Investigation of Driver Speed Choice and Crash Characteristics During Low Visibility Events

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Abstract:

In Virginia, sections of I-77 and I-64 in mountainous parts of the state have significant recurring fog events. These locations have also been the sites of several chain reaction crashes involving more than 50 vehicles during fog. These crashes were typically caused by drivers traveling too fast for the visibility conditions. To improve safety on the I-77 corridor, the Virginia Department of Transportation constructed a variable speed limit (VSL) system that posts dynamic speed limits based on the visibility condition. As of April 2016, the system was undergoing pre-deployment testing. Before the system was activated, it was important to understand existing driver speed choice behavior during low visibility conditions. It was possible that posting a VSL speed based only on the stopping sight distance (SSD) could create significant speed variance and decrease safety if drivers were driving much faster than conditions would warrant. In this study, crash, speed, and visibility data were examined at several locations on I-64 and I-77 where there were recurring fog events.

The crash history for I-77 revealed that crashes during low visibility conditions were more likely to be severe and involve more than two vehicles than crashes during clear conditions. Mean speed analysis found that observed mean speeds exceeded safe speeds for all low visibility conditions and at all sites. In the worst visibility conditions, drivers often exceeded the safe speed by more than 20 mph. Standard deviation analysis found that speed variance did not increase as visibility decreased on I-77, but for several locations on I-64, the standard deviation was different during low visibility when compared to clear conditions.

Models were developed to allow a better understanding of the relationship between speed and visibility. The models showed that although motorists reduce their speeds in low visibility, there is still a significant differential between observed speeds and the safe speed calculated using the SSD. The models showed that speeds for I-64 were much less sensitive to changes in visibility compared to I-77. A possible explanation for this difference is the presence of illuminated in-pavement markers on I-64. The improved delineation provided by these markers during foggy conditions may cause drivers to perceive less of a need to reduce speed during limited visibility. It is also possible that mean speeds in low visibility conditions are higher on I-64 because of the regular commuters who may be more comfortable driving during foggy conditions.

The observed driver behavior from this study is being used as a basis for the VSL control algorithm that is being implemented in the field. A primary concern of the operators of the VSL system is that it will not be heeded by all motorists and thus will result in increased speed variance in foggy conditions. The developed model was used to create a VSL control algorithm to help bridge the gap between current driver behavior and safe speed. It is recommended that future VSL system deployments reflect existing driver behavior in the initial algorithms as well. After VSL activation, speed and crash data for I-77 should be analyzed to determine the operational and safety effects of the system. If the system on I-77 reduces the frequency and severity of crashes, improves speed limit compliance, and reduces speed variance, a similar system should be developed for I-64 using the current driver behavior models from this study as part of the initial algorithm.

FINAL REPORT

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ABSTRACT

In Virginia, sections of I-77 and I-64 in mountainous parts of the state have significant recurring fog events. These locations have also been the sites of several chain reaction crashes involving more than 50 vehicles during fog. These crashes were typically caused by drivers traveling too fast for the visibility conditions. To improve safety on the I-77 corridor, the Virginia Department of Transportation constructed a variable speed limit (VSL) system that posts dynamic speed limits based on the visibility condition. As of April 2016, the system was undergoing pre-deployment testing. Before the system was activated, it was important to understand existing driver speed choice behavior during low visibility conditions. It was possible that posting a VSL speed based only on the stopping sight distance (SSD) could create significant speed variance and decrease safety if drivers were driving much faster than conditions would warrant. In this study, crash, speed, and visibility data were examined at several locations on I-64 and I-77 where there were recurring fog events.

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INTRODUCTION

Reduced visibility created by fog can create a significant safety hazard, particularly on high-speed roads. From 2001 to 2008, there was an average of approximately 20,000 annual police-reported crashes during fog in the United States (Hamilton, et al., 2014). Fog crashes also accounted for around 2% of all fatal crashes that occurred between 1990 and 2012 (Hamilton et al., 2014). Studies have shown that crashes in fog tend to involve multiple vehicles and have a higher percentage of fatalities and injuries than crashes in clear conditions (Hamilton et al., 2014). Fog is often unpredictable and fast setting, which can make it difficult for transportation agencies to address safety issues created by fog. Until recently, there have been relatively few engineering countermeasures that could address safety during foggy conditions.

In Virginia, several interstate locations have recurring fog events that have led to severe multi-vehicle crashes. In most cases, police reports indicated that drivers were traveling too fast for conditions during these crashes. For example, dense and unpredictable fog on I-77 near the Virginia–North Carolina border can create dangerous driving conditions for motorists, which are exacerbated by a steep downhill grade. On March 30, 2013, there was a 95–car, chain reaction crash with three fatalities during a fog event at this site (Associated Press, 2013).

Variable speed limit (VSL) systems are a type of intelligent transportation system technology that dynamically sets speed limits based on roadway conditions. Weather-controlled VSL systems use atmospheric data to calculate a safe driving speed that is displayed on VSL signs. Typically, these systems are used to improve safety in winter weather or low visibility conditions. Several VSL systems have been installed in the United States and abroad including systems in The Netherlands (Hogema and van der Horst, 1994), Tennessee (Jensen, 1995), Alabama (Goodwin, 2003a), Utah (Perrin et al., 2003), and Nevada (Robinson, 2002) that are visibility controlled. Very little quantitative analysis has been performed to evaluate the effectiveness of these systems, although most systems were deemed to improve safety qualitatively.

An Active Traffic & Safety Management System (ATSMS) was recently installed on I-77 in Fancy Gap, Virginia, with the goal of improving safety and operations during low visibility events. As of April 2016, the system was undergoing testing and was not yet operational. A primary component of the ATSMS is a VSL system that will calculate a safe speed given the conditions and display it to motorists on full color dynamic message signs (DMSs). This ATSMS will serve as a pilot for weather-controlled VSL systems in Virginia. An understanding of driver behavior in foggy conditions is needed to develop a VSL control algorithm. Concerns are that if a VSL system is not heeded by all motorists, speed variance may increase. If the I-77 ATSMS is effective, additional systems may be considered at other fog-prone locations, such as I-64 over Afton Mountain in Afton, Virginia.

PURPOSE AND SCOPE

The purpose of this study was to evaluate safety and driver behavior on I-77 in Fancy Gap, Virginia, and on I-64 over Afton Mountain in Afton, Virginia, to aid in the development of the VSL algorithm for the ATSMS on I-77. The specific objectives of this study were as follows:

1. Determine the impact of low visibility on safety by examining crash data and other safety surrogate measures during fog at these two sites.
2. Determine how driver speed and speed compliance vary as a function of weather conditions at both sites.
3. Using this information on driver behavior in fog, develop recommendations for the I-77 VSL control algorithm.

The study objectives were accomplished by collecting traffic, visibility, and crash data for I-77 in Fancy Gap before the ATSMS was installed and for I-64 in Afton.

METHODS

Literature Review

Studies relevant to the study scope were identified and reviewed. Relevant studies were identified by searching research indexed by the Virginia Transportation Research Council library and the Transportation Research Board TRID database. First, studies that examined changes in crash characteristics and risk during fog were reviewed. These included empirical studies of observed changes in crashes and driving simulator studies that assessed changes in driver behavior. Second, deployments of VSL systems for weather-related events were reviewed. Quantitative data and lessons learned from these deployments were synthesized to determine important issues related to future VSL deployments in Virginia.

Site Characteristics

Sites on I-77 in Fancy Gap and on I-64 in Afton were reviewed.

I-77 in Fancy Gap

I-77 in Fancy Gap is a four-lane divided freeway with a posted speed limit of 65 mph. The section studied had a 2014 annual average daily traffic (AADT) of approximately 18,000 vehicles per day in each direction, with trucks representing 27% of this traffic. The site is rural, and the Virginia Department of Transportation (VDOT) Southwest Region Operations (SWRO) indicated that this site has a relatively large proportion of through drivers unfamiliar with the corridor. They noted large volumes of through traffic traveling from Ohio to North Carolina and South Carolina as being particularly prevalent. The grade is approximately 4%, with the peak of the mountain near Milepost (MP) 8. Figure 1 shows a map of the study area on I-77.

