Impacts of the I-77 Variable Speed Limit System on Speed and Crash Characteristics During Low Visibility Conditions

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Low visibility conditions can inhibit a driver’s ability to perceive appropriate operating speeds, particularly during foggy conditions in which the characteristics of the fog can vary spatiotemporally. By reducing visibility and contrast in the visual field, fog obscures crucial driving cues essential for perceiving depth and speed. Studies have shown that fog-related crashes are more likely to involve multiple vehicles and severe injuries than crashes during clear conditions. Numerous agencies have installed countermeasures such as weather advisory systems and variable speed limits (VSLs) to mitigate these conditions, but not many studies have quantitatively analyzed the results of these countermeasures.

In October 2016, the Virginia Department of Transportation (VDOT) activated a VSL system on a 12-mile section of I-77 that runs through mountainous terrain in southwestern Virginia. The area is known to have severe, recurring fog events, so the VSL system was installed to reduce the quantity and severity of crashes in the corridor. This study assessed how the I-77 VSL system has affected speeds and crash characteristics since its activation. Before the installation of the VSL, drivers frequently drove much faster than the safe speed based on the stopping sight distance during fog. The purpose of the VSL system was to influence drivers to travel closer to the safe speed during reduced visibility events by posting appropriate reduced speed limits.

The analysis examined the effect of the VSL system on driver speeds before and after activation at a single site and after activation across the corridor. Effects on crashes for the entire corridor were also examined. The results showed statistically significant reductions in mean speeds and variances after the VSL was activated, and drivers drove closer to the safe speed based on available visibility. Models developed to understand how the VSL system affected speed as a function of visibility showed that speeds were reduced by a statistically significant amount when VSLs were active. Trends in speed by posted speed limit were examined across the corridor, and it was found that compliance generally improved once drivers encountered reduced visibilities. Speeds did not change as much in transition areas leading into the area where the fog was present, however. Crash analysis revealed only two fog-related crashes in the after period, yielding reduced crash rates during low visibility conditions and indicating improved safety. These safety results are considered preliminary, however, because of limited after data. The results of this VSL implementation may be used to refine the current VSL control algorithm to improve compliance even further and could also serve as a reference for other agencies contemplating alternatives to improve safety at fog-prone areas.

Given the results, it is recommended that VDOT’s Southwest Region Operations convene a group to modify the VSL control algorithm. It is further recommended that the Virginia Transportation Research Council re-evaluate the safety effects of the system after at least 3 years of after data are available to make a more definitive determination of the safety effects of the system and to determine its return on investment. Implementation of these recommendations could further improve the efficacy of the system and result in a better quantification of the full benefits of the system.

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ABSTRACT

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FINAL REPORT

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INTRODUCTION

Reduced visibility conditions, such as fog, represent a challenging environment for drivers. Fog reduces visibility and contrast in the visual field, which can negatively affect the perception of depth and speed (Hamilton et al., 2014). When these crucial driving cues are obscured, a driver's ability to judge appropriate operating speeds may be compromised. Some studies indicate that motorists seem to compensate for these losses by changing following distances to ensure that the taillights of a lead vehicle remain visible (Hamilton et al., 2014). Drivers may not reduce speed when driving in fog until they feel their lane-keeping ability is compromised; thus they may maintain operating speeds too great for the close following distances and limited visibilities under fog conditions (Hamilton et al., 2014). These driving behaviors in fog conditions result in a greater likelihood of severe crashes and multiple-vehicle crashes than during clear conditions (Abdel-Aty et al., 2011).

To mitigate safety concerns, agencies sometimes install countermeasures such as weather advisory systems and variable speed limits (VSLs) in areas where fog events are common. Weather advisory systems that include dynamic message signs (DMSs) to relay weather information, speed advisories, and VSLs have been installed in several states and in other countries. However, not many quantitative evaluations of these systems have been performed.

A 12-mile section of I-77 that runs through mountainous terrain in southwestern Virginia has severe, recurring fog events. In the past 20 years, several major fog-related multi-vehicle chain reaction crashes have occurred on this corridor. On February 14, 1997, a chain reaction crash involved 56 vehicles, incurring 12 injuries, during a fog event (Lynn et al., 2002). Another fog-related series of crashes in September 2005 involved 50 vehicles, causing 25 injuries (McDonald, 2015). On November 16, 2010, visibilities were less than 100 ft when more than 70 vehicles were involved in 10 separate crashes that resulted in 2 fatalities and 16 injuries and closed the highway for nearly 10 hours (URS Corporation, 2012). One of the most severe fog events to date happened on March 31, 2013. When fog resulted in limited visibilities to 167 ft at the worst locations, a series of 17 crashes involving 96 vehicles resulted in 3 fatalities and 25 injuries and took almost 11 hours to clear (McDonald, 2015).

In 2002, Lynn et al. (2002), in a study on reducing fog-related crashes on I-77, suggested seeking authorization for experimental use of VSLs. Other less costly countermeasures were employed over the subsequent years, including rumble strips, delineator signs, wider pavement markings, chevrons, and other enhanced signs (McDonald, 2015). In 2014, the Virginia Department of Transportation (VDOT) awarded a $7.5 million contract to build an Active Traffic and Safety Management System (ATSMS) along 12 miles of I-77 in Fancy Gap. The system was activated in October 2016 and had been in operation for a full year at the time of this study. Now that VDOT has gained experience with the system, there is a need to quantify its effect on traffic and safety. Before the evaluation of the VSL system is discussed, it is useful to provide context for previous work that evaluated safety in the area in addition to information on the design of the VSL system.

Previous Studies of I-77

Several safety studies were conducted on this section of I-77 between 1995 and 2016. These studies assessed the relative safety of the corridor by quantifying the traffic incident frequency and severity of fog-related incidents. Four such studies are discussed here.

A 2002 study found that 14 of 139 crashes between Mileposts (MPs) 2 and 9 over a 4-year period were attributable to fog (Lynn et al., 2002). Although this represented 10% of all crashes, these crashes accounted for nearly 44% of all vehicles involved in crashes, averaging nearly 11.21 vehicles per crash event and 2.64 injuries per event (Lynn et al., 2002). The 2007 and 2012 studies had a broader scope and analyzed the corridor from MPs 0 to 32.5. The 2007 study found a total of 1,009 individual crashes involving 1,611 vehicles, and the 2012 study identified 1,118 individual crashes involving 1,718 vehicles (URS, 2012). The proportion and frequency of fog-related crashes decreased from 68 crashes (6.7% of total crashes) from 2001-2005 to 52 crashes (4.7% of total crashes) from 2006-2010. These reductions may be due to some of the enhanced warning and lane departure countermeasures implemented after the 2002 study, but it is difficult to assign causality since the number and duration of fog events were not accounted for in these studies.

The 2016 study examined crash characteristics considering exposure to fog events and driver speed choice under foggy conditions as a safety surrogate measure (McCann and Fontaine, 2016). Crash analysis of police crash reports for crashes between MPs 0 and 15 showed 524 total crashes, 58 of which occurred under low visibility conditions. An overwhelming 84% of the fog-related crashes occurred in the southbound (SB) direction. Five of these crashes resulted in fatalities, and 23 in injuries. Although fog-related crashes accounted for only 11% of total crashes, they accounted for 19% of fatal and injury crashes. More than 90% of fog-related crashes involved two or more vehicles; this proportion was only 47% during clear conditions. Crash rates during fog were calculated to be about 580 crashes per 100 million vehicle miles traveled (VMT), nearly 8.5 times greater than the rate during clear conditions.

The 2016 study reaffirmed the notion that the area between MPs 2 and 9 most commonly had severe fog events. Visibility data collected from Road Weather Information System (RWIS) visibility sensors confirmed that fog varied spatiotemporally and was concentrated most heavily near MPs 5.3 and 6.6. Speed analysis also revealed that drivers traveled much faster than the stopping sight distance (SSD) safe speed based on available visibilities. Although speed reductions were observed during dense fog, at locations with some of the worst visibilities, mean speeds were still 25 mph or higher over SSD safe speeds. Increasing standard deviations of speed were also observed as visibilities worsened. Details of this analysis are provided by McCann and Fontaine (2016).

A baseline model for driver behavior in fog before VSL installation was also developed. McCann and Fontaine (2016) found that driver speeds were inversely related to visibility distance, varied for day and nighttime, and varied by milepost. Although some temperature and precipitation data were available, McCann and Fontaine's model did not reveal those variables to be statistically significant. The final model yielded an adjusted R^2 value of 0.451.

$$S = 64.6 - \frac{4204}{Vis} + (1.13 * DayNight) + (6.07 * SB6) - (2.67 * SB7)$$

where

S = mean speed per 5 minutes (mph)
Vis = visibility distance (ft)
DayNight = day or night dummy variable, with 1 indicating day and 0 indicating night
SB6 = dummy variable, with 1 indicating site MP 6.6 SB
SB7 = dummy variable, with 1 indicating site MP 7.3 SB.

Although the R^2 fit was low, the model was useful to explain the overall trend found. The results of McCann and Fontaine's study served as inputs into the subsequent development of the initial VSL control algorithm for I-77.

Site Characteristics and I-77 VSL Description

I-77 runs 68 miles through the mountainous southwestern region of Virginia. The I-77 ATSMS project is located in the southernmost section of this interstate from MP 0 at the North Carolina border to MP 12, just south of Route 702, as shown in Figure 1. Although grades vary across the site, there is a relatively constant +4% grade between the North Carolina state line and approximately MP 6, with SB traffic traveling downhill. This section of I-77 is a four-lane divided freeway, with an additional truck-climbing lane from MPs 0 to 7 in the northbound (NB) direction. There are also two runaway truck ramps in the SB direction. The base posted speed limit (PSL) during clear conditions is 65 mph. In 2016, the average annual daily traffic was more than 19,000 vehicles per day in each direction and more than 25% of the traffic was trucks. Shoulder widths along the corridor range from 4 to 6 ft for left shoulders and 10 to 12 ft for right shoulders (McDonald, 2015). In addition to steep grades, there are 11 horizontal curves throughout the site.

Before VSL implementation, VDOT had already implemented the following countermeasures (McDonald, 2015; URS, 2012):

- 5 DMSs
- Safety Service Patrol (24 hours/day between MPs 0 and 19), started in 2012

- 11 RWIS stations installed by fall 2009
- shoulder rumble strips installed in fall 2012 on the majority of the roadway sections
- wider 8-in pavement markings added
- chevron signs (MUTCD Sign W1-8) added in all curves
- enhanced regulatory and warning signs upgraded to new prismatic sheeting
- regulatory signs dual indicated.

A $7.5 million contract to construct the I-77 ATSMS was awarded to G4S Technologies in February 2014. Before construction of the system began, 12 miles of power and 14 miles of fiber optic communications infrastructure were installed beginning in July 2011 to support the system installation (McDonald, 2015). The system was initially set to be in operation by the summer of 2015, but because of construction delays, it was not operational until October 2016. When construction was completed, the project had added 13 DMSs, 36 full matrix VSL displays, 8 speed limit signs with dynamic VSL cutouts, 25 CCTV cameras, 22 traffic sensors, and 14 RWIS stations. The locations of these devices are shown in Figure 2, and examples of devices are shown in Figure 3.

Before the entrance to the corridor, static signs reading “Speed Limit May Vary Next 12 Miles” were posted, along with static warning signs with flashers reading “Reduced Speed When Flashing” placed throughout the corridor in both directions (Kimley-Horn and Associates [Kimley-Horn], 2015). DMSs were installed at locations at the start of the corridor in both directions and at various intervals throughout the site to warn users of fog conditions ahead and to reduce speeds downstream. Signs were also posted to indicate the end of the VSL zone, as shown in Figure 3d.

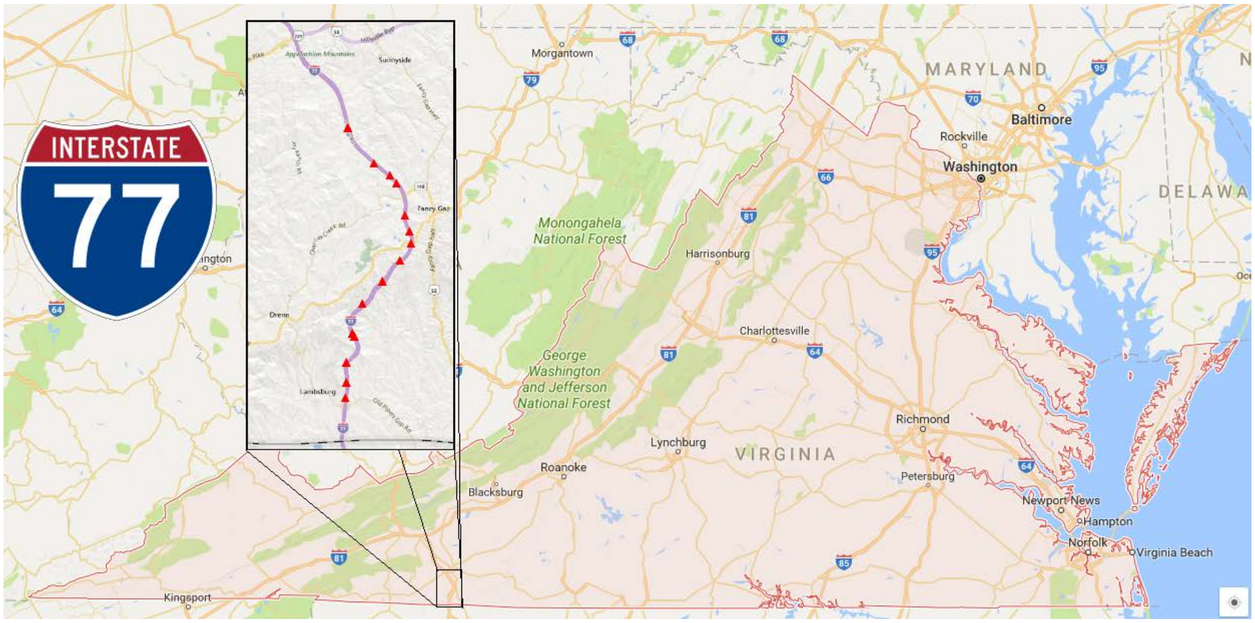

Figure 1. Map of Corridor Location. Red triangles represent VSL sign locations. VSL = variable speed limit.

