monthly crash data the research team obtained from 22 segments (corresponding to 24.4 mi) over 96 mo (January 2010–December 2017). The VSL system on the I-77 corridor (figure 4) activates to manage freeway speeds during hazardous conditions. The VSL's displayed speed is typically constant at 65 mph, and from communications with VDOT personnel, the research team estimated the system can be expected to display lower speed limits about 5 percent of the time (i.e., during weather-adverse conditions).

The research team assessed VSL safety benefits for the following eight crash types: total, night, fatal and injury, PDO, rear-end, fixed-object, nondry, and low-visibility (the last two categories motivated by the purpose of the system as previously described). The team designated the period from June 2016 to February 2017 (4 mo prior to and after the VSL implementation that occurred in October 2016) as the intervention period. The team also excluded 4 mo before and after implementation to prevent the estimation from being biased by the period of construction before, and the novelty effect after, VSL installation.

The research team designated the period from January 2010 to May 2016 as the preintervention period and the period from March 2017 to December 2017 as the postintervention period. Because the comparison sites (or reference sites) were not available, the research team conducted VSL safety evaluations in Virginia using ITS analysis with segmented regression. Because outcomes (monthly crash counts) were mostly 0 or 1 (for more than 95 percent for total and PDO crashes and for more than 99 percent for other crash types), the team utilized a logistic regression model as described in chapter 2. Figure 2 presents the general functional form of the model. In addition to time and intervention, the research team included number of lanes, pre_ramp, road_conne, median type, rumble strip, pre_curve, num_ramp, lane width, LogAADT, and LogLength as predictors in the logistic regression model for Virginia crash data.

The research team employed the GEE method as an estimation approach to account for possible correlation in the outcome variable obtained for multiple months from the same segment. Table 6 contains the estimated coefficients for logistic regression models considered and the corresponding odds ratio estimates. The odds ratio is a direct estimate of the CMF value. The odds ratio is expressed as the expected increase or decrease in crash risk due to VSL presence. An odds ratio greater than 1.0 suggests that VSL presence increases risk, while a value less than 1.0 suggests it decreases risk. As shown in table 6, the research team found statistically insignificant increases in crash risk for fatal-injury, PDO, rear-end, fixed-object, nondry, and low-visibility crashes, as well as a statistically insignificant reduction for night crashes.

Table 6. Generalized linear segmented regression analysis results for Virginia and CMF for VSL treatment (24.4 mi).

Parameter	Level	Total Crashes	Night Crashes	F+I Crashes	PDO Crashes	Rear-End Crashes	Fixed-Object Crashes	Nondry Crashes	Low-Visibility Crashes
Intercept (β_0)	N.A.	−9.2681	−10.431	−6.4886	−16.022	−21.954	2.688	−27.075	−25.568
Time (β_1)	N.A.	0.0029	0.0113	−0.002	0.0024	−0.0056	−0.0031	−0.005	−0.0035
I (β_2)	N.A.	0.2038	−0.1411	0.1862	0.1971	0.5745	0.3545	0.0979	0.0351
Number of lanes (β_3)	N.A.	*0.2304**	0.225	−0.012	**0.3236****	−0.0867	0.0168	0.0407	0.0566
Pre_ramp (β_4)	No	−2.1911	*−2.0248**	−0.3476	−2.3953	−2.5753	−1.4508	−2.4024	−2.4569
Road_Conne (β_5)	No	*0.4167**	0.2054	*0.7046**	0.3434	0.5991	*0.3487**	**0.7866****	**1.0707****
Median type (β_6)	Barrier	0.0181	0.0361	−0.2029	0.1227	−0.0485	−0.3384	0.0108	−0.0439
Median type (β_7)	Depressed	−0.0812	−0.4608	−0.2957	0.0559	0.0506	−0.1676	0.3183	0.2644
Rumble strip (β_8)	Not present	0.3767	0.6935	0.2016	0.5	0.6487	0.4405	0.6492	0.6992
Rumble strip (β_9)	Present	0.2647	−0.0455	−0.2411	0.562	0.9802	0.5652	1.0495	0.9962
Pre_Curve (β_{10})	N.A.	*0.3467**	0.1624	0.1518	**0.4295****	0.3512	**0.7204****	**0.8149****	**0.8658****
Num_ramp (β_{11})	N.A.	−0.8346	**−0.728****	−0.215	*−0.8615**	*−1.2741**	−0.2644	*−1.0093**	*−1.1137**
Lane width (β_{12})	N.A.	0.0688	0.2767	0.2609	0.0345	0.2284	−0.4403	−0.0666	0.0477
LogAADT (β_{13})	N.A.	0.7809	0.5083	0.0818	1.4417	1.8299	0.0424	2.6039	2.2902
LogLength (β_{14})	N.A.	*0.3683**	*0.454**	0.3887	*0.3775**	**0.5563****	0.3897	*0.4502**	0.2977
CMF (odds ratio)	N.A.	1.23	0.87	1.20	1.22	1.78	1.43	1.10	1.04