In February 2014, VDOT awarded a $7.5 million contract to G4S Technologies to construct the I-77 ATSMS. The system was originally expected to be operational in the summer of 2015. Because of construction delays, the system had not yet become operational as of April 2016, although the infrastructure had largely been installed.

Figure 1. I-77 Study Area

A primary component of the I-77 ATSMS is the VSL system. Various sign types will be installed to alert motorists when the VSL system is in use. New weather sensors were installed to supplement the existing sensors to provide denser coverage in the project area. A list of the system components is provided in Table 1 (McDonald, 2015).

Weather information is collected throughout the corridor via 14 Vaisala Road Weather Information System (RWIS) stations. The RWIS stations continuously collect pavement temperature and condition, air temperature, humidity, pressure, precipitation type and intensity, wind speed and direction, and visibility. The visibility sensors are mounted 20 feet in the air and use the forward scatter measurement principle to measure the meteorological optical range (Vaisala, 2015). Visibility is measured over a few inches and extrapolated to estimate a visibility distance in feet. Figure 2 shows the locations of the RWIS stations. RWIS stations are located at MPs 1.2, 1.8, 2.7, 3.05, 4.4, 5.3, 6.6, 7.3, 9.0, 9.6, 11.3, and 16.9.

Safe speeds will be displayed on full color DMSs and VSL cutout signs along the corridor. All speed limit signs are dual mounted in each direction. There are eight VSL cutout signs dual mounted at MP 1.3 and MP 11.6 Northbound (NB) and MP 10.2 and MP 1.8 Southbound (SB). A map of the VSL signs is shown in Figure 4. In the NB direction, full color DMSs are dual mounted at MPs 1.3, 2.4, 3.5, 4.6, 5.6, 6.5, 7.6, 8.1, 9.2, and 10.2, and in the SB direction full color DMSs are dual mounted at MPs 3.4, 4.5, 5.6, 6.5, 7.2, 8.1, 9.5, and 11.6. Figure 5 shows an example of what the full matrix signs will look like when they are activated.

Although the contractor G4S was responsible for installing the physical infrastructure of the ATSMS, the algorithm to control the VSL was undefined. VDOT formed a VSL technical advisory committee composed of staff of VDOT's SWRO, VDOT's Traffic Engineering Division, VDOT's Operations Division, Kimley-Horn and Associates, and the Virginia Transportation Research Council (VTRC) to develop a control algorithm. The final algorithm used to develop speed limits in low visibility conditions was developed as part of a collaborative effort by the VSL technical advisory committee. The VSL algorithm developed relied heavily on results from this study.

Table 1. I-77 ATSMS Components

Component	Description	Quantity
Type 1 DMS	Full Size Walk-in DMS	6
Type 2 DMS	Arterial DMS	3
Type 3 DMS	Corridor Entry DMS	4
Type 4 DMS	Full Color Matrix DMS VSL Display	36
VSL Signs	Static Speed Limit Sign with VSL Cutout	8
Traffic Sensors	Wavetronix	22
CCTV Cameras	Pelco PTZ Dome	25
RWIS	Vaisala (PWD10/12)	14
Flashers	Static Signs with Flashers	12
Power	Redundant Power System	12 miles
Communications	Fiber Optic Network with Leased Backup	14 miles
UPS	6 hour battery backup at each device	-

Source: McDonald, 2015.
ATSMS = Active Traffic & Safety Management System; DMS = Dynamic Message Sign; VSL = variable speed limit; CCTV = closed circuit television; RWIS = road weather information system; UPS = uninterruptible power supply

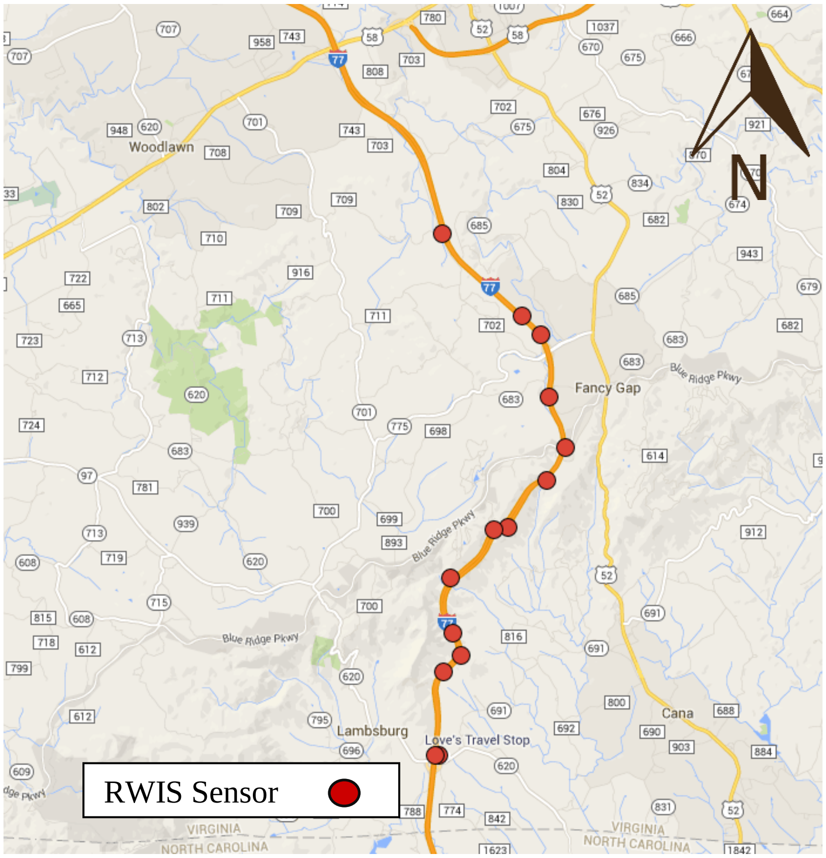


Figure 2. Map of RWIS Visibility Stations for I-77


Figure 3. Vaisala Forward Scatter Visibility Sensor

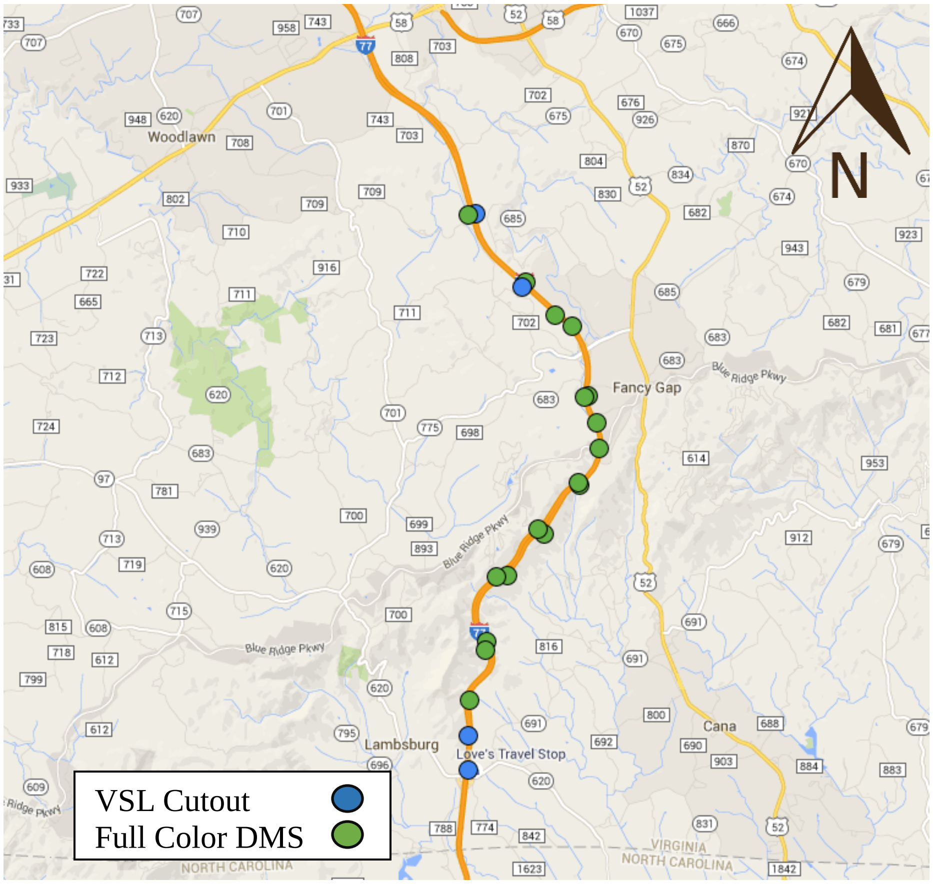


Figure 4. Planned VSL Sign Locations for I-77

Figure 5. Full Color Dynamic Message Sign

I-64 in Afton

I-64 in Afton is a four-lane divided freeway with a posted speed limit of 65 mph. The 2014 AADT was approximately 17,000 vehicles per day in each direction, with trucks representing 9% of this traffic. In contrast to I-77, the Afton site is located at the top of a mountain pass, with the peak occurring around MP 100. There were two data collection sites in each direction of travel, and these sites were located near the midpoint of most fog events. The grade in the eastbound (EB) direction approaching the peak is approximately +2.9% and the grade in the westbound (WB) direction approaching the peak is approximately +4.2%. This site has a high volume of regular commuter traffic according to VDOT's Northwest Region Operations (NWRO). Figure 6 shows the study area on I-64.