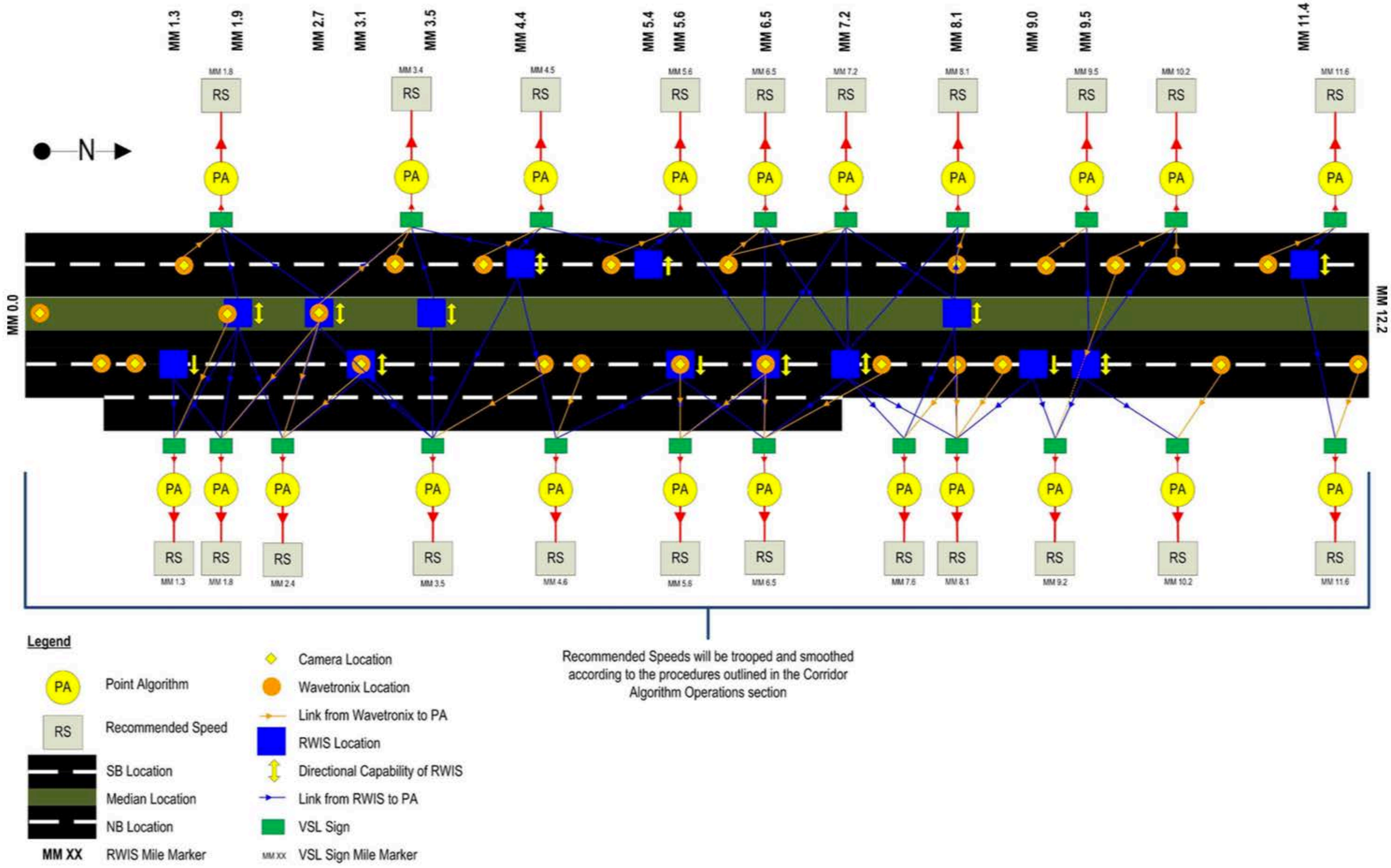

Figure 2. Corridor Diagram (Kimley-Horn and Associates, 2015).

(a) (b) (c)

(d)

Figure 3. VSL System Devices: (a) full matrix DMS VSL display; (b) speed limit signs with dynamic VSL cutout; (c) RWIS station; and (d) traffic sensor, CCTV, and signing at the northern end of the corridor. VSL = variable speed limit; DMS = dynamic message sign; RWIS = road weather information system; CCTV = closed circuit television.

VSL messages are displayed on the full matrix VSL displays and speed limit signs with dynamic VSL cutouts, shown in Figure 3, all of which are dual mounted in each direction and spaced no more than 1.5 miles apart. During clear conditions, VSLs post the base regulatory speed of 65 mph. Speed limits as low as 30 mph can be posted when conditions dictate. VSL speeds are set based on the visibility data from the RWIS stations and traffic data from traffic detection stations. A more detailed description of the VSL algorithm is provided later.

RWIS stations are spaced within 1.7 miles of each other and are located more densely within the fog-prone area near MP 6.6. These stations contain equipment to collect pavement temperature and condition, air temperature, humidity, barometric pressure, precipitation type and intensity, wind speed and direction, and visibility. The visibility sensors at each station are mounted 20 ft in the air and use forward scatter techniques to estimate visibility distance. Near each RWIS station, there are corresponding Wavetronix side-fire radar devices to collect traffic data. Although speeds posted by VSLs are regulatory, speed enforcement during low visibility conditions is limited. Because of safety concerns, enforcement by the Virginia State Police during low visibility conditions is selective to reduce the risk to enforcement officers during limited visibility conditions.

VSL Algorithm

As part of a collaborative effort among VDOT's Southwest Region Operations (SWRO), VDOT's Traffic Engineering Division, VDOT's Operations Division, the Virginia Transportation Research Council (VTRC), and Kimley-Horn, a methodology for operating the I-77 VSLs was prepared. Since the speed data showed that drivers frequently traveled much faster than the SSD-based safe speed, VDOT was concerned that simply posting these speeds would not adequately alter driver behavior and instead would further increase speed variance and interactions between vehicles during low visibilities. Thus, the initial VSL algorithm recommended speeds that were between those of the pre-VSL driving behavior model and the SSD safe speed, which resulted in a step function of visibility to determine the posted speed.

The step function used a modified version of McCann and Fontaine's (2016) driver behavior model equation, requiring fewer parameters. This model mean speed was represented by the following equation (Kimley-Horn, 2015):

$$S = 64.6 - \frac{4204}{Vis} + (2.15 * DayNight)$$

where

S = mean speed per 5 minutes (mph)
Vis = visibility distance (ft)
DayNight = day or night dummy variable, with 1 indicating day and 0 indicating night.

This model mean speed was modified based on the SSD safe speed, which is determined directionally because of uphill/downhill grades. When SSD safe speeds were higher than 50 mph, the model mean speed was used directly to make a posted speed recommendation. When SSD safe speeds were 40 to 50 mph, the model mean speed was reduced by 5 mph. When SSD safe speeds were below 40 mph, the model mean speed was reduced by 10 mph. In addition, the algorithm considered a day/night variable, so there were six step functions considered for both day and night with different cutoff points for steps for the NB and SB directions. A graphical representation of the model is shown in Figure 4 for the SB direction.

At each VSL location, depending on average observed speeds over an interval, the algorithm would determine what the posted VSL should be based on the minimum value of either the mean observed speed or the step-adjusted model fit. VSLs would not post values below 30 mph, and an additional smoothing algorithm would adjust VSLs over the corridor to have a smooth transition between posted VSLs as drivers traveled into and out of fog zones. Speed limits between successive VSL signs could not decrease by more than 15 mph but could return to 65 mph as quickly as possible after the fog zone was exited provided no additional visibility impacts followed downstream. For example, SB VSL signs approaching the fog zone would transition from 60 to 45 to 30 mph at the worst fog locations. As soon as drivers exited the fog zone, the next VSL sign could read 65 mph if visibilities were clear in the remainder of the corridor. VSL speeds at individual locations were also subject to a step range that would not allow them to vary by more than 15 mph over successive 5-minute intervals.

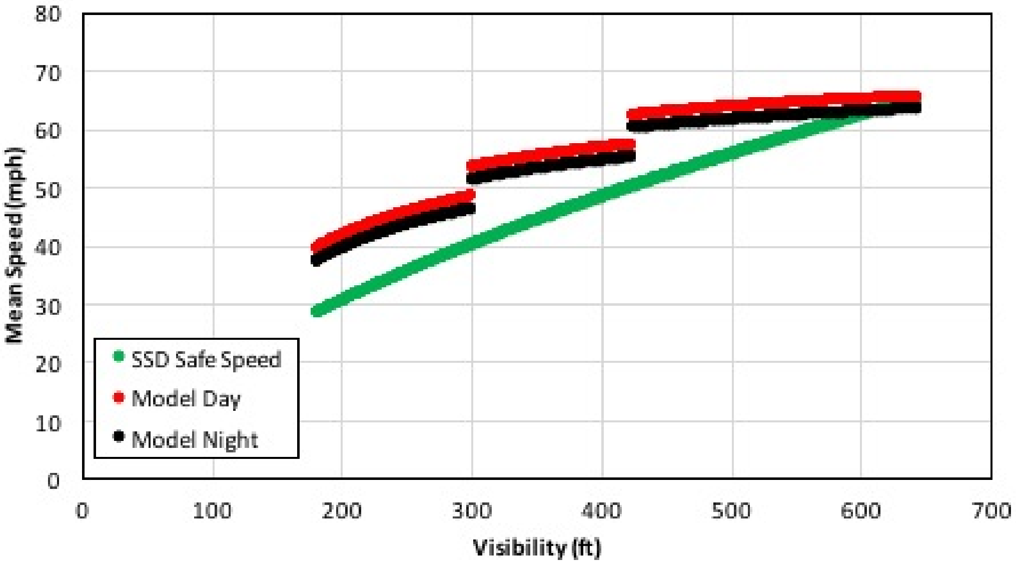

Figure 4. VSL Algorithm Step Function. VSL = variable speed limit; SSD = stopping sight distance.

PURPOSE AND SCOPE

The two primary goals of the I-77 VSL system are to reduce the quantity and severity of crashes in the corridor. The I-77 ATSMS Concept of Operations proposed reductions in total, fatal, property damage, and injury crashes as measures of effectiveness along with changes in speed limit compliance (URS, 2012).

The purpose of this study was to evaluate the effectiveness of the I-77 VSL system during its first year of operations. The objectives were as follows:

1. Determine the effect of the VSLs on driver speeds throughout the corridor.
2. Determine changes in crash characteristics after VSL activation.

The study used data collected from police crash reports, weather sensors, and traffic sensors across the corridor. The scope of the study was limited spatially to the I-77 corridor from MPs 0 to 12 and temporally to the first year of VSL operations. Given that the SB direction had higher speeds and was the direction with the largest associated safety concerns, the analysis focused on only the SB travel direction as the critical use case.

This study built on previous safety evaluations of the site to assess if the system had the desired effect in the first year. Although previous work by McCann and Fontaine (2016) established safety and driver behavior trends before VSL activation, this study focused on assessing whether the system created positive changes in safety on the corridor after system activation.

METHODS

Review Relevant Literature

A review of the literature related to the project scope was performed. Relevant studies were identified by searching research indexed by the VDOT Research Library and research in the Transportation Research Board's TRID database. The literature review focused on previous evaluations of driver behavior during limited visibility conditions and evaluations of the effectiveness of countermeasures to address safety issues during limited visibility.

Identify and Collect Data on I-77

Table 1 summarizes the data used in this study. These data elements are discussed separately in the following sections.

Table 1. Summary of New Data Used in This Study

Data Type	Data Source	Period	Location	Aggregation Interval
Visibility	Vaisala	Jan. 2015-Dec. 2015	MPs 1.2, 1.8, 2.7, 3.0, 4.4, 5.3, 6.6, 7.3, 9.0, 9.6, 11.3, and 16.9	10 min
	SWRO logs	Oct. 2016-Sept. 2017	MPs 1.3, 1.9, 2.7, 3.1, 3.5, 4.4, 5.4, 5.6, 6.5, 7.2, 8.1, 9, 9.5, and 11.4	Approx. 6 min
Weather	Vaisala	Jan. 2015-July 2016	MP 4.4	10 min
Speed	VDOT portable speed detection	Jan. 2015-July 2016	Southbound MP 4.4	15 min
	SWRO logs	Oct. 2016-Sept. 2017	Southbound MPs 1.0, 3.3, 4.3, 4.4, 5.3, 6.2, 6.6, 7.5, 8.1, 8.8, 9.7, 10.2, and 11.3	Approx. 6 min
VSLs	SWRO logs	Oct. 2016-Sept. 2017	Southbound MPs 1.8, 3.4, 4.5, 5.6, 6.5, 7.2, 8.1, 9.5, 10.2, and 11.6	Approx. 6 min
Volume	VDOT Traffic Monitoring System	Jan. 2015-Aug 2016	MPs 0-12	5, 15 min
		Oct. 2016-Aug. 2017	MPs 0-12	
Crash	VDOT Roadway Network System	Jan. 2015-Dec, 2015	MPs 0-12	N/A
		Oct. 2016-Aug. 2017	MPs 0-12	

MP = milepost; SWRO = Southwest Region Operations; VSLs = variable speed limit; N/A/ = not applicable.

Data were available at a limited number of locations along the corridor before VSL activation from both permanent and temporary data collection stations. After VSL installation, some stations were relocated and additional permanent data collection sites were installed. Data before VSL activation were obtained primarily through querying existing databases to update data that were previously collected by McCann and Fontaine (2016). For the after period, SWRO provided logs of VSLs, speeds, and visibility during fog events. Although data were available for both directions of travel, the after analysis of this study focused on the SB (downhill) direction given that previous work indicated this direction was responsible for the vast majority of safety concerns.

Visibility and Weather Data

Visibility data were collected from Vaisala PWD10/12 visibility sensors at each RWIS station. These sensors use forward scatter technology to measure visibility over a short distance and extrapolate it out to estimate visibility distance in feet at the site. Additional weather data collected at RWIS stations included pavement temperature and condition, air temperature, humidity, barometric pressure, precipitation type and intensity, and wind speed and direction.

In the before period, weather data consisted of two types of information. Visibility data consisted of readings archived every 10 minutes from RWIS stations located at MPs 1.2, 1.8, 2.7, 3.0, 4.4, 5.3, 6.6, 7.3, 9.0, 9.6, 11.3, and 16.9 from January 2015–December 2015. Additional visibility and weather data were retrieved from the RWIS station at MP 4.4 for the period January 2015–July 2016, when data were no longer available through the Vaisala external site. These additional data were used to enhance the before condition model of speed behavior.

For the after period, three additional RWIS stations installed at MPs 3.5, 5.6, and 8.1 were available, and several stations were relocated. The RWIS station at MP 16.9 was outside the scope of the study for the after period and thus data from this station were not used. The stations used for the after analysis were at MPs 1.3, 1.9, 2.7, 3.1, 3.5, 4.4, 5.4, 5.6, 6.5, 7.2, 8.1, 9, 9.5, and 11.4. Although RWIS stations were located either on the NB shoulder, on the SB shoulder, or in the median, most stations had the ability to provide visibility readings for both directions regardless of location. After system activation, visibility data were acquired from SWRO logs for fog events from October 2016–September 2017. These visibility readings were updated at an average rate of one reading every 6.5 minutes. In addition, sunrise and sunset times for the years 2015-2017 were acquired from the U.S. Naval Observatory to determine day/night conditions.