F+I = fatal and injury; LogAADT = Log(AADT); LogLength = Log(Segment Length); N.A. = not applicable.
Note: The research team used the GEE approach as an estimation method. Odds ratio estimates are obtained by Exp(β_I), where β_I represents the estimated coefficient of the intervention variable. Bold font with double asterisks indicates statistically significant results at the 95-percent confidence level. Italicized font with a single asterisk indicates statistically significant results at the 90-percent confidence level. Baseline level for median type is “raised.” Baseline level for rumble strip is “unknown.” Baseline level for Pre_ramp and Road_Conne is “yes.”

The VSL system in Virginia is focused on enhancing safety during adverse weather conditions. Although it would be ideal to evaluate safety performance for periods of known fog visibility issues, such an assessment could not be directly performed as this study did not account for weather conditions present at different analysis periods. The safety impacts—if any—under such specific circumstances (i.e., not being able to account for weather conditions) should result in a measurable change in the site's overall safety performance. However, such change in safety performance should be smaller than the change measured from an ideal study that explicitly evaluates the periods and weather conditions while the VSL was actively managing traffic speeds. This study attempted to detect a change in safety performance at that aggregate level for the different crash types and severities analyzed, but unfortunately, the uncertainties of the estimates were larger than their magnitudes. These inconclusive results are not surprising considering system activation (thus, speed limit displays lower than the 65-mph-limit present prior to VSL installation) only occurred 5 percent of the time when weather adverse conditions were present. The short length of the postintervention period (10 mo) may have also contributed to the inconclusive results.

WYOMING CRASH ANALYSIS

The Wyoming crash data consisted of monthly crash data the research team obtained from 63 segments (corresponding to 92.9 mi) for 121 mo (February 2004–February 2014). The research team assessed the safety benefits of VSLs on seven crash types: total, fatal and injury, PDO, rear-end, rear-end fatal and injury, fixed-object, and fixed-object fatal and injury. The team designated the period from November 2008 to May 2009 (3 mo prior to and after VSL implementation, which occurred in February 2009) as the intervention period. The team also excluded 3 mo before and after installation to prevent the estimation from being biased by the period of construction before, and the novelty effect after, VSL installation.

The research team designated the period from February 2004 to October 2008 as the preintervention period and the period from June 2009 to February 2014 as the postintervention period. Because comparison sites (or reference sites) were not available for the Wyoming data, the research team conducted VSL safety evaluation in Wyoming using ITS analysis with segmented regression. Because outcomes (monthly crash counts) were mostly 0 or 1 (for more than 90 percent for total and PDO and for more than 98 percent for other crash types), the team utilized a logistic regression model introducing *Time* (in months) as a variable to control for overall trend and intervention (VSL installation) as a variable to estimate the VSL effect as discussed in chapter 2. Figure 2 shows the functional form of the model. In addition to time and intervention, the research team included Num_lanes, Rshoulder, Lshoulder, Num_curve, Num_connec, lane_width, Pre_VSL, Pre_Curve, Pre_connec, Median, RumbleStr, LogAADT, and LogLength as predictors in the logistic regression model for Wyoming crash data.