A unique feature of the I-64 site is that in-pavement amber warning lights have been installed along the left and right edge lines of the roadway between approximately MPs 98 and 104. Figure 7 shows an example of the lights. The lights are activated by VDOT's Staunton Traffic Operations Center when visibility drops below 1,400 feet and are intended to improve delineation during fog.

Figure 6. I-64 Study Area

Figure 7. Fog Lights on I-64 Over Afton Mountain

Data Collection and Processing

Traffic and weather data were collected on the ATSMS Corridor on I-77 in Fancy Gap and on I-64 in Afton (Figure 8). This section describes the data that were available and the methods used to clean and process the data prior to analysis.

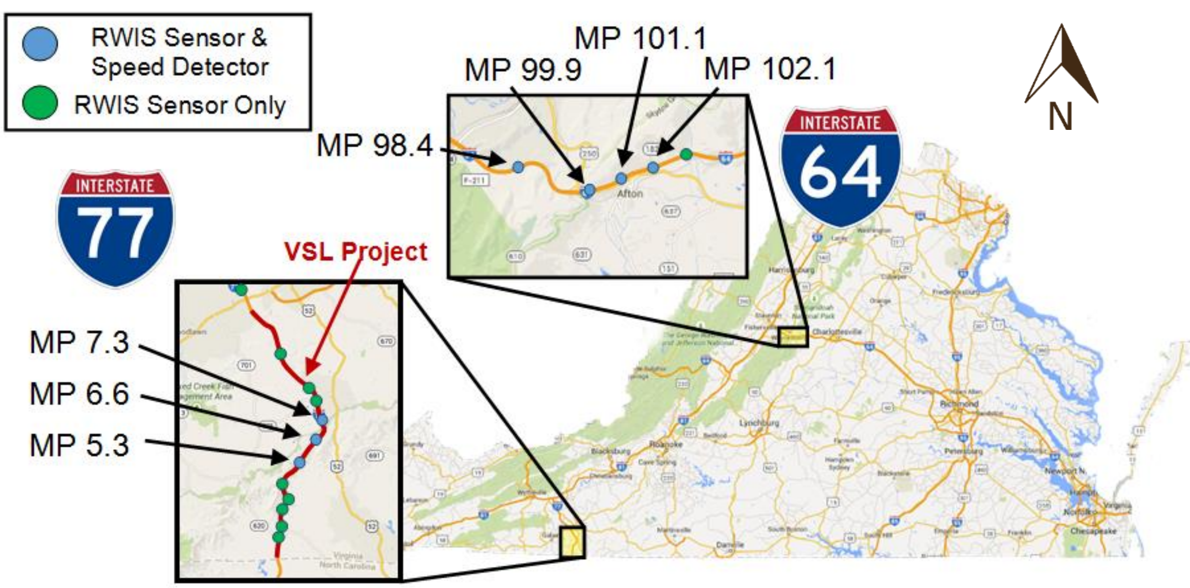


Figure 8. Map with Data Collection Locations

Visibility Data

I-77 in Fancy Gap

The site has RWIS stations at 12 locations over approximately 16 miles, providing a dense network of visibility readings along the corridor. Vaisala RWIS stations with visibility sensors were 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. The visibility sensors used the forward scatter measurement principle to measure the meteorological optical range (Vaisala, 2015). Visibility measurements were provided in feet, and information on precipitation type and road surface condition was also collected. Visibility data were collected every 10 minutes, and sensors were located 20 feet above the surface of the road. The data from these sensors were archived by Vaisala on an external website that could be queried by the researchers.

I-64 in Afton

On I-64, Vaisala RWIS stations were also present, but they were configured slightly differently than on I-77, which resulted in measurements being recorded at different frequencies at this site. Visibility data were collected from the fog light visibility sensors every minute at MPs 98.4, 101.1, 102.1, and 103.1 and every 5 minutes at MP 99.9. The sensors on I-64 were the same as the sensors on I-77. The data were stored locally at VDOT's Staunton Traffic Operations Center, and only a limited data archive was available for analysis in this study. Visibility data were available from July 1, 2014, to December 31, 2014, with approximately 420 hours of low visibility data collected during this period. To be consistent with the analysis for I-77, only the visibility data collected every 5th minute were saved and matched with the 5-minute speed data.

Crash Data

All police crash reports were compiled from VDOT's Roadway Network System using the date ranges for when visibility data were available from the RWIS sensors. The "weather conditions" field on the police report was used to identify crashes that occurred in fog, and the conditions were verified using the visibility data from the RWIS sensors. The crash data were used to examine whether the frequency, rate, or characteristics of crashes along the corridor varied by visibility condition. For I-77 crashes, data were collected from January 1, 2010, to December 31, 2014, between MPs 0 and 15. For I-64 crashes, data were collected from July 1, 2014, to December 31, 2014, between MPs 97 and 103.

Speed and Volume Data

I-77 in Fancy Gap

Speed data were collected by temporary Wavetronix side-fire radar installations at MP 5.3, MP 6.6, and MP 7.3 adjacent to the RWIS stations. At each location, traffic data were recorded in 5-minute bins for vehicles traveling in the SB lanes of I-77. Only the SB lanes were monitored since all major crash events have occurred on the SB, downhill portion of the site.

The data collected by the detectors included volume by vehicle class, mean speed, and 85th percentile speed. Speed and weather data were matched using timestamps. Because the weather data were reported every 10 minutes and speed data were reported every 5 minutes, visibility was linearly interpolated between 10-minute readings to get estimated visibility data in 5-minute intervals. The Wavetronix readers were initially installed in September 2014. When low visibility periods were observed from the RWIS stations, corresponding speed data were collected from the speed stations. Speed and visibility data were available for 10 low visibility events between September 2014 and March 2015, representing approximately 180 hours of data. Speeds were also collected for two 3-day periods in November and December 2014 to represent behavior in clear conditions.

I-64 in Afton

In contrast to I-77, permanent speed stations were present in the study corridor on I-64. Speed data were collected in 1-minute bins using permanent Wavetronix devices mounted on the same poles as the visibility sensors at MPs 98.4, 99.9, 101.1, and 102.1. Volume-weighted speeds were calculated for 5-minute periods and matched with the visibility data by timestamp. The MP 101.1 EB, MP 102.1 EB, and MP 98.4 WB sites are on a downhill grade; the MP 102.1 WB, MP 101.1 WB, MP 99.9 EB, and MP 98.4 EB sites are on an uphill grade. The MP 99.9 WB site is located on a downhill grade just downstream of the peak of Afton Mountain, so vehicles have not begun to pick up downhill momentum with respect to mean speed. Speed data were collected continuously for 6 months from July 1, 2014, to December 31, 2014, to match the available visibility data. The maximum recorded visibility value was 2,000 feet, which was dictated by the sensor hardware. For the analysis, speed recorded during visibility periods recorded as 2,000 feet represents behavior in clear conditions. Speed recorded during visibility periods between 645 and 2,000 feet were not used in the analysis, so clear condition data were not influenced by periods of medium visibility surrounding low visibility events.