Speed and Volume Data

Before VSL activation, continuous speed data were available only at MP 4.4 SB from the VDOT Traffic Monitoring System (TMS). The detectors recorded the count of vehicles in 5-mph speed bins in 15-minute intervals. In order to match speeds to visibility readings, these 15-minute intervals were converted to 10-minute intervals. This conversion involved evenly splitting 15-minute intervals into 5-minute intervals assuming a linear distribution of data during each 15-minute interval. Then, average speeds for the new 10-minute intervals were calculated assuming all vehicles were traveling at the midpoint of each 5-mph bin and finding the volume weighted average speed.

In the after period, new sensors came online to support VSL operations, adding to the data available from the TMS. Every time the VSL was activated, SWRO would generate a log file including mean speeds and PSLs for every location in the corridor. The recording interval averaged approximately 6.5 minutes. Mean speeds for each interval were collected by Wavetronix speed detectors at MPs 1.0, 3.3, 4.3, 4.4, 5.3, 6.2, 6.6, 7.5, 8.1, 8.8, 9.7, 10.2, and 11.3 in the SB direction. Posted speeds were recorded from each VSL sign location at MPs 1.8, 3.4, 4.5, 5.6, 6.5, 7.2, 8.1, 9.5, 10.2, and 11.6.

Since SWRO logs provided only mean speeds, volume data needed to be retrieved from the TMS for the entire after period. Volume data for the entire corridor were retrieved from the TMS for the before period and for the October 2016–June 2017 after period. In the NB direction, volume data for links MP 0-0.94, MP 0.94-8.57, and MP 14.85-19.03 were retrieved. In the SB direction, data for the links MP 0-1.07, MP 1.07-8.99, and MP 15.22-19.53 were retrieved. The volume data were recorded in 5- and 15-minute intervals. The 15-minute intervals were converted into 5-minute intervals again assuming a linear distribution of data during 15-minute intervals. The before period data were further converted to 10-minute data to match the temporal aggregation of the visibility data.

VSL Posted Speed Logs

VSL signs for the SB direction were at MPs 1.8, 3.4, 4.5, 5.6, 6.5, 7.2, 8.1, 9.5, 10.2, and 11.6. In the after period, posted VSLs at each VSL location were recorded in the SWRO logs at approximately 6.5-minute intervals. Posted speed values were 30, 35, 40, 45, 50, 55, 60, and 65 mph. Periods when VSLs were offline were recorded in SWRO logs as “Blank” and were discarded from the analysis.

Crash Data

Police crash reports were retrieved from VDOT’s Roadway Network System in order to understand crash characteristics and frequencies before and after system activation. After crash data from October 2016–August 2017 were collected to perform a preliminary crash analysis after VSL activation. For both datasets, crashes coded as fog were then matched with visibility data to confirm whether low visibility conditions indicated in the police crash report were verified by field measurements.

Data Matching

Since the different datasets used different reporting intervals, data had to be conflated in several ways. For crash rate calculations, visibility and volumes needed to be matched and crashes and visibilities needed to be matched. For the before data, volume data from the entire corridor were converted to 10-minute bins to match visibility data. For after data, volume data were converted to 5-minute intervals since visibility readings in the after period were roughly 6 minutes to maintain as much granularity as possible. Visibility readings were then matched to 5-

minute volume readings by linear interpolation between visibility readings. Visibility readings for times outside those in the SWRO logs were considered to be under clear conditions. For the post-VSL period, if intervals between valid visibility readings were ever more than 30 minutes apart, the 5-minute intervals to be matched in between periods with data were marked as being missing.

To match visibility data to police crash records, visibilities at the nearest visibility stations and timestamps closest to crash record times were determined. Then visibilities were linearly interpolated between the nearest RWIS stations with visibility readings.

Data Analysis

The following section presents the analysis performed in this study. The analysis examined the effect of the VSL system on driver speeds before and after at a single site; speeds across the corridor in the after period; and crashes for the entire corridor before and after system activation.

Visibility Analysis

To be consistent with previous work, visibility conditions were categorized into groups corresponding to a range of SSD safe speeds. Boundaries for each of these visibility bins were calculated by solving for speeds of 65, 55, 45, 35, and 25 mph using the equation for SSD:

$$SSD = 1.468 \times V \times t_r + \frac{2.155 \times V^2}{2 \times a}$$

where

SSD = stopping sight distance (ft)
V = speed (mph)
t_r = perception-reaction time (sec), assumed to be 2.5 sec
a = deceleration rate (ft/sec^2), assumed to be 11.2 ft/sec^2.

Deceleration rates and perception-reaction times were taken from *A Policy on Geometric Design of Highways and Streets* (AASHTO, 2011). The SSD calculated for each of the speeds was rounded up to the nearest multiple of 5. This resulted in the following visibility bins for corresponding speed ranges:

- >645 ft ≥ 65 mph
- 495-645 ft = 55-65 mph
- 360-494.9 ft = 45-55 mph
- 250-359.9 ft = 35-45 mph
- 155-249.9 ft = 25-35 mph
- <155 ft ≤ 25 mph.

These categories were used to construct a visibility profile of the corridor by RWIS station. The visibility profile served to indicate if fog exposure during the before and after periods were similar. This visibility distribution was also critical to subsequent analyses of crash rates and speeds.

VSL Utilization

VSL utilization was summarized by how often each PSL was posted at each VSL sign. Average posted speeds on each SB VSL sign location were also calculated. This utilization provided a metric of the exposure of the drivers to reduced speeds and indicated how VSL usage varied throughout the corridor.

Speed Analysis

Before-After Evaluation at MP 4.4 SB

There were only two sites along the corridor that provided continuous speed and visibility data both before and after system activation: MP 4.4 SB and MP 6.6 NB. Since the focus of this study was on the SB direction and speeds were consistently higher in the downhill direction, only the data from the station at MP 4.4 SB were analyzed to compare changes in speed after VSL activation. Speed data were summarized into counts, mean speeds, and standard deviations by visibility bin for both periods. Z-tests were used to determine if mean speeds in the after period were statistically different from those in the before period. F-tests were also performed to assess if the variance in speeds by visibility bin changed for the periods tested.

Weather and VSL data were also used to develop models that showed how mean speed varied at MP 4.4 before and after VSL activation. Stepwise regression was performed in order to describe speeds as a function of visibility, weather conditions, and/or VSL factors for each of the models considered. Independent variables considered were as follows:

- available visibility distance
- weather data (pavement temperature and condition, air temperature, humidity, barometric pressure, precipitation type and intensity, and wind speed and direction)
- day/night conditions
- presence/absence of a VSL (0 if not present, 1 if present).

Transformations and interactions of these variables within their respective models were also taken into consideration. Periods with visibilities more than 645 ft (clear conditions) and of 0 ft were discarded from the model. Theoretically, visibilities of 645 ft or more should provide adequate SSD for the base speed limit of 65 mph. Based on feedback from VDOT, visibility readings of 0 ft were taken to be errors and were discarded from the dataset. Further, speed data during crash events and their aftermath were ignored since the intent of this analysis was to understand speed under undisturbed, low visibility conditions and not during congestion.

Models were further refined using the Cook’s distance value to exclude outlier data points that were excessively influencing the models. To check if regression assumptions were satisfied, residual plots and probability-probability plots were reviewed. Adjusted R^2 values and average absolute error and bias were also checked.

Speed Changes During Fog Along Corridor

Although speed data throughout the entire corridor were not available in the before period, they were available in the after period. To understand speed changes during fog along the corridor, speed data were summarized in several forms: posted speeds by MP, observed speeds versus posted speeds by milepost, and speed differentials between observed and posted speeds by milepost. To analyze the effect of the posted speed on the mean speed, paired *t*-tests were performed on observed speeds to determine if mean speeds for a set posted speed at a milepost were significantly different.

Crash Analysis

Crash Frequency and Characteristics

Crashes that occurred during measured low visibility periods were summarized by crash type, severity, and number of vehicles involved. These were summarized also by visibility bin and direction to examine crash changes as a function of the magnitude of reduced visibility. All other crashes were considered “clear conditions” and were summarized similarly.

For the before period, crash characteristics of the corridor were summarized for 6 full years immediately before VSL activation. Because of the limited amount of crash data that had been reported since VSL activation, analysis is discussed more qualitatively for the after period, although similar summaries are provided.

Crash Rates

Crash rates along the corridor were calculated using visibility, volume, and crash data. After visibility and volume data were matched by time and space, VMT per visibility bin needed to be estimated. First, the corridor was broken into segments according to the number of RWIS stations corresponding to each direction. The NB direction was broken into 13 segments with the midpoints between RWIS station MPs 1.3, 1.9, 2.7, 3.1, 3.5, 4.4, 5.6, 6.5, 7.2, 8.1, 9, 9.5, and 11.4 as the segment boundaries. Similarly, the SB direction was broken into 11 segments with the midpoints between RWIS station MPs 1.9, 2.7, 3.1, 3.5, 4.4, 5.4, 6.5, 7.2, 8.1, 9.5, and 11.4 as segment boundaries. For each segment, the VMT was determined by multiplying segment length with corresponding link volume. This was done for all intervals. The sum of VMT per visibility bin was found, and crashes per 100 million VMT per visibility bin were calculated. The crash rate for all combined low visibilities was also calculated.

VSL Algorithm Assessment

Depending on the effect of the system, modifications to the current VSL algorithm may be warranted to increase system effectiveness. To assess the VSL algorithm, modifications to different constraints in the algorithm were examined. Modifications to the algorithm could entail altering spatial and temporal step ranges or altering the values used in the algorithm to determine the recommended speed. Other alternatives to improve system effectiveness beyond the control algorithm itself were also discussed.

RESULTS

Literature Review

Driver Behavior During Reduced Visibility

Drivers' ability to determine appropriate operating speeds relies greatly on their visual perception. Reductions in visibility can impair drivers' judgment and negatively affect safety. Early research in driving in fog focused on identifying perceptual changes that influenced speed, often modeling fog as a uniform reduction in contrast. These studies have considered both simulated and test track data to understand the effects of visibility on driver behavior and safety.

In a virtual environment driving simulation, Snowden et al. (1998) found that drivers' sense of speed decreased in fog, as drivers tended to drive faster as fog became denser. First, the test subjects were shown two scenes that moved at the same speed, one with "clear" conditions, another with "clear," "misty," or "foggy" conditions. Foggier scenes were perceived as slower moving. Second, drivers were asked to match a certain operating speed in the different simulated conditions. In foggier scenes, subjects drove at faster speeds, causing the authors to conclude that perceived speed depends on level of contrast, with lower contrast yielding higher speeds. However, these results consider fog as a contrast reduction evenly dispersed across the entire visual field.

Another study (Brooks et al., 2011) used driver simulator data that more accurately coded fog as a distance-dependent contrast reduction to provide insight into driver behavior under reduced visibility. The study measured the ability of participants to stay in their lane and maintain speed. In the study, participants were assigned into one of six groups classified by a combination of a factors including presence or absence of auditory speed indicators, ability to maintain speed task priorities, and speedometer availability. Participants were first given practice sessions to become acquainted with driving in the simulator before running through six fog scenarios. Results showed that throughout each group, drivers did not decrease speed significantly as visibility decreased. In fact, results suggested that as long as drivers were able to maintain vehicular control, they would maintain high speeds while driving in fog. The findings of this study, however, are limited because of small sample sizes within the groups. Since the sample consisted only of college students, the results may also not accurately represent the overall population of drivers on the road.

Case studies using actual traffic data have also been performed to gain a better understanding of real world driving in low visibility conditions. In a case study of the effects of visibility and other environmental factors on driver speed, Liang et al. (1998) studied the speed-visibility relationship on a rural Idaho freeway before the installation of a storm warning system. The data used in this study were collected from an operational test of weather and visibility sensing systems at a spot site from December 1995–April 1996, during which extreme weather conditions were present on 21 days. In this period where no external information or warning signs were shown to the drivers, mean speed reductions of 8.0 km/h during fog events were observed; however, this was accompanied by a doubling in the variation in speeds. This study was unable to determine if trends in speed reductions were sufficient to ensure adequate sight distances given no periods of visibility were less than 528 ft.

Field Deployments of Visibility Warning Systems

Table 2 summarizes the effectiveness of past field deployments of various visibility warning systems. These systems have taken a variety of forms, including VSLs, advisory speeds posted on changeable message signs, and fog advisories that did not provide recommended speeds. Although a variety of systems have been deployed within the past 30 years, there is a general lack of quantitative evaluations of the results of these implementations. Those evaluations that exist also have several limitations.

Four of the field deployments did not provide any performance measures on the effectiveness of the system. Another system qualitatively reported improvements without any quantitative data to support the statements. Two deployment evaluations reported low to no fog-related crashes after activation, and another reported both reductions and increases in fog-related crashes. Because of the rarity of the occurrence of crashes, a simple crash frequency before-after comparison does not conclusively demonstrate safety effects, and neither of these evaluations considered exposure to fog or traffic volumes. It could be possible that the low visibility conditions in the after period were not representative of those in the before period. The evaluation of the California Motorist Warning System attempted to account for fog exposure by considering crashes per 100 heavy fog days (Goodwin, 2003). This measure of exposure arguably could have been more accurate if it had used weather data from its nine weather stations rather than visibility conditions at the nearest airport. These results point toward the expected positive impacts but present possible bias.

Four deployment evaluations reported mean speed reductions during low visibility conditions under the system, and one reported mean speed increases. The mean speed reductions in these deployments considered reductions from either clear conditions in the same study period or low visibility conditions before system activation. Classifying both of these conditions within one deployment would more accurately characterize effects.

A common trend across studies in the literature is a lack of quantitative data on system performance and a failure to account for the exposure to fog in terms of both temporal and spatial distribution of reduced visibilities.