The research team employed the GEE method as an estimation approach to account for possible correlation in the outcome variable obtained for multiple months from the same segment. Table 7 contains the estimated coefficients for logistic regression models considered and the corresponding odds ratio estimates. The odds ratio is a direct estimate of the CMF and is expressed as the expected increase or decrease in the crash risk due to VSL presence. An odds ratio greater than 1.0 suggests VSL presence increases risk, whereas a value less than 1.0 suggests VSL presence decreases risk.

Table 7. Generalized linear segmented regression analysis results for Wyoming and CMF for VSL treatment (92.9 directional mi).

Parameter	Level	Total Crashes	F+I Crashes	PDO Crashes	Rear-End Crashes	Rear-End F+I Crashes	Fixed-Object Crashes	Fixed-Object F+I Crashes
Intercept (β_0)	N.A.	−13.554	15.5789	−22.292	−59.697	−4.121	−34.7	−49.979
Time (β_1)	N.A.	**0.0051****	0.0033	**0.0059****	**0.0136****	*0.0154**	**0.0090****	*0.0143**
I (β_2)	N.A.	**−0.422****	**−0.7085****	**−0.3393****	**−1.0563****	−1.0667	**−0.5276****	−0.946
Num_lanes (β_3)	N.A.	0.1167	−0.1317	0.1937	*0.6153**	0.4876	0.1118	0.2376
Rshoulder (β_4)	N.A.	0.0049	−0.0382	0.0077	0.054	0.178	0.1199	0.058
Lshoulder (β_5)	N.A.	0.0864	0.072	0.1036	**0.276****	0.0167	0.0846	0.1013
Num_curve (β_6)	N.A.	*0.2156**	0.2035	0.1924	−0.1466	0.2846	**0.6596****	*1.021**
Num_connec (β_7)	N.A.	*0.276**	0.2924	0.2435	0.1717	−0.3529	0.3095	0.6614
Lane_width (β_8)	N.A.	*0.3649**	0.2351	*0.4044**	**0.7167****	*0.7513**	**0.6553****	0.3082
Pre_VSL (β_9)	No	−0.048	−0.0046	−0.0961	−0.2181	−0.1932	0.0018	0.44
Pre_Curve (β_{10})	No	0.2897	0.3255	0.2489	−0.0214	0.585	**0.8359****	*1.3082**
Pre_connec (β_{11})	No	*0.3223**	0.3446	0.2825	0.2234	−0.5372	0.3744	0.3849
Median (β_{12})	Depressed	−0.8093	−0.7702	−0.9184	−0.7129	−0.512	−1.2335	−0.9025
RumbleStr (β_{13})	No	0.0642	*0.2851**	−0.0605	−0.4379	−0.3072	**0.4237****	0.6534
RumbleStr (β_{14})	Unknown	0.082	0.0431	0.1159	−0.0587	0.6173	0.3193	0.1704
LogAADT (β_{15})	N.A.	0.7299	−2.2562	1.5728	4.7896	−1.4024	2.2658	4.044
LogLength (β_{16})	N.A.	**1.3053****	**1.111****	**1.3238****	**1.6945****	**2.1406****	**1.4552****	**1.4033****
CMF (odds ratio)	N.A.	**0.66****	**0.49****	**0.71****	**0.35****	0.34	**0.59****	0.39
Percent crash reduction	N.A.	**34.4****	**50.8****	**28.8****	**65.2****	65.6	**41.0****	61.2

F+I = fatal and injury; LogAADT = Log(AADT); LogLength = Log(Segment Length); N.A. = not applicable.
Note: The research team used the GEE approach as an estimation method. Odds ratio estimates are obtained by Exp(β_I), where β_I represents the estimated coefficient of the intervention variable. Bold font with double asterisks indicates statistically significant results at the 95-percent confidence level. Italicized font with a single asterisk indicates statistically significant results at the 90-percent confidence level.