Categorization of Data by Stopping Sight Distance Safe Speed

A safe speed based on stopping sight distance (SSD) was determined for different visibility categories. This allowed actual operating speeds to be contrasted with a theoretical safe speed for various densities of fog. For this analysis, any visibility measurement below 645 feet was considered "low visibility." This threshold corresponds to a safe speed of 65 mph calculated from the SSD assuming a flat grade and a 2.5-second perception-reaction time. I-77 and I-64 have a 65 mph posted speed limit, so there should theoretically be no need to reduce speed when visibilities exceed 645 feet. A flat grade was assumed in this analysis so that visibility categories would remain constant for uphill and downhill sections, although obviously downhill sections would require longer SSDs in reality. A safe speed was determined using the following SSD equation, substituting visibility measurements for SSD and solving for V.

$$SSD = 1.47 \times V \times 2.5 + \frac{1.075 \times V^2}{11.2\ ft/s^2}$$

where

SSD = stopping sight distance (feet)

V = speed (mph).

Observation of the speed data suggested that driver speeds do not vary with visibility above the 645-foot threshold. Visibility was further divided into bins according to the SSD safe speed, as shown in Table 2. Bins of a 10-mph width were used to ensure that sample sizes were large enough in each bin for statistical analysis. These bins were used to analyze driver behavior by severity of low visibility. It is worth noting that the I-64 fog lights were activated for visibilities below 1,400 feet, which would correspond with a technically safe speed of more than 100 mph based on SSD.

Table 2. Safe Speeds by Visibility Bin

Bin Range	Safe Speed	
≥645 ft	65 mph	Clear Conditions
495-644.9 ft	55 mph	Low Visibility
360-494.9 ft	45 mph	
250-359.9 ft	35 mph	
155-249.9 ft	25 mph	
<155 ft	<25 mph	

Data Analysis

Visibility Profiles

Visibility data were compiled from the RWIS stations to determine the frequency and magnitude of fog events. For I-77, yearly visibility was averaged for the years 2010 to 2015. For I-64, visibility data were compiled from July 1, 2014, to December 31, 2014. Visibility was assigned based on the safe SSD analysis bins, and for I-77 the average hours of low visibility each year were calculated for each RWIS station. Hours of low visibility were summed for I-64 for the 6-month period.

Crash Analysis

Crash Frequency and Characteristics

Crashes were matched with visibility data so that crash characteristics in varying degrees of low visibility could be compared to crashes in clear conditions. Crash severity, collision type, and number of vehicles involved in the crash were all tabulated for easy comparison of the proportions of crashes by visibility bin. This was done to examine how fog density affected crash occurrence and type, which had not been examined in other studies. Full analysis was performed for 5 years of crashes on I-77. Because of the limited availability of visibility data for I-64, crash analysis is discussed qualitatively for the 6-month period when visibility data were available. Crashes for which the police indicated fog was present were examined for the full 5-year period on I-64, but there were no visibility data archived that could be used to validate the officer's assessment.

Crash Rate Analysis

Crash rates on the corridor were calculated for I-77 using visibility and crash data from 5 years prior to the activation of the ATSMS (2010 to 2015). Since real-time volume data were not available throughout the corridor, hourly volume profiles were determined using available short-term counts, which were assumed to represent the typical temporal distribution of travel on I-77 for all days. The yearly AADT was multiplied by this hourly distribution to get an estimated hourly AADT for a given day in each analysis year. Visibility data were used to calculate the hourly breakdown of visibility in each visibility bin. The vehicle miles traveled (VMT) were then calculated by multiplying hourly AADT by the hours of visibility throughout the year recorded in that bin in that hour of the day. Finally, each of the 24 hourly VMTs was summed to get the VMT for each of the analysis years. The crashes were each assigned a visibility and placed in the appropriate bin. Since this site is in a rural area and does not have great variability in traffic, this approach was expected to provide a reasonable estimate of VMT, but it does not account for changes in travel that may occur because of poor weather conditions. If travel is reduced during poor visibility, then the crash rates calculated may be higher than what was determined during low visibility periods. Because only 6 months of visibility data were available for I-64, crash rates were not calculated for that study area.

Driver Speed Choice Behavior

Speed Analysis

Crashes are an obvious indicator of safety, but because they are random events it may be difficult to get a large enough sample to draw meaningful conclusions, particularly when the analysis is focused on fog events. Alternatively, mean speed and standard deviation of speed can be used as a surrogate indicator to evaluate safety. Mean speed was calculated for each visibility bin at all collection sites. Hypothesis testing was done to determine whether there was a statistically significant difference between the mean speed for each low visibility bin and the mean speed during clear conditions. The null hypothesis, H_0, was that the mean speed for each low visibility bin is equal to the mean speed for clear conditions. Z-tests with an alpha value of 0.05 were used in this testing. Z-tests were also applied to examine the difference in speed between the right and left lane, termed the lane speed differential. Further hypothesis testing using an F-test was performed to compare the speed variance for each low visibility bin to the speed variance for clear conditions. The null hypothesis, H_0, was that the speed variance for each low visibility bin was equal to the speed variance for clear conditions. An alpha value of 0.05 was used to determine the $F_{critical}$ value.

At MP 6.6 on I-77 and MPs 89.4 and 102.1 on I-64, vehicles speeds were collected in 5-mph bins. For data from these sensors, standard deviation of speed, coefficient of variation, and pace speed were calculated for each visibility bin. For each 5-minute observation, the number of vehicles exceeding the safe speed based on the SSD was used to measure compliance with safe speed by visibility condition. The pace speed, which is defined as the 10-mph range with the largest number of observations, was also determined. The pace speed and the percentage of vehicles traveling in the pace were examined to assess the consistency in travel speeds. Finally, mean speed by lane for each visibility bin was calculated to determine trends in driver behavior that might be masked when mean speeds are calculated across both lanes. At other data collection sites, only aggregate mean and standard deviation values were available and no information on the distribution of speeds was collected. As a result, these analyses could not be performed at other locations.

Modeling of Mean Speed as a Function of Visibility

The data were analyzed to determine if a relationship between observed mean speed and visibility could be established. The mean speed per 5 minutes was identified as the dependent variable for the data analysis. Independent variables considered included visibility (in feet), total vehicular volume per 5 minutes, truck volume per 5 minutes, day or night, and site location. Site location and day/night were modeled using binary indicator variables. Transformations of these variables were also investigated. Precipitation rate, precipitation type, temperature, and interaction combinations of these variables were also considered as independent variables; however, none proved to be a statistically significant predictor of speed.

Stepwise linear regression was performed using these independent variables. Stepwise regression is an iterative process that adds and removes independent variables one at a time into and out of the model. Independent variables are removed from the model if they have a significance value greater than 0.05. For each site, the adjusted R^2 model fit values, average absolute error and bias, and visual inspection of the model fit and the residuals were used to evaluate individual models. Different candidate models were created by summarizing the data based on direction of travel, individual sensor site, and whether the traffic was traveling uphill or downhill at a specific location. Ultimately, although some individual models performed better than others, the models combining all data for each site provided the best representation of the datasets.

The I-64 dataset was further analyzed with a generalized linear model. This allowed for hypothesis testing to compare the effects of visibility and site on mean speed. This analysis was performed on the I-64 dataset only because of the apparent insensitivity of speed to visibility and high variation in the I-64 linear regression model.

RESULTS AND DISCUSSION

Literature Review

Crash Characteristics in Fog

Most safety studies of fog examined aggregate safety impacts without differentiating between fog densities. One recent study reviewed two decades of crashes during low visibility conditions throughout the United States. The crash analysis examined fatal crashes from 1990 to 2012 collected from the Fatality Analysis Reporting System and all crash severities using data from the National Automotive Sampling System General Estimates Systems between 1990 and 2008 (Hamilton et al., 2014). The crash analysis found that, in general, the raw number of fatal crashes in fog had decreased over the study period (Hamilton et al., 2014). Possible explanations for this trend include improvements in weather monitoring and driver alert systems, changes in crash coding, and overall improvements in vehicle safety. Since the study did not account for changes in exposure, it is also possible that there were fewer foggy days over time. The analysis supported the common belief that fog crashes are often likely to involve multiple vehicles. According to the study, 20% of fatal crashes involving 10 or more vehicles and 4.5% of crashes involving 6 to 9 vehicles occur in fog (Hamilton et al., 2014). The study concluded that although fog crashes are a small percentage of overall crashes, crashes are more likely to occur in low visibility conditions than in clear conditions and that these crashes are more likely to be serious and involve multiple vehicles (Hamilton et al., 2014). There were several limitations with this crash analysis, however. There was no attempt to correct for exposure in terms of VMT or days of exposure to different conditions. Further, there was no analysis of the severity of the fog, so light fog and dense fog were not differentiated. Crash trends and characteristics may vary by the severity of the visibility reduction.