Table 2. Summary of Visibility Warning Systems

System	Type of System	Major Findings	Limitations
Alabama, I-10 Low Visibility Warning System (Murphy et al., 2012)	• Regulatory VSL • Manual	• Reduced average speeds • Qualitative crash risk reduction during low visibility conditions	• No specific quantitative results
Australia, F6 Tollway (Robinson et al., 2002)	• Advisory VSL • Automated	• No reports on results	• No reports on results
California, SB I-5 and WB CA-120 CAWS (Goodwin, 2003)	• (Speed) Advisory • Automated (manual override option)	• 1.1 mph reduction in mean speeds • 8.0 mph increase in potential collision speed • 242% increase in fog-related crashes in one study area	• Control road used for crash comparison • Normalized fog crashes by “heavy fog” days, not actual visibility conditions during collision
California, Rt. 99 (Liu, 2013; Murphy et al., 2012)	• Speed Advisory • Automated	• No reports on results	• No reports on results
Georgia, I-75 Automated Adverse Visibility Warning and Control System (Abdel-Aty et al., 2012; Gimmestad et al., 2004)	• Speed Advisory • Automated	• No reports on results	• No reports on results
Idaho, I-84 Storm Warning System (Goodwin, 2003; Kyte et al., 2000)	• Advisory • Manual	• At visibilities <0.1 miles and no DMS, speed reductions from 67.7 to 58.4 mph • When DMS is used with high winds, high winds and moderate to heavy precipitation, and snow / high wind events, speed reductions of 23%, 12%, and 35%, respectively	• Insufficient data at low visibility only conditions to show effect • No crash analysis • No consideration of fog exposure
Netherlands, A16 (Robinson et al., 2002)	• VSL • Automated	• Mean speed reductions during fog conditions of approximately 5-6 mph	• No crash analysis • No consideration of fog exposure
Oregon, I-5 and US-97 (Kimley-Horn, 2014)	• Advisory VSL • Automated	• No reports on results	• No reports on results
South Carolina, I-526 (Goodwin, 2003)	• Speed Advisory • Semi-Automated	• No crashes 1992-2003	• No speed analysis • No consideration of fog exposure
Tennessee, I-75 Low Visibility Warning System (Murphy et al., 2012)	• VSL • Automated/ Manual	• Only 1 fog-related incident 1993-2012 • Effective for general incident management	• No speed analysis • No consideration of fog exposure at large
Utah, I-215 ADVISE (Goodwin, 2003)	• Speed Advisory • Automated	• 15% increase in speeds • 22% decrease in standard deviation of speeds	• Speed limit increase implemented same year as system, road widened before and after

Data Analysis

Visibility

There were 106 separate reduced visibility events that resulted in VSL activations from October 2016–September 2017. These activations resulted in at least some portion of the corridor having a reduced VSL for a total of 702.5 hours. From the VSL activation logs, visibilities were retrieved to construct a visibility profile for the after period, which is shown in Figure 5. The figure shows a concentration of low visibility conditions between MPs 7.3 and 5.3, which was consistent with previous findings by McCann and Fontaine (2016) in the before period.

For the after VSL activation period, RWIS stations at MPs 6.6 and 5.6 had the longest total duration of reduced visibility, with 386 and 275 hours (4.4% and 3.1% of the time in the after period, respectively) of visibilities less than 645 ft. This is about 1% less than the length of the before period documented in the previous study (McCann and Fontaine, 2016), but visibilities less than 360 ft occurred approximately 3.1% of the total time for both the before and after periods at MP 6.6. Visibility data were available only when at least one VSL was active, and it was assumed that clear conditions were present at all other times.

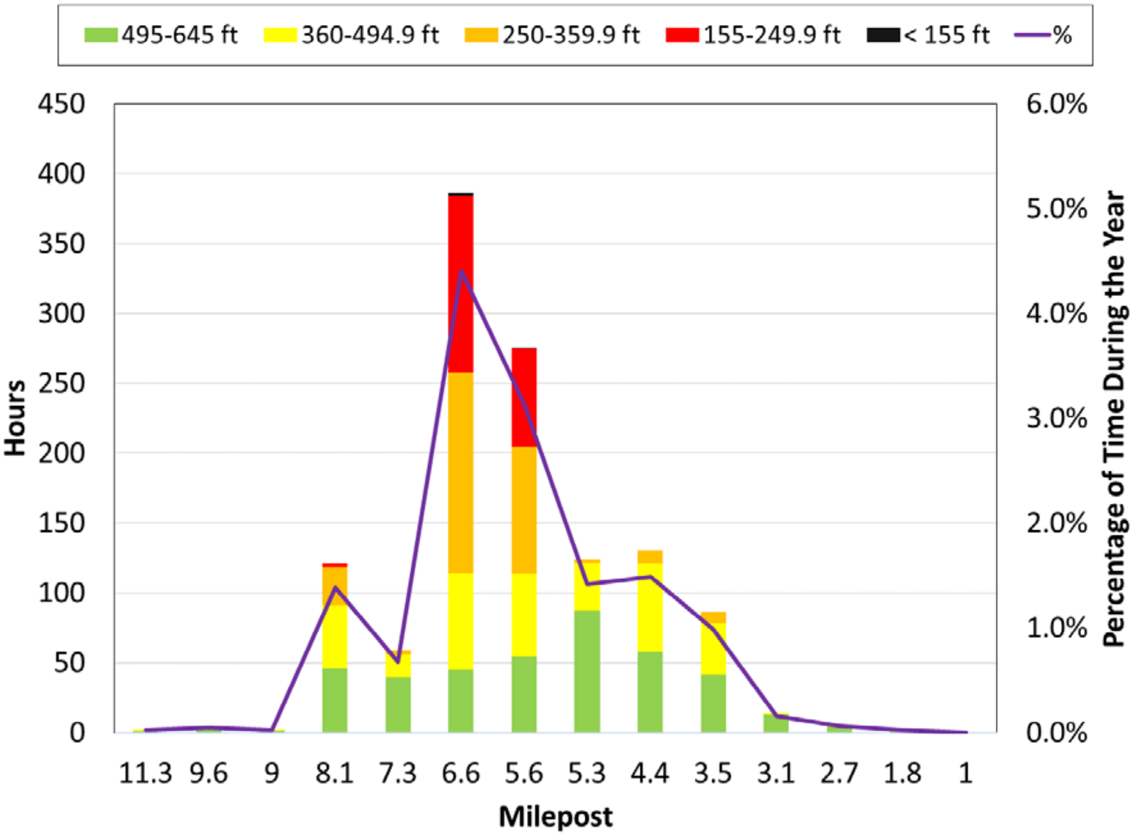

Figure 5. After Period (10/16-9/17) Visibility Profile

RWIS stations at MPs 9.6, 7.3, and 1.8 had the most missing hours of data, with 34 to 42 hours of missing data during the reduced visibility events. Since RWIS stations at MPs 9.6 and 1.8 fall outside the worst fog zone area, these missing data likely do not greatly affect the overall visibility profile. At MP 7.3, there is a sudden drop, which can partially be attributed to the missing data. Overall, however, the visibility in the corridor for the after period was spatially similar in distribution to the average low visibility conditions summarized by McCann and Fontaine (2016) for the 2010-2015 period.

Summary of VSLs Posted

Figure 6 shows the amount of time and overall percentage of the after period in which reduced speed limits were posted in the SB direction. Milepost numbers decrease as drivers travel SB, so drivers would be traveling into the densest fog area moving from left to right in the figure. Figure 6 shows that speeds were most frequently reduced between MPs 7.2 and 5.6, with these locations posting reduced speeds for more than 5% of the after period. In general, this figure shows how during fog events the VSL system will post speeds that gradually reduce as drivers traveling SB encounter the first VSL sign at MP 11.6 until the worst fog area between MPs 7.2 and 5.6 where reduced speeds are the lowest. After drivers traversed the worst fog zone, posted speeds quickly increased back up to the base speed limit.

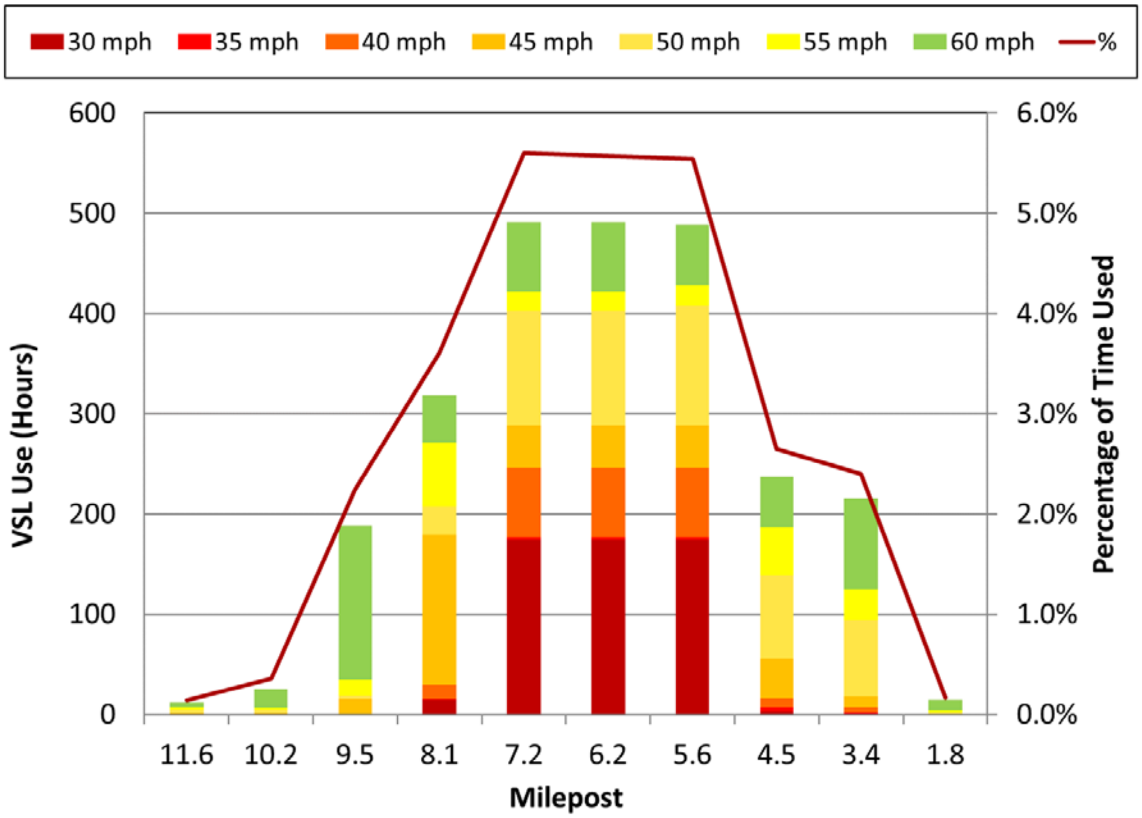

Figure 6. I-77 Southbound VSL Usage by Milepost. Milepost numbers decrease as drivers travel southbound, so drivers would be traveling into the densest fog area moving from left to right in the figure. VSL = variable speed limit.

Figures 5 and 6 show that the need to reduce speeds gradually before transitions into the areas of densest fog results in a potential discrepancies between the VSL posted speeds and the visibility at a specific location. For example, Figure 5 shows that MP 8.1 had reduced visibilities only for less than 1.5% of the year. However, Figure 6 shows that reduced speed limits were posted more than 3% of the time to allow for gradual transitions into the areas with the worst fog. As a result, there is the potential that the visibility at a specific location does not align directly with the VSL posted at that spot. This indicates a need to examine how speeds vary as a function of both the PSL and the visibility.

Case Study: Incident WX3150436

Before overall trends in the results are discussed, a case study is presented to illustrate how the system works over the course of an event. This allows for a more granular presentation of results and helps illustrate common performance trends.

Incident WX3150436 began on December 17, 2016, at 8:38:39 PM and lasted until December 18, 2016, at 11:01:46 AM, for a total duration of 14 hours and 23 minutes. During this event, all RWIS stations and VSL signs were operational with no missing data. All SB speed sensors were operational with no missing data except for those at MPs 8.1, 6.2, and 4.4, which were offline for the entire event. At the event's most critical point, visibilities were as low as 177 ft at MP 5.6, with reduced visibilities extending from MPs 2.7 to 8.1. On average, there was a median spread of fog of 2.2 miles centered about MP 6.6. The overall visibility profile for the event is shown in Figure 7.

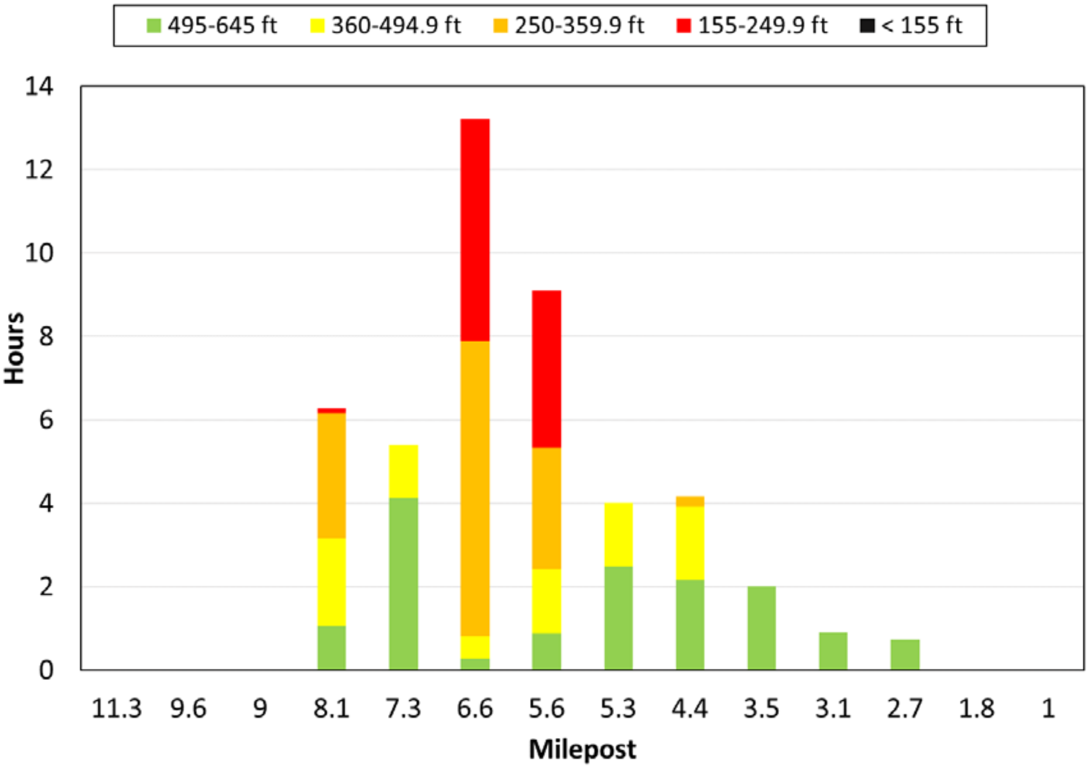

Figure 7. Case Study Visibility Profile for Incident WX3150436

The VSLs were used as shown in Figure 8. From Figure 8, it may be seen that the VSLs used at MPs 7.3, 6.6, and 5.6 were almost identical, posting reduced speeds of 30 mph for more than 60% of the event duration. Although visibilities at MP 7.3 were slightly more than for the preceding station at MP 8.1, the grouping process used in the VSL algorithm caused all speeds in this region to be equal, and VSLs at MP 8.1 were posted at 45 mph for a majority of the time. This again shows how VSLs may not strictly match the visibility of a specific location.

Figures 9 to 11 show how speeds and visibilities varied over time at successive VSLs for this event. Only visibilities less than 1,000 ft are graphed. Upon entrance to the corridor at the north end, mean speeds closely followed the posted speeds, which remained at 65 mph for the vast majority of the time. When drivers approached the first reduced speed limits at MP 9.5, observed speeds remained higher than posted speeds by around 5 mph. The lowest posted speeds were first seen at MP 7.2, and downstream speeds were first recorded at MP 6.6 where the most severe fog was concentrated. The greatest differentials between posted speeds and observed speeds were at these locations. Posted speeds over time at this location fluctuated between 45 mph and 30 mph, but as time progressed, the vehicles passing through this section maintained speeds in the 50s. Speeds remained far above posted speeds until drivers encountered the VSL at MP 4.5, where there were instances where even average speeds were below the posted speeds. Here the delayed reaction to VSLs after the fog was seen most prominently.