Results indicate that statistically significant reductions (at the 95-percent confidence level) (table 7) for total, fatal and injury, PDO, rear-end, and fixed-object crashes were linked to the VSL implementation in this Wyoming corridor.

GEORGIA CRASH ANALYSIS

The Georgia crash data consisted of monthly crash data the research team obtained from 63 segments (corresponding to 48.9 mi) for 72 mo (January 2012–December 2017). Out of 63 segments, 43 segments (corresponding to 30.6 mi) were treatment sites with VSLs installed in October 2014, and the remaining 20 segments (corresponding to 18.3 mi) were comparison sites. The research team assessed the safety benefits of VSLs on the following crash types: total, day, night, fatal and injury (FI), day FI, rear-end, rear-end FI, and nondry. Initially, the research team intended to include nondry FI crashes in the evaluation, but the team did not include the evaluation because of limited crash data. Upon inspection, 96 percent of treatment-site periods, as well as 98 percent of control-site periods, did not have any crashes (i.e., the crash type equaled zero). The research team designated the period from July 2014 to January 2015 (3 mo prior to and after VSL implementation, which occurred in October 2014) as the intervention (VSL installation) period. The team also excluded data from 3 mo before and after installation to prevent the estimation from being biased by the period of construction before, and the novelty effect after, VSL implementation.

The research team designated the period from January 2012 to June 2014 as the preintervention period, and the period from February 2015 to December 2017 as the postintervention period for both treatment sites and comparison sites. Because comparison sites were available for the Georgia data, the research team conducted VSL safety evaluation in Georgia using an ITS-CG method along with segmented regression analysis including indicator variables for the intervention and control series as well as their interactions. Specifically, the team employed a negative binomial regression model with the log of expected number of monthly crashes in month t at site i (μ_{it}) as given in figure 3 and described in more detail in chapter 2.

In addition to *Time*, *I*, *Trt*, and an interaction between *Trt* and *I* ($Trt \times I$), the research team included Rnumlane, Pre_curve, lane width, right shoulder width, left shoulder width, RumbleStr, LogAADT, and LogLength as predictors in the negative binomial regression model for Georgia crash data. The team employed the GEE approach as an estimation method to account for potential correlation in crash counts obtained for multiple months from the same segment.

Table 8 contains the estimated coefficients for negative binomial regression models the research team considered and the corresponding VSL index of effectiveness (CMF) and percent crash-reduction estimates.

Table 8. Generalized linear segmented regression analysis results for Georgia and CMF for VSL treatment (48.9 directional mi).

Parameter	Total Crashes	Day Crashes	Night Crashes	F+I Crashes	Day F+I Crashes	Rear-End Crashes	Rear-End F+I Crashes	Nondry Crashes
Intercept (β_0)	9.0017	15.7852	**−19.617****	4.2784	11.4901	7.7834	4.8522	1.9247
Time (β_1)	0.005	0.0059	−0.0016	−0.0065	−0.0034	0.0056	−0.0048	**−0.0163****
I (β_2)	**0.6064****	**0.5413****	**1.1042****	**0.9179****	*0.7004**	**0.6706****	**0.9784****	**0.7661****
Trt (β_3)	**1.012****	**1.0631****	**0.9057****	0.557	0.5862	**1.0559****	0.7838	**1.0054****
Trt × *I* (β_4)	**−0.346****	*−0.3173**	−0.6038	−0.1165	−0.0932	**−0.4332****	−0.1937	0.0063
Rnumlane (β_5)	0.2529	*0.3899**	−0.2466	0.12	0.2796	0.2583	0.171	0.0233
Pre_curve (β_6) (No)	0.0002	−0.0456	0.177	0.0248	−0.0589	−0.0183	−0.0016	0.1086
Lanewidth (β_7)	−0.2997	−0.289	−0.2545	−0.3754	−0.4737	−0.2705	−0.3643	−0.4384
Rightshoul (β_8)	0.027	0.0394	0.0083	0.0269	0.0521	−0.0134	−0.0005	−0.0636
Leftshoul (β_9)	−0.1455	−0.1458	−0.1321	−0.0444	0.0002	−0.1908	−0.0821	−0.0653
LogAADT (β_{10})	−0.5902	−1.2452	**1.7977****	−0.1993	−0.8261	−0.5034	−0.2776	0.1561
LogLength (β_{11})	**1.0009****	**1.1196****	**0.5303****	**0.9195****	**1.0318****	**0.9443****	**0.9677****	**0.8252****
CMF	**0.708****	*0.728**	0.547	0.89	0.911	**0.648****	0.82	1.01
Percent crash reduction	**29.2****	*27.2**	45.3	11.0	8.9	**35.2****	17.6	−0.6