A study of crashes in Florida from 2003 to 2007 looked at various factors that might contribute to fog and smoke crashes such as lighting, posted speed, number of lanes, median type, and driver age (Abdel-Aty et al., 2011). Odds ratios were calculated to examine crash type and severity for fog and smoke crashes compared to crashes in clear conditions. This analysis revealed that crashes in fog or smoke were more likely to involve a fatality or severe injury and involve multiple vehicles than crashes in clear conditions. Head-on crashes were found to be the most likely crash type for fog or smoke crashes; however, this dataset included undivided roadways and divided highways. The study also did not examine the severity of the visibility reduction.

Several other studies looked at raw numbers of crashes in fog compared to crashes in clear conditions; however, no analysis was performed with regard to crash cause or characteristics (Goodwin, 2002, 2003b). One study of crashes in fog and other adverse weather conditions focused on economic impacts and mitigation techniques but did not look at contributing factors (Pisano et al., 2000).

Driver Behavior in Fog

Driving simulator studies have often been used to assess changes in behavior during foggy conditions. Studies of driver behavior in fog revealed that drivers are not able to perceive their speed accurately because of the decrease in contrast in their surroundings (Snowden et al., 1998). This leads to speeds that are much higher than the appropriate safe speed for the conditions. Another driving simulator study tested drivers' ability to stay in their lane and maintain their speed under varying degrees of low visibility (Brooks et al., 2011). The study concluded that drivers would choose a speed that allowed them to stay in their lane effectively; however, driver speeds were often greater than a SSD safe speed given the visibility. Another driving simulator study found that headways decreased in the worst fog conditions (Kang et al., 2008).

A study of driving behavior in low visibility was conducted between December 1995 and April 1996 on I-84 in Southeast Idaho (Liang et al., 1998). The study found that there was a reduction in mean speed during low visibility conditions from 66 mph to 61 mph but an increase in speed variance. This suggests that drivers naturally reduce their speed if they perceive a need to do so even without any external information or warning systems. However, the study used data from only 2 days of low visibility and 1 day of clear conditions at a single location. Further, the severity of the fog event was not characterized.

Weather-Controlled VSLs

Tables 3 and 4 summarize the description, findings, and limitations from all reviewed weather VSL systems. There have been several deployments of visibility-controlled VSL systems in the United States and abroad. The basic components of these systems are the same: VSL signs controlled by a central computer at an operations center, weather detection stations collecting visibility information, and vehicle sensors continuously collecting vehicle speeds. However, very little quantitative analysis has been performed on these systems. VSL systems on I-10 in Alabama (Goodwin, 2003a) and I-75 in Tennessee (Jensen, 1995) were not evaluated quantitatively but rather qualitatively; the studies reported that safety improved with respect to crashes and speed. A VSL system installed on I-80 in Nevada was not evaluated because of malfunction in the sensors and operation of the system (Robinson, 2002).

VSL systems on A16 in The Netherlands (Hogema and van der Horst, 1994) and on I-215 in Utah (Perrin et al., 2003) were studied to measure their effectiveness; however, neither study looked at crashes or speed compliance, only the mean speed as a function of visibility. The study on the A16 system concluded that the presence of the VSL system caused the mean speed to decrease by 8 to 10 km/h (5 to 6 mph) in visibility of 35 meters (115 feet) or greater; however, in visibility less than 35 meters, the mean speed was less when the system was not present (Hogema and van der Horst, 1994). Further, the vehicle speeds decreased as visibility decreased at approximately the same rate with and without the VSL system present (Hogema and van der Horst, 1994). A study of the I-215 system concluded that mean speed along the corridor increased by 15% and the standard deviation of speed decreased because of the VSL system (Perrin et al., 2003). However, it is possible that the addition of another lane of highway had a greater influence on driver speeds than the introduction of the VSL signs. In addition, the VSL signs on I-215 were advisory as opposed to regulatory, which could also influence driver compliance (Perrin et al., 2003).

Table 3. Summary of Reviewed Visibility-Controlled VSL Systems

Location of VSL Implementation	Description of System	Major Findings	Limitations
Alabama: I-10(Goodwin, 2003a)	• Manually activated fog system on 7.5-mile bridge • Step-function visibility thresholds for speed limits: 660-900 ft—65 mph 450-660 ft—55 mph 280-450 ft—45 mph 175-280 ft—35 mph <175 ft—Road closure	• Control operators observed decreased speeds and Alabama DOT reported improved safety	• No quantitative analysis available
Nevada: I-80 (Robinson, 2002)	• Two VSL signs in each direction approaching fog problem area • Algorithm to determine speed using 85th percentile speed, visibility, and roadway surface condition • Fully automated with regulatory speed limit	• Study could not be conducted because of visibility sensor issues	• No reported system evaluation
Oregon: I-5 and US-97 (Kimley-Horn, 2014)	• Fog, congestion, surface condition • Fully automated advisory VSL signs spaced 1.5 miles • Combination of visibility and grip factor • Reduced visibility is <500 ft, no further visibility bins	• No report of effects	• No report of effects
Tennessee: I-75 (Goodwin, 2003a; Jensen, 1995)	• 10 VSL signs, manually activated for fog • Step-function visibility thresholds for speed limits: 480-1320 ft—50 mph 340-480 ft—35 mph <240 ft—Road Closure	• Reduction of fog-related crashes	• No quantitative analysis • No speed data or any baseline comparison
Utah: I-215 (Perrin et al., 2003)	• Fog system with advisory VSLs • 2-mile corridor with VSL signs on each end of corridor • Step-function visibility thresholds for speed limits: 492-656 ft—50 mph 328-492 ft—40 mph 197-328 ft—30 mph <197 ft—25 mph	• Decrease in spread of vehicle speeds when VSL system used • Mean speed increased by 15% • Cautious drivers sped up rather than aggressive drivers slowing down to comply with recommended speed	• No crash analysis • No analysis of compliance
The Netherlands: A16 (Hogema and van der Horst, 1994)	• Fog • 12-km corridor • Step-function visibility thresholds for speed limits >140 m—100 km/h 70 m-140 m—80 km/h <70 m—60 km/h	• Mean speed 8 to 10 km/h less with system than without it in visibility >35 m • In visibility <35 m, mean speeds greater with system than without it	• Control road used for comparison • No crash analysis • Lowest speed limit was 60 km/h • No before and after data