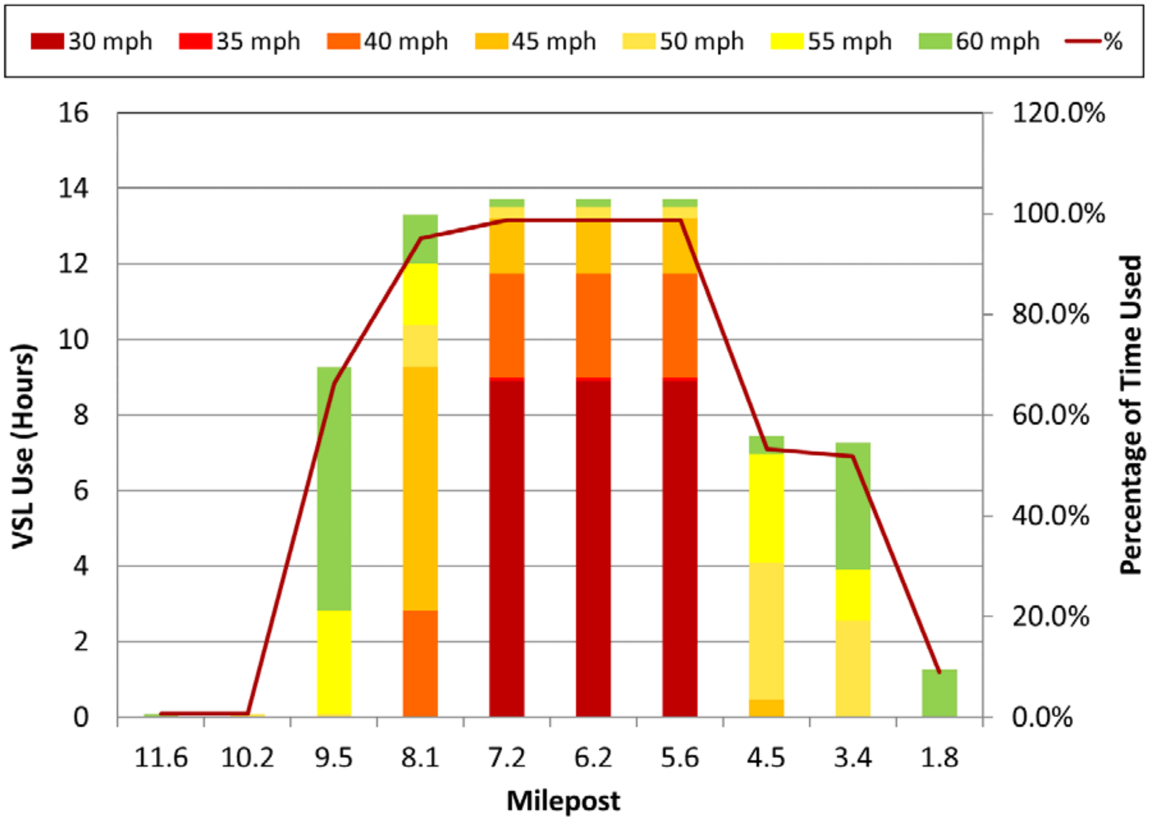

Figure 8. Case Study Southbound VSL Usage for Incident WX3150436. VSL = variable speed limit.

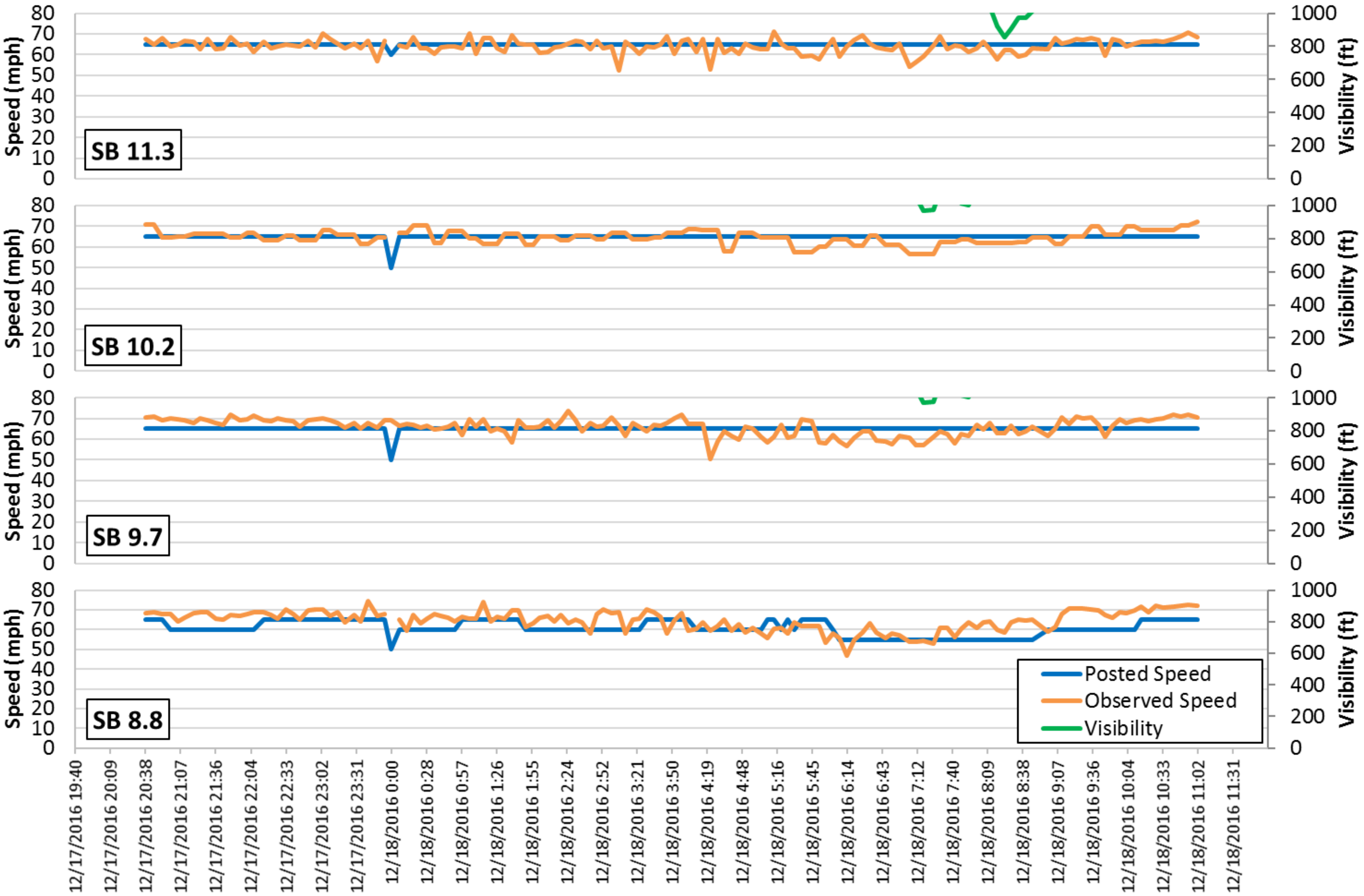

Figure 9. Southbound Speeds Over Time for Incident WX3150436, Mileposts 11.3, 10.2, 9.7, and 8.8

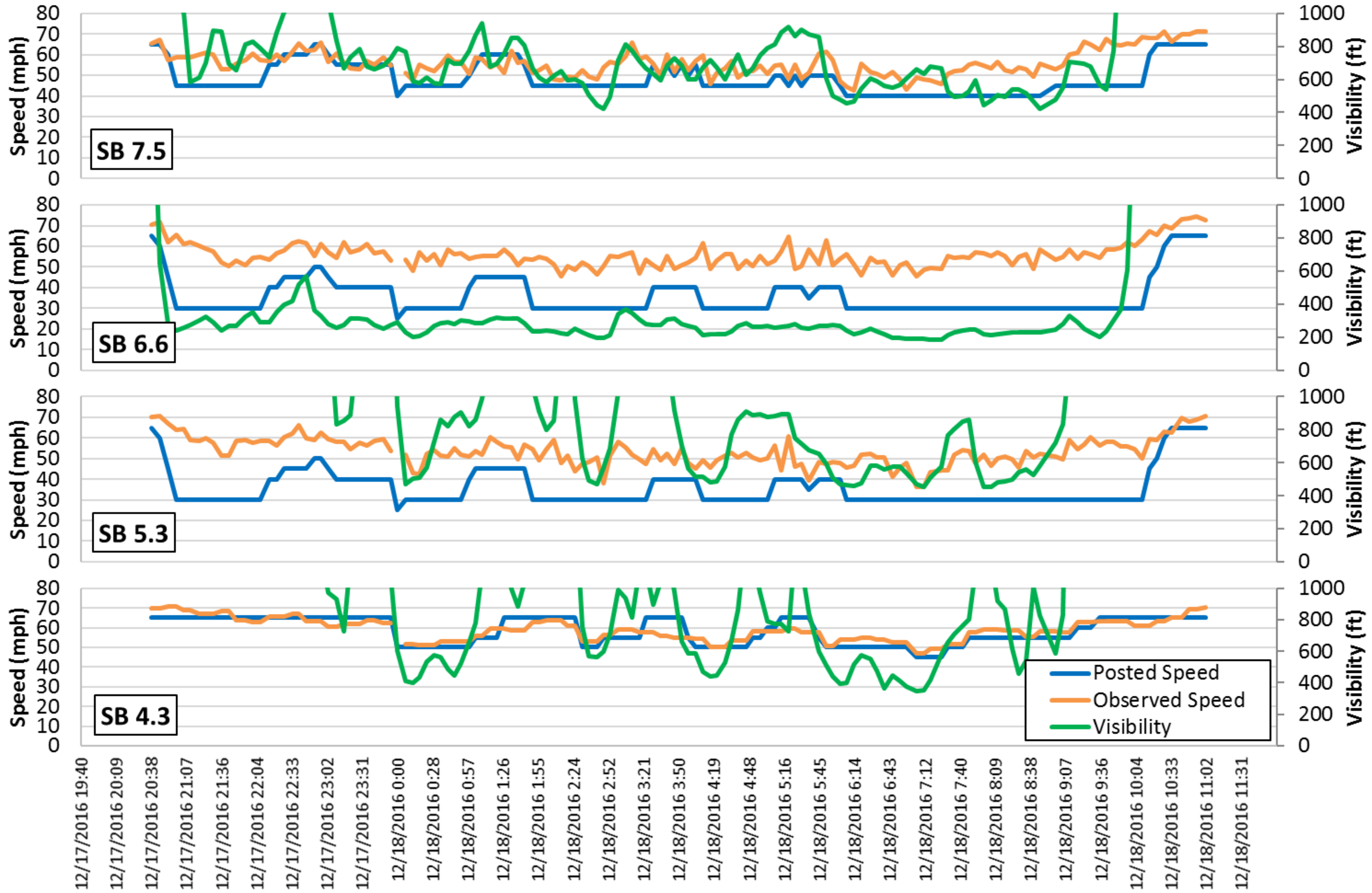

Figure 10. Southbound Speeds Over Time for Incident WX3150436, Mileposts 7.5, 6.6, 5.3, and 4.3

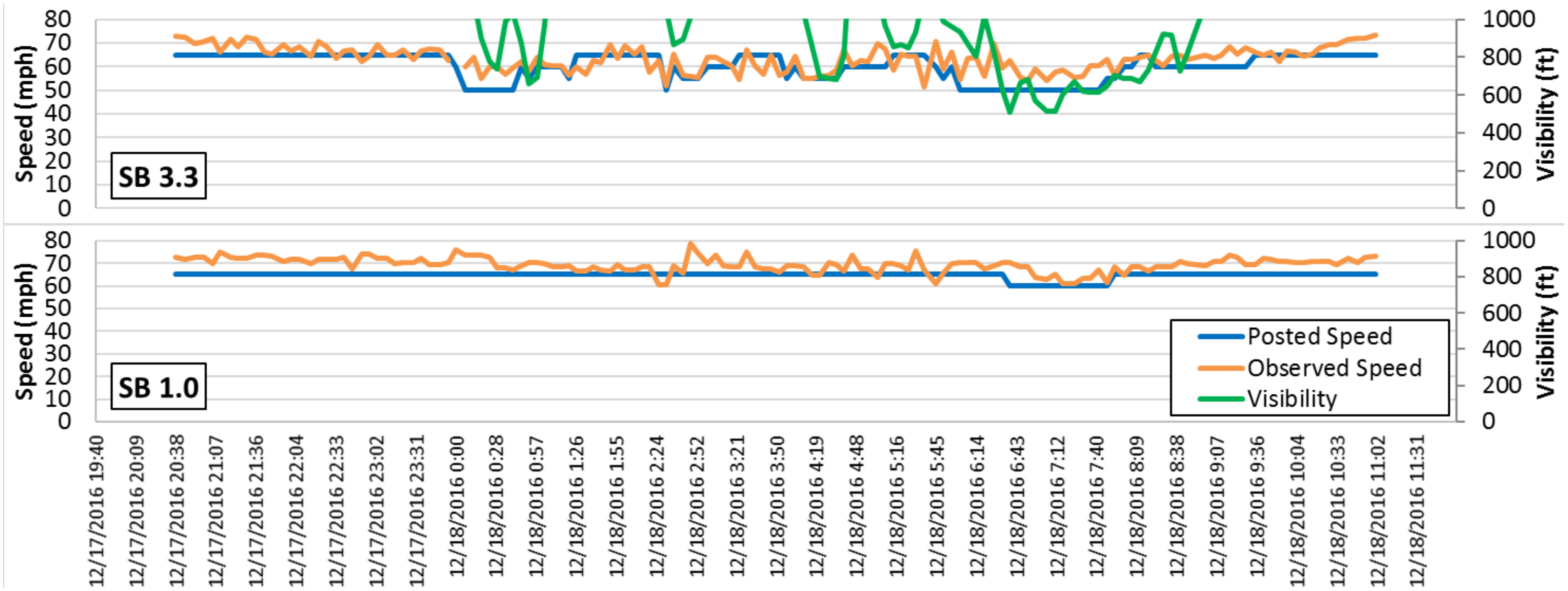

Figure 11. Southbound Speeds Over Time for Incident WX3150436, Mileposts 3.3 and 1.0

This case study illustrated a common phenomenon observed during fog events where drivers must be exposed to fog for some time before decelerations occur. Unfortunately, the TMS station where data were available before and after deployment is located after the densest fog zone in Fancy Gap. As a result, the speed compliance seen at MP 4.4 may represent a best-case scenario in terms of speed reductions produced by the VSL.