F+I = fatal and injury; LogAADT = Log(AADT); LogLength = Log(Segment Length).

Note: The research team used the GEE approach as an estimation method. CMF is estimated by Exp($\beta_{Trt\times I}$), where $\beta_{Trt\times I}$ represents the difference between the change in level in the control and treatment group associated with the intervention. Percent crash-reduction estimates are obtained by (1 − CMF) × 100. Bold font with double asterisks indicates statistically significant results at the 95-percent confidence level. Italicized font with a single asterisk indicates statistically significant results at the 90-percent confidence level.

Table 8 shows there were statistically significant crash reductions for total, day, and rear-end crashes (at the 95-percent confidence level for total and rear-end crashes and at the 90-percent confidence level for day crashes). There were statistically insignificant crash reductions for night, fatal and injury, day fatal and injury, and rear-end fatal and injury crashes and a statistically insignificant crash increase for nondry crashes.

CHAPTER SUMMARY

This chapter documented the statistical evaluations of the three databases developed in this study to estimate CMFs for VSL. Separate analyses were implemented for each dataset attending to differences in the data structure. For Virginia and Wyoming, the study design was an interrupted time series and the analysis method was logistic segmented regression with GEEs. For Virginia, the database included safety data obtained from 22 segments (corresponding to 24.4 mi) for 96 mo (January 2010–December 2017). No statistically significant safety shifts from VLS installations were found in this dataset. Table 9 summarizes the results from these evaluations.

Table 9. Summary of CMFs by State.

State	Total Crashes	F+I Crashes	PDO Crashes	Rear-End Crashes	Rear-End F+I Crashes	Fixed-Object Crashes	Day Crashes	Nondry Crashes
Virginia	1.23	0.87	1.20	1.22	1.78	1.43	—	1.10
Wyoming	**0.66****	**0.49****	**0.71****	**0.35****	0.34	**0.59****	—	—
Georgia	**0.71****	0.89	—	**0.65****	0.82	—	*0.73**	1.01

— = Variable was not included in the model; F+I = fatal and injury.
Note: Bold font with double asterisks indicates statistically significant results at the 95-percent confidence level. Italicized font with a single asterisk indicates statistically significant results at the 90-percent confidence level.

Similar to the Virginia evaluation, the Wyoming rural corridor evaluation was based on an ITS design and estimated using logistic generalized linear segmented regression analysis with the GEE method. The research team obtained safety data from 63 segments (corresponding to 92.9 mi) for 121 mo (February 2004–February 2014). This analysis yielded statistically significant and large crash reductions.

In the case of Georgia, a treatment group and a control group of corridors were available for analysis. The research team then implemented an ITS-CG, design, and the estimation was again negative binomial generalized linear segmented regression analysis with the GEE method. Results from this analysis were consistent with the findings from the analysis of the Wyoming dataset: there were statistically significant crash reductions for total and rear-end crashes (at the 95-percent confidence level) and day crashes (at the 90-percent confidence level).