Table 4. Summary of Reviewed Weather-Controlled VSL Systems

Location of VSL Implementation	Description of System	Major Findings	Limitations
Maine: I-95 (Belz and Garder, 2010)	• Snow/rain • VSL signs that can be set at any speed • Only a 45 mph speed was used during study period • Manually activated, only Maine State Police has authority to turn on system	• Variable speed limit had little no effect on driver speeds	• Only 45 mph speed limit was tested • Only 13 days used for analysis • Sometimes the 45 mph speed limit was displayed during clear conditions • No control scenario • System not automated
New Jersey Turnpike (Goodwin, 2003a; Robinson, 2002)	• Snow/rain system for 150-mile corridor • VSL system in place since 1960s • 120 VSL signs • Regulatory speed limit • Manually activated by TOC operators who decided appropriate speed limit	• New Jersey Turnpike Authority thought system improves daily operations and safety	• No formal test of system • Would be difficult to do comparison analysis with before data or control road
Washington: I-90 (Goodwin, 2003a; Ulfarsson et al., 2002)	• Snow/rain/ice system for 40-mile corridor • 13 dynamic message signs with VSLs • Manually activated • Automated speed limit calculation by computer	• Decrease in mean speed • Increase in speed variance	• No breakdown of weather type or severity • Only 1 experimental site very close to end of corridor • No speed compliance analysis
Wyoming: I-80 (Buddemeyer et al., 2011)	• Snow/rain/ice • 52-mile corridor • Manually activated • Speed limit determined by Wyoming Highway Patrol	• Driver speeds lowered 0.47 to 0.75 mph for every 1 mph of speed limit reduction • Significant factors for driver speed are surface condition, wind speed, dew point, and visibility	• Sensors and VSL signs spread out, not representative of entire corridor • No good before data for weather and speed for comparison
Finland: E18 (Rämä, 1999)	• Snow/rain • 14-km corridor • 36 VSL signs • Weather collection stations and speed sensors	• Decrease in mean speed and standard deviation of speed • Percentage of headways less than 1 second decreased • Most effective with undetectable adverse weather	• Control road used for comparison, 100 km away, no before data • Low volume roadway • Data matched using weather conditions • No fog-related weather events
Sweden: E6 (Lind, 2007; Lindkvist and Landerfors, 2008)	• Snow/rain/ice • 55-km corridor • Conditions classified by coefficient of friction with corresponding reduced speed limit	• 12 to 20 km/h decrease in mean speeds during ice/very slippery road surface conditions • No significant speed difference in less severe weather	• System not automated • Speed analysis at only one location • Limited crash and compliance analysis

Gaps in Previous Research

From the literature review it is clear that there are several gaps in the previous research with regard to driver behavior and safety during limited visibility. Although a few studies looked at crashes in low visibility, relatively limited research has been conducted regarding the causes and characteristics of crashes during fog. Several studies examined raw numbers of crashes by type and severity, but fog was treated as a homogenous condition and varying intensities of fog were not examined. This is likely due to a lack of detailed visibility data for the crash locations. With regard to driver behavior, a majority of the research was performed using driving simulators as opposed to collecting data in the field. Given the rarity and unpredictability of fog, it is not surprising that many more driving simulator studies have been performed. The availability of visibility data required for meaningful field research is a major barrier. The I-84 study in Idaho (Liang et al., 1998) looked at only 2 days of low visibility with driver speeds. Very few field evaluations of crashes and driver behavior in varying degrees of low visibility with and without the presence of VSL systems have been conducted. Data availability was again the primary barrier because of the amount of visibility, speed, and crash data needed for this type of analysis.

The current study fills some of these gaps. Speed and visibility data were available across multiple locations on I-77 in Fancy Gap and on I-64 in Afton during low visibility and clear conditions. This availability of data allowed for more in-depth modeling than was seen in previous research and a better understanding of safety as a function of the severity of visibility conditions.

I-77 in Fancy Gap

Visibility Profiles

Figure 9 shows the visibility profile for the I-77 study section using all data from 2010 to 2015. The purple line shows the percentage of time the RWIS sensor was reporting reduced visibility once invalid readings were removed from the analysis. Figure 9 shows that the distribution of fog varied spatially along the corridor. The worst visibility occurred between MPs 4.4 and 7.3, with MP 6.6 having reduced visibility for more than 5% of the year on average. The proportion of very severe fog events was also highest at MP 6.6. At MP 6.6, visibility was less than 360 feet during 60% of fog events. This percentage was 50% at MP 5.3 and 47% at MPs 4.4 and 3.0. Thus, even within this relatively short corridor, the characteristics of fog varied substantially. This indicates that treating fog as a homogeneous condition may not be appropriate.

Every station had problems with missing data. The RWIS station at MP 3.0 was off-line for all of 2013, and the RWIS station at MP 2.7 did not collect any visibility data in 2015. Averaging the amount of missing data each year revealed that several sites had more problems than others. The RWIS station at MP 4.4 had the most missing data with an average of 23% missing per year. The stations at MPs 1.8, 6.6, 9.0, 9.6, and 11.3 performed the best with less than 10% missing data a year on average.

There was some variability in the amount of fog from year to year, but the spatial distribution of fog was relatively consistent over the 5-year study period. Examination of the low visibility distribution at each site from year to year revealed that MP 6.6 had the most low visibility conditions every year. Low visibility at MP 6.6 ranged from 4.01% in 2010 to 7.13% in 2013. This variability was also typical of the other sites. Across all sites, 2010 had a combined 920 hours of low visibility, and 2013 had 2,355 hours of low visibility. The other sites had 1,646, 1,614, 1,180, and 998 hours of low visibility in 2011, 2012, 2014, and 2015, respectively. The relationships between the amount of low visibility recorded at each site were consistent year to year, so variability between years is likely a function of a given year being foggier or less foggy than another.

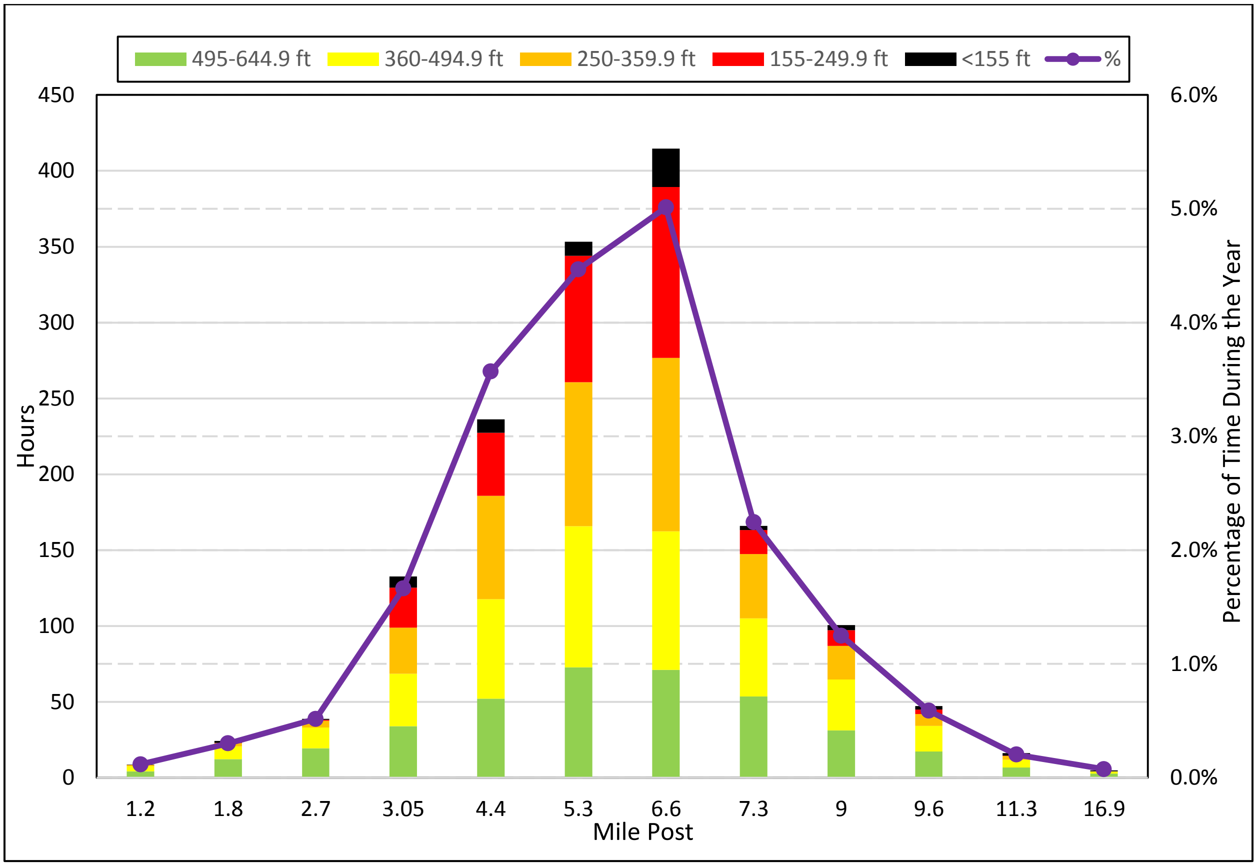


Figure 9. I-77 Average Annual Visibility Profile.