Speed Choice

Before-After Evaluation at MP 4.4

Although the case study illustrates that the MP 4.4 location represents a best-case scenario for system effectiveness, it was the only location where speed data were available continuously for both the before and after periods. Table 3 compares mean speeds and standard deviations by visibility range for the before and after periods. In this case, visibility is used to group the intervals since PSLs remained constant at 65 mph in the before period. Although the aggregation interval for both periods differ, the numbers of intervals for both periods are given to establish the number of observations used in the analysis. As may be seen, the number of intervals available for visibilities more than 645 ft in the before period is substantially greater than in the after period. In the after period, visibilities more than 645 ft were recorded only if there was fog elsewhere on the corridor.

Hypothesis testing at a confidence level of $\alpha = 0.05$ showed that all mean speeds were reduced across every visibility range in the after period. For every visibility range available, mean speed reductions of 2 to 5 mph were seen. At a 95% confidence interval, there were also reductions of standard deviation across all visibility ranges available. Reductions in speed and variance suggested that safety improved after the VSL was activated. No periods of visibilities less than 250 ft were recorded in the after period at this station, so effects during very dense fog could not be evaluated. These reductions point toward the overall positive impact of the VSL system.

Table 3. Before-After Comparison of Mean Speed at MP 4.4 SB

		Before			**After**			***p*-value**	
Visibility Bin (ft)	**SSD Safe Speed (mph)**	**No. of Intervals (10-min intervals)**	**Mean Speed (mph)**	**Standard Deviation (mph)**	**No. of Intervals (5-min intervals)**	**Mean Speed (mph)**	**Standard Deviation (mph)**	**Mean**	**Variance**
>645	65	69307	67.07	7.31	5158	64.34	5.41	0.000	0.000
495-645	55-65	513	59.88	8.45	526	55.12	6.33	0.000	0.000
360-494.9	45-55	524	56.63	9.03	561	51.83	5.40	0.000	0.000
250-359.9	35-45	297	52.43	8.83	73	50.49	5.04	0.018	0.000
155-249.9	25-35	22	49.75	7.96	0	-	-	-	-
<155	<25	0	-	-	0	-	-	-	-

MP = milepost; SB = southbound; SSD = stopping sight distance.

Next, models were developed to explain the trends in speeds as a function of visibility and additional variables discussed in the Methods section. Of the several types of speed models used, the combined before-after model at MP 4.4 was found to be most useful for understanding the changes in speeds as a result of the VSL system.

Models were developed using data that were available across both the before and after periods. For the after period, PSL and the interaction of PSL and visibility were found to be the best predictors of speed. For the before period, the only value for PSL was the base posted speed of 65 mph. Although these models yielded R^2 values greater than 0.7, these models were not useful in relating how speeds changed from the before period.

The combined before-after model best illustrated how the VSL system affected SB driver speeds in the corridor. The results of the modeling showed that PSLs were more strongly correlated with mean observed speed than with visibility variables. However, since the pre-VSL activation period had only one PSL of 65 mph and PSLs in the post-activation period were highly correlated with visibility, the PSL variable and interactions were dropped from model building. Unlike McCann and Fontaine's (2016) original model and the VSL algorithm model, the day/night indicator variable was not significant in the after data.

After different variations of the models without variables that were highly correlated were compared, the model equation was selected:

$$Speed = 67.236 - \frac{4242.723}{Vis} - 2518.621 * \frac{VSL}{Vis}$$

where

Speed = mean speed per time interval (mph)

Vis = visibility distance (feet)

VSL = indicator variable, with 1 indicating VSL is active and 0 indicating VSL is inactive.

This model indicates that the presence of the VSL effectively further decreases speeds at similar visibility levels. Table 4 shows that all model parameters were highly significant. With the exception of the day/night variable, the magnitude of the constant and the coefficient of the inverse visibility variable found in this model were similar to those found in McCann and Fontaine's original model (2016) and the VSL algorithm model. Although the adjusted R^2 value was only 0.32, this was similar to earlier efforts used to define the VSL algorithm for previous models (McCann and Fontaine, 2016). The data in the after period were more varied about the model fit than in the before period. The smaller aggregation intervals in the after period (6 minutes versus 10 minutes) may contribute to the noise seen in the after period that weakens the R^2 values. This model implies that when active, the presence of the VSL produces an additional 60% reduction in speeds over what would have occurred based on visibility alone, showing that the VSL does in fact positively affect driver speed reductions.

Table 4. Before-After Model Parameters

Model Element	Coefficients Unstandardized	 Standardized	*t*-statistic	*p*-value
Constant	67.235978		149.382	.000
Inverse visibility	-4242.722554	-0.367	-22.578	.000
VSL × Inverse visibility	-2518.621476	-0.439	-27.069	.000

VSL = variable speed limit.

Figures 12 and 13 show the mean observed speeds during reduced visibility conditions before and after VSL activation at MP 4.4 SB. The SSD safe speed remained constant as a function of visibility. Although mean observed speeds were somewhat noisy as a function of visibility, a downward trend in mean speeds as visibilities decreased can be seen for both the pre- and post-VSL conditions at MP 4.4. Figure 13 shows that speeds generally shifted lower for comparable visibilities in the after period, indicating the VSL had a positive effect. The SSD safe speed line drawn for reference also suggested that speeds in the post VSL activation period aligned more closely to the safe speeds for a given available visibility. Figure 14 shows that the general trend in post-VSL activation average speeds fell below that of the VSL algorithm model. This may indicate that the VSL algorithm can be further refined to align mean speeds more closely to SSD safe speeds.

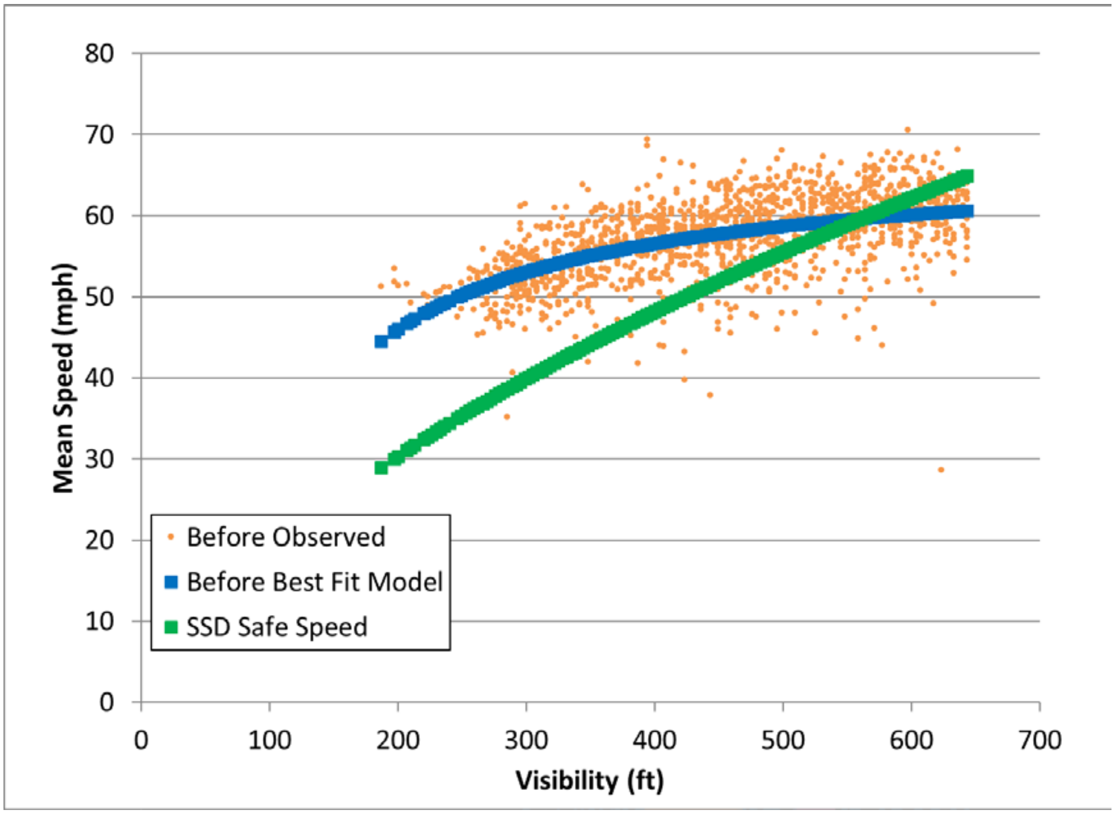

Figure 12. Mean Observed Speeds Before VSL Activation at Milepost 4.4 Southbound. VSL = variable speed limit; SSD = stopping sight distance.

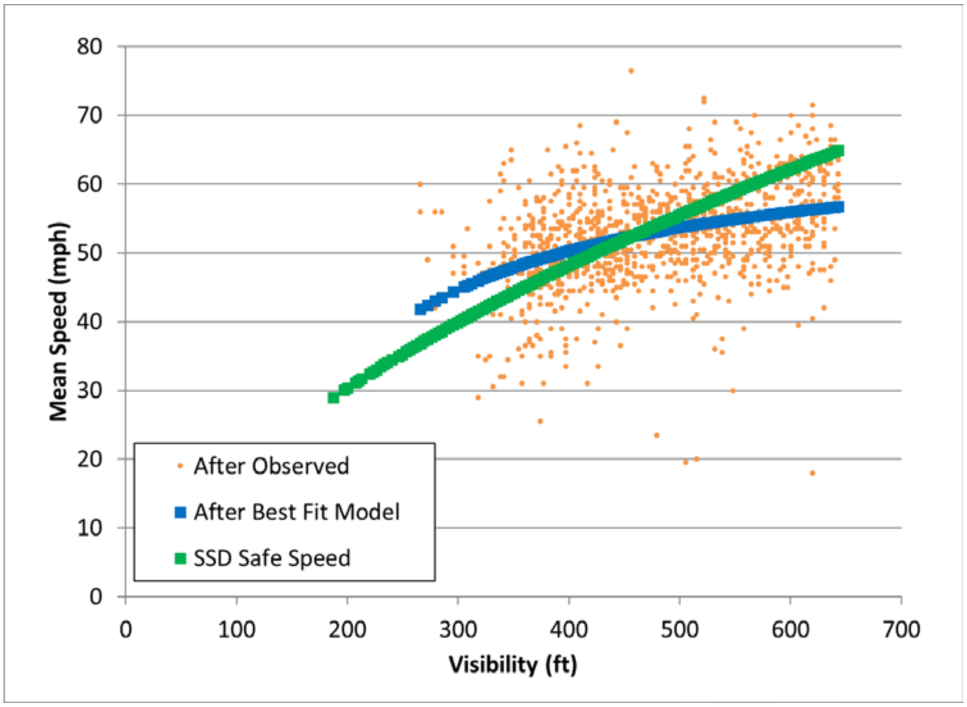

Figure 13. Mean Observed Speeds After VSL Activation at Milepost 4.4 Southbound. VSL = variable speed limit; SSD = stopping sight distance.

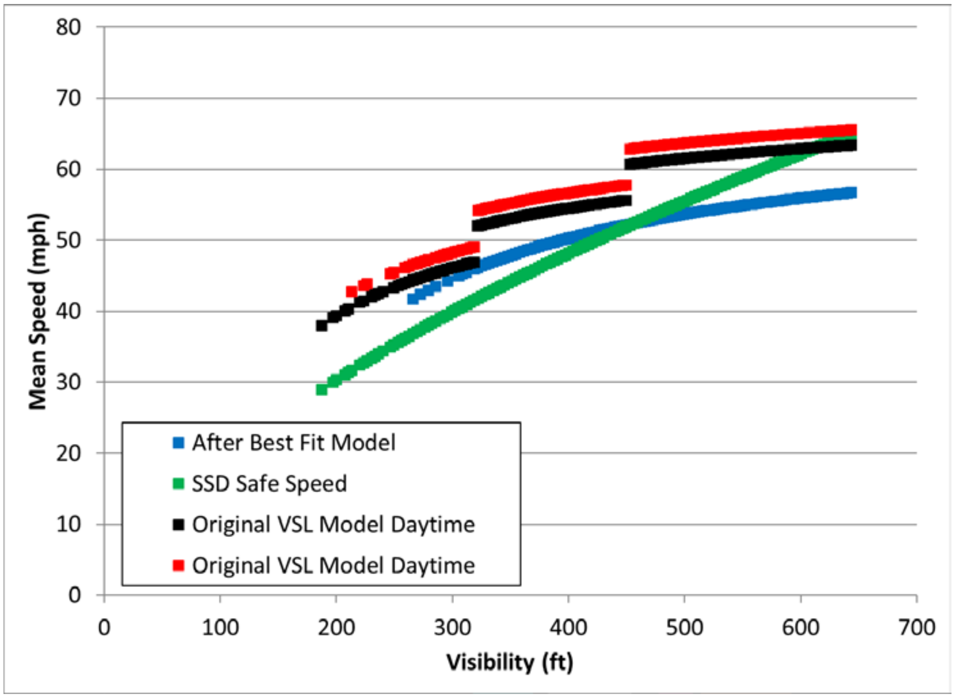

Figure 14. After Speed Model With VSL Algorithm Model for Reference. SSD = stopping sight distance; VSL = variable speed limit.

Speed Changes During Fog Along Corridor

Unfortunately, data were not available continuously along the corridor before VSL activation. As a result, the analysis of speeds along the corridor is limited to a comparison of the observed speeds and posted speeds along the entire site. Tables 5 through 8 provide a summary of how mean speeds differed for various posted speeds along the corridor. The tables summarize mean speeds, counts of intervals where VSLs were posted, differences between the posted speed and mean speed, and standard deviations of speeds by milepost and posted speed along the corridor. In the absence of individual speed data to show compliance, differentials between mean observed speed and posted speeds were included to provide a surrogate picture of compliance. Again, it should be emphasized that the PSLs were sometimes lower than would be justified based on visibility at a specific location because of the way VSLs were stepped down as vehicles moved into severe fog or were grouped to minimize transitions between signs.

Table 5. Mean Observed Speeds by Posted Speed Limit SB

Location (Milepost)			**Posted Speed Limit**							
VSL	**RWIS Station**	**Downstream Speed Sensor**	**65**	**60**	**55**	**50**	**45**	**40**	**35**	**30**
11.6	11.3	11.3	**65.0**	64.8	57.0	59.0	57.4	-	-	-
10.2	9.6	9.7	67.6	62.5	63.5	59.4	-	-	-	-
9.5	9.0	8.8	68.0	64.7	59.2	57.9	49.5	-	-	-
8.1	7.3	7.5	65.7	62.4	60.7	56.4	56.3	50.3	-	42.1
7.2	6.6	6.6	69.1	67.2	62.6	62.2	58.6	57.5	57.3	52.9
5.6	5.3	5.3	66.0	65.5	59.8	60.2	55.8	55.3	52.2	51.3
4.5	4.4	4.4	**65.1**	62.7	58.5	55.6	49.9	48.1	41.4	-
4.5	4.4	4.3	65.5	63.3	58.5	55.1	48.8	45.8	40.3	-
3.4	3.1	3.3	67.9	64.8	58.5	57.1	50.6	49.6	-	-
1.8	1.0	1.0	68.4	64.7	-	-	-	-	-	-

SB = southbound; VSL = variable speed limit; RWIS = road weather information system. Bold type indicates that observed speed was not significantly different from the posted speed limit.