CHAPTER 5. ECONOMIC ANALYSIS

The research team conducted an economic analysis to estimate benefit–cost (B/C) ratios for VSLs on urban arterials. Except for the case of Virginia (for which the results did not indicate clear safety improvements associated with VSL installations), the safety evaluations indicated statistically significant changes in safety associated with VSL installations. In general, these results suggest that VSLs provide clear safety benefits. The research team performed the cost-benefit analysis (CBA) documented in this chapter considering the two potential safety outcomes the analysis revealed (either a safety benefit or no change in safety performance).

To perform a CBA, the research team followed the procedures recommended in the Federal Highway Administration's (FHWA's) *Highway Safety Benefit-Cost Analysis Guide* (FHWA 2018). The team also obtained the value of a statistical life (VSLIFE) from the most recent memorandum posted on the USDOT website (Trottenberg and Rivkin 2016). The recommended range for VSLIFE is $5.2 million to $12.9 million in 2012 U.S. dollars. Knowing the range for 2001 dollars allowed the research team to compute the underlying geometric rate of inflation. Therefore, the team determined the 2019 range to be $5.7 million to $14.9 million and adopted a nominal value of $10.08 million in U.S. dollars for this evaluation.

COSTS AND BENEFITS OF VSL INSTALLATIONS

The research team compiled cost information from various sources to incorporate this information in the CBA. In a report prepared for FHWA in 2015, cost per directional mile ranges from $950,000 up to $7.5 million per directional mile depending on the types of ATM strategies, one of which is VSL (FHWA 2015). Communications with GDOT personnel indicated the total cost of the contract for their VSL system installation was $5.1 million for 35 mi, which translates to about $72,900 per directional mile. This is substantially lower than the FHWA-reported cost (FHWA 2015). The reason for this difference could be incremental deployment of VSL on infrastructure already present for other ATM strategies (i.e., communications, posts for variable message signs). In the economic analysis, the research team assumed the capital cost as that from the FHWA report for the metropolitan area listed (i.e., $950,000 per directional mile in Philadelphia, PA, in 2014). Considering economic data in the last decade (Bureau of Labor Statistics 2019), the cumulative inflation rate between 2014 and 2019 in the United States. is 8.71 percent. Therefore, the corresponding capital cost figure for 2019 is $1.03 million per directional mile. The team also used a 15-yr service life in the calculations, as this is the center value in the range provided in the FHWA report (FHWA 2015). The team assumed $40,000 for yearly maintenance cost, per the estimation by the National Center for Rural Roadway Safety (National Center for Rural Road Safety 2019). Additionally, the FHWA report estimates about $125,000 of additional cost per year for law enforcement to ensure compliance (FHWA 2015).

The research team computed the average cost of a crash using all severities, guidance from USDOT, and average distribution of severe crashes in the assembled databases (Trottenberg and Rivkin 2016). The team computed the KABC proportions as follows: 25 percent for Georgia, 15 percent for Wyoming, and 26 percent in Virginia. The research team also computed the B/C ratio for the corridor in Atlanta, per the safety Georgia analysis, and the corridor analyzed in

Wyoming. The team did not consider Virginia as they found no clear safety benefits in that analysis.

The FHWA report offered a spreadsheet tool for estimating the operational benefits of ATM strategies, including VSL (FHWA 2015). The research team used this tool to estimate the savings in nonrecurring delay for each of the two States in this economic analysis (Georgia and Wyoming). In the case of Wyoming, a rural corridor operating comfortably below its capacity, the estimate of this benefit was negligible ($11.89 per year) compared to the estimate for the urban and congested corridor in Georgia ($2,712.43 per year).