Crash Analysis

Crash Frequency and Characteristics

To represent the crash distribution before the installation of the ATSMS, police crash reports were analyzed from 2010 to 2014 on I-77 between MPs 0 and 15. The 5-year crash history revealed 524 total crashes with 77 "fog" crashes coded on the police crash report. Each crash was assigned a visibility reading by the matching of data from the RWIS stations with the use of the timestamp and MP listed on the crash report. Linear interpolation between stations and 10-minute readings was used to estimate the visibility associated with each crash.

After the matching was performed, 58 crashes could be associated with visibility measurements less than 645 feet, representing 11% of the total crashes during this time period. Since fog was always present at MP 6.6 during fog events, this indicated that crash likelihood was higher than would be expected based purely on the amount of time fog was present in the corridor (approximately 5.0% of the time), as shown in Figure 9. It also meant that 19 of the 77 crashes for which police recorded "fog" on the crash report actually occurred during periods when no visibility reduction was measured by the RWIS stations. Although it is possible that a time lag between crash occurrence and police arrival on the scene may have contributed to this discrepancy, these 19 crashes generally occurred during time periods when visibility exceeded 645 feet for some time before and after the crash time stamp. This indicates an inconsistent definition and interpretation of fog by reporting officers versus what is measured at RWIS stations.

The 58 crashes occurred on only 10 distinct days, all of which were between September and May. Of these crashes, 49 occurred in the SB direction and 9 in the NB direction. Rear-end collisions were the most common crash type, consisting of 37 crashes (63.8%). There were 5 fatal crashes and 23 injury crashes. Ten crashes occurred when visibility was 495-644.9 feet, 5 crashes each occurred when visibility was 360-494.9 feet and 250-359.9 feet, and 1 crash occurred when visibility was less than 155 feet. The remaining 37 crashes all occurred when visibility was 155-249.9 feet. The high proportion of crashes when visibility was 155-249.9 feet can be explained by the crash dates: 26 crashes occurred on March 23, 2013, and 5 crashes occurred on September 21, 2013, accounting for 31 of the 37 crashes in this visibility range. A review of the low visibility crashes found that 42 of the 58 crash descriptions on the police reports used the phrase "slow or stopped traffic ahead." Several of these descriptions mentioned traffic stopped for an accident ahead. Thus, it appears that many of these crashes were secondary collisions created by reduced visibility coupled with traffic that was unexpectedly stopped because of prior crashes.

Table 5 shows the breakdown by crash severity on I-77 for crashes during clear conditions and fog. The table shows that fatal and injury crashes made up a greater proportion of crashes during fog versus clear conditions, which is supported on a larger scale in the study by Hamilton et al. (2014). During reduced visibility, fatal and injury crashes were almost twice as common as they were during clear conditions (48% versus 25%). The proportion of injury and fatal crashes showed no clear trend across the visibility categories, so there is no indication of increasing likelihood of fatal or injury crashes as fog gets more severe. No statistical testing of proportions was done given the small sample size.

Table 5. Crash Severity for I-77 Crashes by Visibility Bin: 2010-2014

Visibility Bin	Fatal (No. and % of Crashes)		Injury (No. and % of Crashes)		Fatal + Injury (No. and % of Crashes)		Property Damage Only (No. and % of Crashes		Total
≥645 ft, 65 mph	9	2%	105	23%	114	25%	348	75%	462
All low visibility	5	9%	23	40%	28	48%	30	52%	58
495-644.9 ft, 55 mph	2	20%	4	40%	6	60%	4	40%	10
360-494.9 ft, 45 mph	0	0%	2	40%	2	40%	3	60%	5
250-359.9 ft, 35 mph	1	20%	2	40%	3	60%	2	40%	5
155-249.9, 25 mph	2	5%	15	41%	17	46%	20	54%	37
<155 ft, <25 mph	0	0%	0	0%	0	0%	1	100%	1
Error, no visibility information	0	0%	2	50%	2	50%	2	50%	4
All conditions	14	3%	130	25%	144	27%	380	73%	524

Hamilton et al. (2014) also found that a high proportion of fatal crashes in fog involved multiple vehicles. The data from I-77 suggest a similar trend. Table 6 shows the number and percentage of crashes by visibility bin and number of vehicles involved. Table 6 indicates that in clear conditions, only 47% of crashes on the corridor involved multiple vehicles. During fog, this number increased to an average of 91%. The percentage of crashes involving 3 or more vehicles was more than 4 times greater during foggy versus clear conditions (45% versus 10%). The proportion of multi-vehicle crashes appears to have increased as visibility decreased. When visibility was 360-644.9 feet, approximately 80% of crashes involved more than one vehicle. This increased to 97% when visibility was 155-359.9 feet. Only one crash occurred when visibility was lower than 155 feet, and it involved only one vehicle.

Table 7 shows the breakdown by crash type for fog crashes and crashes during clear conditions. Rear-end crashes represent 64% of fog crashes compared to 25% of crashes during clear conditions. This trend coincides with the finding of increased multi-vehicle crashes shown in Table 6. Not surprisingly, the proportion of rear-end crashes appears to have been greater as visibility decreased. Although the likelihood of rear-end crashes was higher overall during fog, it appears that the risk of rear-end crashes was particularly high as the safe speed dropped below 45 mph.

Table 6. Number and Percentage of I-77 Crashes by Number of Vehicles Involved and Visibility Bin: 2010-2014

	No. and % of Vehicles Involved in Crash						
Visibility Bin	**1**		**2**		**3+**		**Total**
≥645 ft, 65 mph	246	53%	172	37%	44	10%	462
All Low Visibility	*5*	9%	27	47%	26	45%	*58*
495-644.9 ft, 55 mph	2	20%	5	50%	3	30%	10
360-494.9 ft, 45 mph	1	20%	3	60%	1	20%	5
250-359.9 ft, 35 mph	0	0%	0	0%	5	100%	5
155-249.9 25 mph	1	3%	19	51%	17	46%	37
<155 ft, <25 mph	1	100%	0	0%	0	0%	1
Error, no visibility information	2	50%	2	50%	0	0%	4
All Conditions	253	48%	201	38%	70	13%	524

Table 7. I-77 Crash Type by Visibility Bin: 2010-2014

Visibility Bin	Rear End (No. and % of Crashes)		Fixed Object–Off Road (No. and % of Crashes)		Angle (No. and % of Crashes)		Sideswipe–Same Direction (No. and % of Crashes)		Other (No. and % of Crashes)		Total
≥645 ft, 65 mph	116	25%	178	39%	23	5%	45	10%	100	22%	462
All Low Visibility	37	64%	3	5%	10	17%	6	10%	2	3%	58
495-644.9 ft, 55 mph	4	40%	1	10%	4	40%	0	0%	1	10%	10
360-494.9 ft, 45 mph	2	40%	0	0%	1	20%	1	20%	1	20%	5
250-359.9 ft, 35 mph	5	100%	0	0%	0	0%	0	0%	0	0%	5
155-249.9 25 mph	26	70%	1	3%	5	14%	5	14%	0	0%	37
<155 ft, <25 mph	0	0%	1	100%	0	0%	0	0%	0	0%	1
Error, no visibility information	1	25%	3	75%	0	0%	0	0%	0	0%	4
All Conditions	154	29%	184	35%	33	6%	51	10%	102	19%	524

Crash Rate

Although the crash frequency analysis provided some insight into crashes in fog, it did not control for exposure in any way. Some fog events occurred during low volume traffic and overnight hours, and others occurred during the day. To address this, crash rates were calculated per 100 million VMT and are shown in Table 8. This analysis showed that in worsening visibility conditions, the crash rates increased. Crash rates when safe speeds were less than 65 mph were more than 8.5 times the crash rates during clear conditions. The crash rates were greater in the SB direction than in the NB direction, which was expected given the downhill grades in the SB direction and the high truck percentages at the location with the worst visibility. Although the general trend toward greater crash rates in low visibility compared to clear conditions is likely reliable, the magnitude of some of the calculated rates was driven by the relatively small sample size of crashes. In particular, the crash rates for the 25 mph safe speed bin were a function of a large number of crashes occurring during a few, very severe fog events.

Although this analysis showed that fog was correlated with higher crash rates, the analysis had several limitations. Crash times and locations were taken from the police reports that are recorded at the scene following a crash. The accuracy of the time and location had a large effect on the visibility value assigned to the crash and thus which visibility bin it was placed in for the crash rate calculation. This analysis assumed a linear relationship in visibility between weather sensors and between 10-minute sensor readings.