Table 6. Count of Observations by Posted Speed Limit SB

Location (Milepost)			**Posted Speed Limit**							
VSL	**RWIS Station**	**Downstream Speed Sensor**	**65**	**60**	**55**	**50**	**45**	**40**	**35**	**30**
11.6	11.3	11.3	6,209	45	23	28	10	-	-	-
10.2	9.7	9.7	6,153	92	18	29	-	-	-	-
9.5	8.8	8.8	4,625	1,403	142	31	54	-	-	-
8.1	7.5	7.5	3,498	429	577	248	1,368	132	-	56
7.2	6.6	6.6	1,924	649	178	1,029	384	621	24	1,508
5.6	5.3	5.3	1,949	561	191	1,072	388	619	24	1,510
4.5	4.4	4.4	3,130	242	304	427	199	38	12	-
4.5	4.3	4.3	4,173	452	442	763	356	66	21	-
3.4	3.3	3.3	4,450	765	297	688	86	26	-	-
1.8	1.0	1.0	6,204	100	-	-	-	-	-	-

SB = southbound; VSL = variable speed limit; RWIS = road weather information system.

Table 7. Difference Between Mean Observed Speed and Posted Speed by Posted Speed Limit SB

Location (Milepost)			Posted Speed Limit							
VSL	**RWIS Station**	**Downstream Speed Sensor**	**65**	**60**	**55**	**50**	**45**	**40**	**35**	**30**
11.6	11.3	11.3	0.0	4.8	2.0	9.0	12.4	-	-	-
10.2	9.7	9.7	2.6	2.5	8.5	9.4	-	-	-	-
9.5	8.8	8.8	3.0	4.7	4.2	7.9	4.5	-	-	-
8.1	7.5	7.5	0.7	2.4	5.7	6.4	11.3	10.3	-	12.1
7.2	6.6	6.6	4.1	7.2	7.6	12.2	13.6	17.5	22.3	22.9
5.6	5.3	5.3	1.0	5.5	4.8	10.2	10.8	15.3	17.2	21.3
4.5	4.4	4.4	0.1	2.7	3.5	5.6	4.9	8.1	6.4	-
4.5	4.3	4.3	0.5	3.3	3.5	5.1	3.8	5.8	5.3	-
3.4	3.3	3.3	2.9	4.8	3.5	7.1	5.6	9.6	-	-
1.8	1.0	1.0	3.4	4.7	-	-	-	-	-	-

SB = southbound; VSL =variable speed limit; RWIS = road weather information system. Colors indicate the degree of deviation between observed speed and posted speed limit, with green indicating lower differences and red indicating larger differences.

Table 8. Standard Deviations of Observed Speed by Posted Speed Limit SB

Location (Milepost)			Posted Speed Limit							
VSL	**RWIS Station**	**Downstream Speed Sensor**	**65**	**60**	**55**	**50**	**45**	**40**	**35**	**30**
11.6	11.3	11.3	5.4	2.8	1.5	6.6	9.3	-	-	-
10.2	9.7	9.7	4.8	12.0	4.0	12.5	-	-	-	-
9.5	8.8	8.8	6.0	6.2	5.7	10.4	17.5	-	-	-
8.1	7.5	7.5	5.5	5.5	4.4	4.7	5.8	5.8	-	13.7
7.2	6.6	6.6	6.8	4.5	8.7	6.1	6.4	6.0	6.5	7.1
5.6	5.3	5.3	4.7	3.4	3.4	5.2	5.8	6.2	14.1	6.5
4.5	4.4	4.4	3.7	2.5	2.9	3.6	3.3	5.9	8.9	-
4.5	4.3	4.3	4.6	4.0	3.5	4.2	3.3	5.6	7.6	-
3.4	3.3	3.3	4.6	3.6	3.4	5.2	4.4	7.4	-	-
1.8	1.0	1.0	2.8	3.5	-	-	-	-	-	-

SB = southbound; VSL = variable speed limit; RWIS = road weather information system.

Upon entrance to the corridor from the north, for every PSL, mean speeds exceeded the posted speeds, with differences increasing to the highest levels at MP 6.6. After that, downstream speeds started to decrease to speeds below those upon entrance to the corridor. This may suggest that drivers do not follow the reduced speed as closely until they enter the actual fog zone. The reaction to the VSL speeds is more pronounced right before the worst part of the fog zone is exited, after which drivers resume their regular speeds. In general, the difference in observed speeds and posted speeds increased with decreasing posted speed at every milepost, especially at posted speeds below 50 mph. However, compliance with lower limits improved past MP 5.3 SB. This may suggest that drivers will not immediately reduce speeds upon seeing the VSLs and that they must experience some reduced visibility before altering speeds.

In Table 5, the speeds in bold type were not significantly different from the PSL at a 95% confidence level. With a few exceptions, all mean speeds were greater than the posted speeds. Excluding posted speeds of 50 mph, for the first couple of miles upon entrance to the corridor, the average speeds tended to be no more than 5 mph over the PSLs. When posted speeds were below 50 mph, the average speeds tended to be about 10 mph higher than the posted speeds in this zone. As drivers traversed the worst fog zone between MPs 7.5 and 4.4, the difference between mean speeds and posted speeds increased to almost 10 mph above the PSLs. Differentials increased even more for posted speeds below 50 mph. After the fog zone was exited, compliance improved, even for posted speeds below 50 mph, as mean speeds returned to being within 6 mph of the posted speed. With a few exceptions, observed speeds were still within 10 mph of the posted speed after the fog zone was traversed.

Some different trends are apparent when the results from before and after VSL activation at MP 4.4 are compared to these speeds along the corridor. The results from MP 4.4 in Table 3 and Figures 12 and 13 show that speeds declined in each visibility level, although they were still often higher than the SSD safe speed. The results across the corridor, however, indicated that speeds often exceeded the posted VSL, especially at lower values. Speed differentials between the posted VSL and observed speeds were greatest north of MP 5.6, as shown in Table 7. This again may have been because VSLs were being posted as being lower than warranted for a visibility level to transition drivers into the dense fog zone. This can create cases where the visibility at a specific location does not align with the VSL that is posted so as to allow for speed transitions.

Crash Analysis

Crash Frequency and Characteristics

Although McCann and Fontaine (2016) had already performed a 5-year crash analysis with 2010-2014 data, data from 2015 were added to gain additional insight into crash characteristics during the before period. In 2015, 5 of 108 crashes on the corridor were coded as occurring during fog, but only 4 of these were found to have occurred during low visibility conditions. One crash was an injury crash, and 3 were property damage only crashes. One crash involved one vehicle, 2 involved two vehicles, and 1 involved three or more vehicles. Two were rear-end crashes, 1 was a sideswipe same direction crash, and 1 was a non-collision. Overall, the addition of 2015 data to the 2010-2014 average minimally shifted average values, making it a fairly representative year of crash characteristics for pre-VSL activation. Updated crash characteristics for the entire 2010-2015 period are shown in Tables 9 through 11.

Table 9. Before Period Crash Frequency by Visibility Bin and Severity, 2010-2015

Visibility Bin (ft)	Fatal		Injury		Fatal + Injury		Property Damage Only		Total
	No.	**%**	**No.**	**%**	**No.**	**%**	**No.**	**%**	
>645	9	2%	124	22%	133	23%	433	77%	566
All Low Visibility	5	8%	24	39%	29	47%	33	53%	62
495-645	2	20%	4	40%	6	60%	4	40%	10
360-494.9	0	0%	2	29%	2	29%	5	71%	7
250-359.9	1	14%	3	43%	4	57%	3	43%	7
155-249.9	2	5%	15	41%	17	46%	20	54%	37
<155	0	0%	0	0%	0	0%	1	100%	1
Error, No Reading	0	0%	2	50%	2	50%	2	50%	4
All Conditions	14	2%	150	24%	164	26%	468	74%	632

Table 10. Before Period Crash Frequency by Visibility Bin and Number of Vehicles Involved, 2010-2015

Visibility Bin (ft)	No. of Vehicles Involved in Crash						
	1		2		3+		Total
	No.	%	No.	%	No.	%	
>645	302	53%	209	37%	55	10%	566
All Low Visibility	6	10%	29	47%	27	44%	62
495-645	2	20%	5	50%	3	30%	10
360-494.9	2	29%	4	57%	1	14%	7
250-359.9	0	0%	1	14%	6	86%	7
155-249.9	1	3%	19	51%	17	46%	37
<155	1	100%	0	0%	0	0%	1
Error, No Reading	2	50%	2	50%	0	0%	4
All Conditions	310	49%	240	38%	82	13%	632

Table 11. Before Period Crash Frequency by Visibility Bin and Crash Type, 2010-2015

Visibility Bin (ft)	Rear-End		Fixed Object Off Road		Angle		Sideswipe Same Direction		Other		Total
	No.	%	No.	%	No.	%	No.	%	No.	%	
>645	138	24%	213	38%	30	5%	59	10%	126	22%	566
All Low Visibility	39	63%	3	5%	10	16%	7	11%	3	5%	62
495-645	4	40%	1	10%	4	40%	0	0%	1	10%	10
360-494.9	2	29%	0	0%	1	14%	2	29%	2	29%	7
250-359.9	7	100%	0	0%	0	0%	0	0%	0	0%	7
155-249.9	26	70%	1	3%	5	14%	5	14%	0	0%	37
<155	0	0%	1	100%	0	0%	0	0%	0	0%	1
Error, No Reading	1	25%	3	75%	0	0%	0	0%	0	0%	4
All Conditions	178	28%	219	35%	40	6%	66	10%	129	20%	632

Crash analysis for the after period was limited to 11 months of crash data from October 2016–August 2017. Of 89 crashes that occurred on the corridor during this time, 12 were reported to have occurred during times when the VSL was active. There were six crash reports that had weather condition types labeled as fog; one of the crashes occurred outside a VSL activation time. After visibility was matched with the corresponding times and locations of these crashes, only 2 crashes actually occurred in conditions in which visibilities were less than 645 ft. These 2 crashes occurred on December 16, 2016, when visibilities were 155-200 ft during a 54-hour event, one of the longest continuous VSL activations to date. Of these crashes, the first was an injury crash and involved six vehicles, including a tractor trailer. The second was a property damage crash for which it was reported that vehicles “were stopped in traffic due to dense fog and a separate crash ahead” when a rear-end crash occurred. This crash and secondary crash are the common types expected in reduced visibility conditions. Crash characteristics for the after period are summarized in Tables 12 through 14.

Table 12. After Period Crash Frequency by Visibility Bin and Crash Severity, October 2016-August 2017

Visibility Bin (ft)	Fatal		Injury		Fatal + Injury		Property Damage Only		Total
	No.	%	No.	%	No.	%	No.	%	
>645	1	1%	20	23%	21	24%	66	76%	87
All Low Visibility	0	0%	1	50%	1	50%	1	50%	2
495-645	0	0%	0	0%	0	0%	0	0%	0
360-494.9	0	0%	0	0%	0	0%	0	0%	0
250-359.9	0	0%	0	0%	0	0%	0	0%	0
155-249.9	0	0%	1	50%	1	50%	1	50%	2
<155	0	0%	0	0%	0	0%	0	0%	0
Error, No Reading	0	0%	0	0%	0	0%	0	0%	0
All Conditions	1	1%	21	24%	22	25%	67	75%	89

Table 13. After Period Crash Frequency by Visibility Bin and Number of Vehicles Involved, October 2016–August 2017

Visibility Bin (ft)	No. of Vehicles Involved						Total
	1		2		3+		
	No.	%	No.	%	No.	%	
>645	37	43%	39	45%	11	13%	87
All Low Visibility	0	0%	0	0%	2	100%	2
495-645	0	0%	0	0%	0	0%	0
360-494.9	0	0%	0	0%	0	0%	0
250-359.9	0	0%	0	0%	0	0%	0
155-249.9	0	0%	0	0%	2	100%	2
<155	0	0%	0	0%	0	0%	0
Error, No Reading	0	0%	0	0%	0	0%	0
All Conditions	37	42%	39	44%	13	15%	89

Table 14. After Period Crash Frequency by Visibility Bin and Crash Type, October 2016–August 2017

Visibility Bin (ft)	Rear-End		Fixed Object Off Road		Angle		Sideswipe Same Direction		Other		Total
	No.	%	No.	%	No.	%	No.	%	No.	%	
>645	29	33%	28	32%	2	2%	16	18%	12	14%	87
All Low Visibility	2	100%	0	0%	0	0%	0	0%	0	0%	2
495-645	0	0%	0	0%	0	0%	0	0%	0	0%	0
360-494.9	0	0%	0	0%	0	0%	0	0%	0	0%	0
250-359.9	0	0%	0	0%	0	0%	0	0%	0	0%	0
155-249.9	2	100%	0	0%	0	0%	0	0%	0	0%	2
<155	0	0%	0	0%	0	0%	0	0%	0	0%	0
Error, No Reading	0	0%	0	0%	0	0%	0	0%	0	0%	0
All Conditions	31	35%	28	31%	2	2%	16	18%	12	13%	89

Given the small number of crashes during reduced visibility in the after period, it is difficult to assess fully the effect of the system on crashes. Comparing Tables 9 and 12, crash severity by visibility bin during low visibility conditions showed about an even split between fatal and injury crashes and property damage only crashes in both the before and after periods. Although proportions were similar, the low frequency in the after period as compared to the 10 crashes per year average in the before period suggested possible reductions in overall frequency. Crash severity by visibility bin for clear conditions showed that crash severity percentages in the after period remained within ±1% of those in the before period, indicating that overall conditions in the after period were characteristic of the corridor.

The percentages of crashes with different numbers of vehicles involved during low visibility conditions listed in Tables 10 and 13 showed that in the before period, 44% of crashes involved 3+ vehicles versus 100% of crashes in the after period. Similarly, a shift in crash type to all rear-end crashes in the after period occurred. Given that only two crashes occurred in the after period during low visibility, it is difficult to draw conclusions from these data.

Crash Rates

Table 15 provides updated crash rates by visibility for the entire before period. In 2015, 10% of the 10-minute periods were missing visibility data. The 2010-2015 average crash rates were 49.3 and 58.8 crashes per 100 million VMT for the NB and SB directions, respectively. The crash rates for all low visibility conditions were 181 and 854 crashes per 100 million VMT for the NB and SB directions, respectively.

Table 16 provides crash rates for the after period. Since all times when the VSL was not active were assumed to have clear conditions in the after period, there were less visibility data missing than during the before period. The two crashes that occurred happened when visibility was 155-200 ft, and the resulting crash rate of 2,226.6 crashes per 100 million VMT was nearly as large as the 2010-2015 crash rate for the same bin of 2,779.7 crashes per 100 million VMT. However, the overall crash rate during low visibility was lower in the post-VSL period than from 2010-2015, dropping from 854.1 to 366.8 crashes per 100 million VMT in the SB direction. Similar reductions in crash rate were observed for the NB direction. The reduction of crash rate during low visibility conditions indicated that the VSL may have improved safety at the site, although limited data were available to assess post-installation safety effects.