The research team then estimated the average cost of a crash at sites with VSLs as $639,158.83 for Georgia and $258,417.53 for Wyoming. The main reason for this noticeable difference in average cost is the larger percent of fatal crashes in Georgia compared to Wyoming. Considering all of the factors in the economic analysis, the research team estimated the B/C ratios as 40.4 in the case of Georgia and 9.05 in the case of Wyoming.

CHAPTER SUMMARY

This chapter described the economic analysis the research team performed to estimate the economic effectiveness of VSLs. The team estimated B/C ratios only for Georgia and Wyoming, as these were the two analyses that yielded statistically significant results. The chapter began with an outline of the resources and assumptions involved in developing B/C ratios. The economic analysis yielded B/C ratios larger than 1.0 for both States, indicating larger benefits than costs resulting from these types of implementation.

CHAPTER 6. SUMMARY AND CONCLUSIONS

The objective of this study was to perform a rigorous safety effectiveness evaluation of VSLs on freeways. To accomplish the goal of this study, the research team compiled safety data from Virginia, Wyoming, and Georgia. The evaluation included total, fatal and injury, night, rear-end, and other crash types depending on the State and purpose of VSL installation.

Results from Wyoming and Georgia found changes in safety associated with VSL implementations. Although the Virginia analysis found shifts in safety for fatal and injury, PDO, rear-end, fixed-object, nondry, low visibility, and night crashes associated with Virginia's VSL system, the research team found none of these shifts to be statistically significant. However, this result is not unexpected, as the system activates to manage freeway speeds during hazardous weather conditions. The research team estimated the displayed speed to be constant at 65 mph for about 95 percent of the time.

The research team found statistically significant reductions at the 95-percent confidence interval from the analysis of the Wyoming data for total, fatal and injury, PDO, rear-end, and fixed-object crashes. In contrast with the Virginia corridor, VSL installation in the Wyoming corridor was motivated by safety and operational considerations rather than assisting users during weather-hazardous conditions. Since the Wyoming system continually manages operations in response to traffic stream characteristics, it is not surprising that the safety effectiveness appears clearer from this analysis than Virginia's. Additionally, the largest safety association found (i.e., crash reduction) was for rear-end crashes, although the magnitude of the crash reduction produced a very large estimate (a 65-percent reduction in rear-end crashes).

The research team considers the Georgia dataset analysis to be most robust because of the availability of comparison sites. Results of this evaluation were in agreement with results from Wyoming (i.e., reductions for most crash types), but with smaller magnitudes in general. The research team only found statistically significant reductions at the 95-percent level of confidence for two crash types: total and rear-end. The team also found only day crashes have a crash reduction associated with VSL system installation at the 90-percent confidence level. All other crash types (except nondry crashes) also indicated statistically insignificant crash reductions. These results are generally aligned with past research (Downey 2015; Edara et al. 2016; Pu et al. 2017; Sohrab and Al-Kaisy 2017).

This study compared safety performance (i.e., crash expectation in a given period of analysis) without considering differences in management strategies by the different transportation agencies. The findings only quantify a systematic, measurable change in safety performance after VSL system implementation. For this reason, the results do not provide insight on the relative contributions of other factors not explicitly considered in the evaluation (e.g., agency-management approach, specific algorithm determining speed to display, level of congestion) for explaining the observed changes in safety performance.

Additionally, the inconclusive Virginia results are not evidence of lack of effectiveness of the State's VSL system. Since this system is triggered by fog, some measure of exposure to foggy conditions is an additional covariate that future work should consider explicitly. An evaluation focused on crashes during foggy conditions would better capture the safety impact of the system when the signs are actively regulating the operating speed. Recent work by VDOT suggests preliminary reductions in crash rates during reduced visibility conditions, although there was not a large change in overall crash occurrence (Gonzalez and Fontaine 2018).

The economic analysis for Georgia and Wyoming indicated larger benefits than costs for VSL installations. The B/C ratios were 40.38 and 9.05 for Georgia and Wyoming, respectively. Both evaluations indicated VSL installation benefits outweighed the costs.

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