Table 15. 2010-2015 Crash Rates

	No. of Crashes			**Crash Rate**			**% of Total VMT**		
Visibility Bin (ft)	**North**	**South**	**Both**	**North**	**South**	**Both**	**North**	**South**	**Both**
>645	278	288	566	52.9	56.4	54.6	45%	44%	89%
All Low Visibility	12	54	66	181.0	854.1	509.5	0.57%	0.54%	1.11%
495-645	0	10	10	0.0	619.9	302.8	0.14%	0.14%	0.28%
360-494.9	2	5	7	107.4	281.6	192.4	0.16%	0.15%	0.31%
250-359.9	1	6	7	60.0	375.7	214.4	0.14%	0.14%	0.28%
155-249.9	6	31	37	514.3	2,795.7	1,626.0	0.10%	0.09%	0.19%
<155	1	0	1	409.1	0.0	211.7	0.02%	0.02%	0.04%
Error, No Reading	2	2	4	3.5	3.1	3.3	4.83%	5.51%	10.34%
All Visibilities	290	342	632	49.3	58.8	54.0	50%	50%	100%

VMT = vehicle miles traveled.

Table 16. After Crash Rates, October 2016–August 2017

Visibility Bin (ft)	No. of Crashes			Crash Rate			% of Total VMT		
	North	South	Both	North	South	Both	North	South	Both
>645	55	33	88	75.7	45.4	60.6	48%	48%	96%
All Low Visibility	0	2	2	0.0	366.8	165.2	0.44%	0.36%	0.80%
495-645	0	0	0	0.0	0.0	0.0	0.11%	0.12%	0.23%
360-494.9	0	0	0	0.0	0.0	0.0	0.12%	0.10%	0.22%
250-359.9	0	0	0	0.0	0.0	0.0	0.12%	0.08%	0.19%
155-249.9	0	2	2	0.0	2,226.6	885.7	0.09%	0.06%	0.15%
<155	0	0	0	0.0	0.0	0.0	0.00%	0.00%	0.00%
Error, No Reading	0	0	0	0.0	0.0	0.0	1.78%	1.86%	3.64%
All Visibilities	55	35	90	72.3	46.0	59.2	50%	50%	100%

VMT = vehicle miles traveled.

VSL Algorithm Assessment

Given the positive initial results from this deployment, it is possible that the VSL control algorithm could be modified to attain better results. Currently, the VSL algorithm uses a step-adjusted model fit of pre-VSL observed speeds to generate proposed VSLs. These recommendations are then smoothed throughout the corridor and grouped to ensure that successive VSLs cannot decrease by more than 15 mph. The algorithm sets VSLs using a step-adjusted model fit at an intermediate level between previously observed speeds and SSD safe speeds because of a concern that simply posting SSD safe speeds would not adequately alter driver behavior and instead would further increase speed variance and interactions between vehicles under low visibilities. A 15-mph step range between VSL signs, rather than a 10-mph step range, was chosen as it was thought to ensure the message remained credible to motorists (Kimley-Horn, 2015). Although the results showed that the VSL was able to produce reduced speeds in each visibility category, the need to transition vehicles slowly into low speeds in the dense fog areas sometimes may have resulted in lower posted VSLs than necessary based on visibility upstream of the critical fog area. The analysis of speed limits along the corridor indicated that this may have been a source of driver noncompliance with the VSLs.

It seems possible that drivers did not slow down until they encountered the fog. Based on this possible delayed reaction to VSLs, the key to achieving increased compliance across the entire corridor may lie in improving compliance before drivers encounter the worst fog area. Given these trends, there are several ways to reduce non-compliance in the transition zone leading into the fog. First, additional VSL signs could be installed so that speeds could spatially be stepped down more rapidly going into the fog. This would decrease the spatial distance required to alert drivers to the fog, although it would incur additional costs. A second option would be to increase the 15-mph maximum decrease to a higher level. This has the potential to increase speed variance, however, in order to reduce the transition distance into the lower fog speeds. Although both options might improve compliance with VSLs, they both have drawbacks.

A third possible way to improve performance would be to readjust the algorithm to match current behavior better with the VSL in place. Currently, the VSL algorithm uses a 5-mph decrease from the model fit when SSD safe speeds are below 50 and a 10-mph decrease from the model fit when SSD safe speeds are below 40 mph. These boundaries could be shifted to align posted speeds better with observed behaviors. One possibility would involve stepping down 5 mph when the SSD safe speed is 55 mph, with additional 5-mph reductions at SSD safe speeds of 45 and 35. Figure 15 depicts this possible adjusted model. This adjusted model fit would yield speeds closer to the mean observed speeds in the post-VSL period. Since average observed speeds were falling below the current VSL step-adjusted model, this proposed readjusted model should continue to have observed speeds lower than if not equal to the model fit.

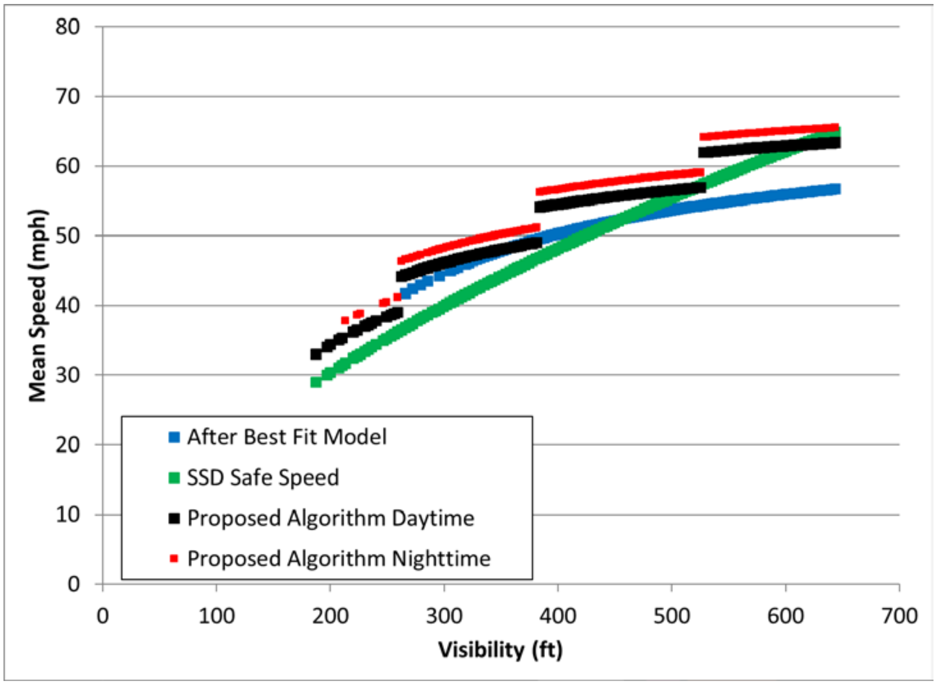

Figure 15. Possible Modification to Variable Speed Limit. SSD = stopping sight distance.

Summary of Results

The results to date showed positive effects on driver speeds during reduced visibility and some early positive indications of safety benefits. A before-after analysis at one site showed statistically significant reductions in speeds across all visibility ranges of approximately 2 to 5 mph for every range. Speed models reconfirmed that speed was inversely correlated with visibility and that the VSL has had a role in further reducing speeds. Although R^2 values were not as strong as with the previous models, there was a trend in decreasing speeds during reduced visibility, and the speeds post-VSL activation were closer to SSD safe speeds.

Speeds throughout the corridor post-VSL activation showed varying driver compliance with posted VSLs along the corridor. Although observed speeds varied by location and posted speed throughout the corridor, it seems possible that drivers did not comply as much with reduced speed limits until they had experienced fog for some time. Further, this may have been tied to the need to transition speeds gradually into reduced speed zones. There may have been a delayed reaction to the VSL until drivers traversed fog and saw the need for reduced speeds. In addition, although speeds did decrease with decreasing PSLs, there remained significant differences between observed and posted speeds when the lowest speed limits were posted.

Despite issues with compliance during low PSLs, the crash analysis for the post-VSL data showed preliminary signs of improvement. The two crashes that were matched to fog conditions occurred back-to-back during a fog event within the first 3 months of activation. The SB crash rate for all low visibility conditions was cut by more than one-half from the before period, although this was based on limited data. When exposure is taken into consideration, this reduced crash rate alone suggests the system has been initially successful in improving safety.

DISCUSSION

Before-after analysis at a single site showed statistically significant reductions in speeds of 2 to 5 mph for reduced visibilities of 250-645 ft. Although ideally a before-after comparison at all locations throughout the corridor would have shown a clearer picture of how speeds changed as a result of the VSLs, having data for the SB location at the edge of the worst fog area gave an indication of how drivers may have reacted at the rest of the locations. Although speeds were still higher than SSD safe speeds at MP 4.4 SB, the combination of reduced speeds and reduced variances implied positive safety changes in the corridor. Regression models related speeds as a function of visibility and showed positive impacts from the VSL at that site. There were no periods of reduced visibilities less than 250 ft, so speeds during dense fog could not be assessed.

Because of limitations in the way data were reported, direct speed limit compliance figures could not be determined. However, a surrogate measure of compliance could be inferred from the differentials between mean observed speeds and posted speeds along the entire corridor. Analysis of speeds along the corridor revealed a seeming lag in reaction to the VSLs; drivers continued to travel above the PSL until they were almost through the fog zone, perhaps until they could visually confirm the sustained need for reduced speeds. Upon entrance to the corridor, differences in mean observed speeds and posted speeds were within 10 mph, and they increased to as much as 23 mph over the posted speeds in the thickest part of the fog, returning to within 10 mph of posted speeds after the densest section was traversed. The possible need to transition from 65 mph to reduced speeds may have resulted in cases where VSLs were posted lower than the visibility at a specific location would dictate, which may have been driving the compliance results upstream of the fog zone.

In addition, analysis of speed along the corridor revealed that compliance was worst at the lowest posted speeds. This was seen prominently with posted speeds below 50 mph between MPs 7.3 and 4.4. If greater compliance can be achieved upstream of the worst fog zone, it is possible that compliance at the lower speed limits can also be improved. Overall, the reductions in mean speeds are an indication that the VSL was achieving the desired effect but could be modified to maximize results. There is an apparent lack of response to VSLs during very dense fog, which is a concern, however.

The 11 months of crash data are not sufficient to allow definitive claims as to the system's effectiveness in improving safety by reducing the overall frequency and severity of crashes. Given that the only fog-related crashes occurred early in the system's activation lifetime and that these events were correlated, the reductions in crash rates are potentially indicative of improved safety under the system. The crash rate for all low visibility bins for the SB direction of 366.8 crashes per 100 million VMT, although still greater during reduced visibilities than in clear conditions, was less than one-half of the crash rate of 854 crashes per 100 million VMT for the years 2010-2015. This may provide an indication that the VSLs are increasing driver awareness of hazards, even if speeds are still higher than desired during fog.

CONCLUSIONS

- *Average vehicle speeds and standard deviations were reduced after VSL activation.* Statistically significant reductions in average observed speeds of 2 to 5 mph and in standard deviations of 1 to 2 mph were observed when visibilities were 250-645 ft at MP 4.4. No visibilities less than 250 ft were available.

- *At low visibilities, speeds were still above the PSL but were closer to SSD safe speeds than before VSL activation.* Reductions in speed were smaller at lower visibilities. However, the combination of reduced speeds and reduced variances implies increased safety in the corridor.

- *Mean speeds in the dense fog zone were higher than desired, but they more closely aligned with posted speeds as drivers exited the zone of densest fog.* Speed compliance as drivers left the areas of dense fog was higher than within the dense fog zone, indicating a possible lag in response to the VSLs. This might be an indication that drivers must travel in reduced visibility for some time before reducing speed. VSLs seemed often to be posted lower than dictated by the visibility at a specific site upstream of a dense fog zone possibly because of the need to transition to lower speeds, which might also negatively affect compliance.

- *Crash rates during low visibility were less than one-half of pre-VSL activation crash rates.* Although this finding was based on limited data, it is a positive early indication that the system is having a positive impact on safety.

- *Based on the speed and safety data analyzed in this study, VSLs are a useful tool to affect speeds positively at locations with frequent reduced visibility events.* The system was able to reduce speed during fog, and preliminary data indicate safety improvements. Although the economic and engineering viability of VSLs would need to be analyzed on a site-by-site basis, the results from I-77 indicate that weather VSLs are a positive countermeasure.

RECOMMENDATIONS

1. *VDOT's SWRO, in consultation with VTRC, VDOT's Traffic Engineering Division, and VDOT's Operations Division, should modify the VSL system to improve compliance.* Now that a full year of VSL operations has passed, these initial findings indicate that the VSL has resulted in reduced speeds, but some compliance issues remain. Alternate speed limit step downs between successive VSL signs, installation of additional signs, or changes in the

algorithm that vary by fog severity may increase the effectiveness of the system. A group should be convened to define additional modifications to the system that should be pursued.

2. *VTRC should schedule a new project to re-evaluate the crash analysis when at least 3 years of after data are available.* This study was limited to the first year of system operations. As time elapses and more data accumulate, larger sample sizes will give more weight to the results of the safety analysis. The safety findings from this study should also establish the return on investment for the project.

IMPLEMENTATION AND BENEFITS

Implementation

With regard to Recommendation 1, VDOT's SWRO will review the findings of this study and this report and convene a group to discuss modifications to the VSL system. The group should consist of representatives from the SWRO, the Traffic Engineering Division, the Operations Division, and VTRC. Recommendations for system modifications from the group, if any, should be developed within 1 year of the publication of this report, with possible implementation of algorithm changes by fall 2019.

With regard to Recommendation 2, VTRC, in cooperation with VDOT's SWRO, will conduct a study of the crashes on the corridor when at least 3 years of after data are available. The results of that crash analysis will be used to define the return on investment of the project. The calculation will include operating costs in addition to crash costs that reflect the skew toward multiple-vehicle crashes during fog. A technical assistance project will be conducted, with results available in spring 2020.

Benefits

The results of this study showed that the I-77 VSL system created some positive changes in driver speeds, although insufficient crash data have accumulated to determine impacts on safety conclusively. Speed reductions during fog were observed versus pre-installation conditions, although some evidence indicates that drivers may not decelerate substantially during dense fog until they have traveled in it for some time. The results show that VSLs can have positive impacts for weather-related safety issues and indicate that systems such as this may be beneficial at other locations with similar problems.

The benefits of implementing Recommendation 1 are that further reductions in speed may be possible, given the positive initial findings. This could further improve the safety benefits of the system.

The benefits of implementing Recommendation 2 are that a quantitative effect of the VSL system on safety could be established. This would permit a fuller accounting of the benefits and return on investment of the system, which could possibly be used to help establish the economic viability of other similar projects.

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