Another limitation was that real-time volumes were not available continuously throughout the corridor. Average hourly volume profiles were used to create estimates of AADT by hour, which may deviate from the actual values for the site. This was expected to be a minor concern, however. If volumes had dropped during fog, then the crash rates would be even higher than what is shown in Table 8.

Table 8. Crash Rate by Visibility Condition for I-77, 2010-2014

	No. of Crashes			Crash Rate (Crashes/100 Million VMT)		
Visibility Bin	**North**	**South**	**Both**	**North**	**South**	**Both**
≥645 ft, 65 mph	231	231	462	66.8	69.1	67.9
All Low Visibility	9	49	58	175.3	1000.5	578.1
495-644.9 ft, 55 mph	0	10	10	0.0	879.3	429.3
360-494.9 ft, 45 mph	1	4	5	73.3	307.0	187.4
250-359.9 ft, 35 mph	1	4	5	74.5	311.3	190.4
155-249.9 25 mph	6	31	37	591.5	3213.3	1869.6
<155 ft, <25 mph	1	0	1	448.7	0.0	232.4
No Visibility Information	2	2	4	6.0	4.8	5.3
All Conditions	242	282	524	63.0	74.0	68.5

Driver Behavior

Speed Analysis

The mean speeds at each station by visibility bin are shown in Table 9. The N column represents the number of 5-minute speed observations included in each bin. Table 9 shows an overall trend that speeds decreased as visibility decreased but that speeds were often far greater than the SSD speed, particularly for the lowest visibility bins. Hypothesis testing at a confidence level of $\alpha = 0.05$ revealed that the mean speed for each low visibility bin was statistically different than the mean speed during clear conditions for all cases even though it exceeded the SSD speed.

For each 5-minute speed observation, the speed differential between lanes was calculated by subtracting the right lane speed from the left lane speed. The differentials were aggregated in the same manner as the mean speeds and are shown in Table 10. Sample sizes differed from those in Table 9 because periods that did not have traffic in both lanes were discarded.

Increased speed differentials during reduced visibility could indicate safety concerns because of potential conflicts between vehicles in adjacent lanes. Hypothesis testing at a confidence level of $\alpha = 0.05$ revealed that the mean speed differential for the 495-644.95 feet and the 250-359.9 feet bins were not statistically different than the mean speed differential for clear conditions at MP 5.3. The mean speed differential for the 360-494.9 feet and 155-249.9 feet bins were statistically different than the mean speed differentials for clear conditions at MP 5.3. The mean speed differentials for all low visibility bins were statistically different from those for clear conditions at MP 6.6. This suggested that in low visibility, drivers in the right lane were reducing their speeds and drivers in the left lane were maintaining their speed. An increased speed differential between lanes points to a potential safety concern. At MP 7.3, mean speed differential for visibility bins less than 495 feet were not statistically different from those for clear conditions. These results imply inconsistent effects by site, although there were pronounced increases in differentials at the location that is prone to the worst fog events, i.e., MP 6.6.

Table 9. I-77 Mean Speed by Visibility Bin

	I-77 Southbound					
	MP 5.3		MP 6.6		MP 7.3	
Visibility Bin	**N**	**Speed (mph)**	**N**	**Speed (mph)**	**N**	**Speed (mph)**
≥645 ft (65 mph)	445	68.6	1322	66.7	849	65.7
495-644.9 ft (55 mph)	398	58.2	273	62.0	104	56.0
360-494.9 ft (45 mph)	480	55.8	448	61.0	98	51.6
250-359.9 ft (35 mph)	189	49.6	729	57.6	22	49.9
155-249.9 ft (25 mph)	15	47.2	738	51.2	0	-
<155 ft (<25 mph)	0	-	9	44.3	0	-

Table 10. I-77 Speed Differential Between Lanes by Visibility Bin

	MP 5.3		MP 6.6		MP 7.3	
Visibility Bin	**N**	**Mean Speed Differential (mph)**	**N**	**Mean Speed Differential (mph)**	**N**	**Mean Speed Differential (mph)**
≥645 ft (65 mph)	443	3.15	1318	5.16	849	3.84
495-644.9 ft (55 mph)	397	3.21	270	7.39	104	4.92
360-494.9 ft (45 mph)	480	3.59	442	7.70	98	3.87
250-359.9 ft (35 mph)	187	3.36	715	7.22	22	3.14
155-249.9 ft (25 mph)	14	6.61	701	6.54	0	-
<155 ft (<25 mph)	0	-	2	-1.10	0	-

More detailed speed analysis was performed using the 5-mph binned speed data available for MP 6.6 and shown in Table 11. Standard deviation of speed is sometimes used as a surrogate measure of safety since it represents the variability of speeds on a road. It appears that the standard deviation remained relatively consistent with visibility condition. Hypothesis testing at $\alpha = 0.05$ revealed that the standard deviation speed for every low visibility bin was not significantly different than the standard deviation of speed for clear conditions. At approximately 9 mph, the standard deviation was higher than expected for an interstate highway, but this might be a result of the steep grade and heavy truck traffic in the SB direction. Thus, there is no evidence that variability in speeds increased as visibility declined.

Since mean speeds declined as visibility dropped, the coefficient of variation might be a better measure of the dispersion of speed data since it accounts for the amount of variation relative to the mean speed. The coefficient of variation appears constant between visibility from 250 feet to 645 feet and then increases in visibility of less than 250 feet. This potentially indicates a higher likelihood of severe interactions between vehicles at these severely reduced visibilities.

Compliance with the SSD may also provide an indicator of safety across visibility levels. For all reduced visibility bins, at least 74% of drivers exceeded the SSD safe speed. For the lowest visibility bin, nearly every vehicle exceeded the SSD safe speed. The same trend was apparent with the percentage of vehicles traveling within 10 mph of the SSD safe speed. In fact, for SSD safe speeds of 45 mph or less, more than 90% of vehicles exceeded the SSD safe speed and more than 71% traveled more than 10 mph above the SSD safe speed.

Figure 10 shows the aggregate distribution of vehicle speeds for each visibility category using data from all fog events since September 2014 at MP 6.6. The distribution appears relatively consistent for visibilities between 360 and 645 feet. For visibilities less than 360 feet, the profile for each subsequent lower visibility bin shifts to the left. For each of these bins, the peak also appears increasingly spread out. This is reflected by the percentage of vehicles traveling the pace speed, as shown in Table 11. During clear conditions, nearly 50% of vehicles traveled in the 10 mph pace. Under the worst visibility category, about 38% of vehicles traveled in the 10 mph pace. This spreading of the peak would likely increase interactions between vehicles traveling at different speeds, which could create negative safety effects.

The speed analysis results reinforce the crash analysis results presented earlier. As fog became more severe, the differences between the safe speed and the observed travel speeds increased. Since drivers were "over-driving" the available visibility, this may lead to increased conflicts between vehicles and more rear-end and multi-vehicle crashes. The speed data also support the finding that safety concerns increased when visibility dropped below a 35 to 45 mph safe speed. Additional attention to driver performance and behavior in those conditions appears to be warranted.

Table 11. I-77 Speed Profile Characteristics

Visibility Bin	SSD Safe Speed	N	Mean Speed (mph)	Standard Deviation (mph)	Coefficient of Variation	Pace Speed	% of Vehicles Traveling in Pace Speed	Percent Vehicles	
								>SSD	>SSD + 10 mph
≥645 ft	65 mph	1,322	66.7	8.70	0.13	65-75 mph	49%	N/A	N/A
495-644.9 ft	55 mph	250	61.7	9.37	0.16	60-70 mph	44%	74%	33%
360-494.9 ft	45 mph	404	60.7	9.11	0.15	60-70 mph	43%	92%	71%
250-359.9 ft	35 mph	683	57.5	8.99	0.16	55-65 mph	44%	98%	87%
155-249.9 ft	25 mph	737	51.2	9.09	0.18	50-60 mph	38%	98%	92%
<155 ft	<25 mph	9	44.3	9.39	0.22	45-55 mph	38%	99%	91%

SSD = stopping sight distance.

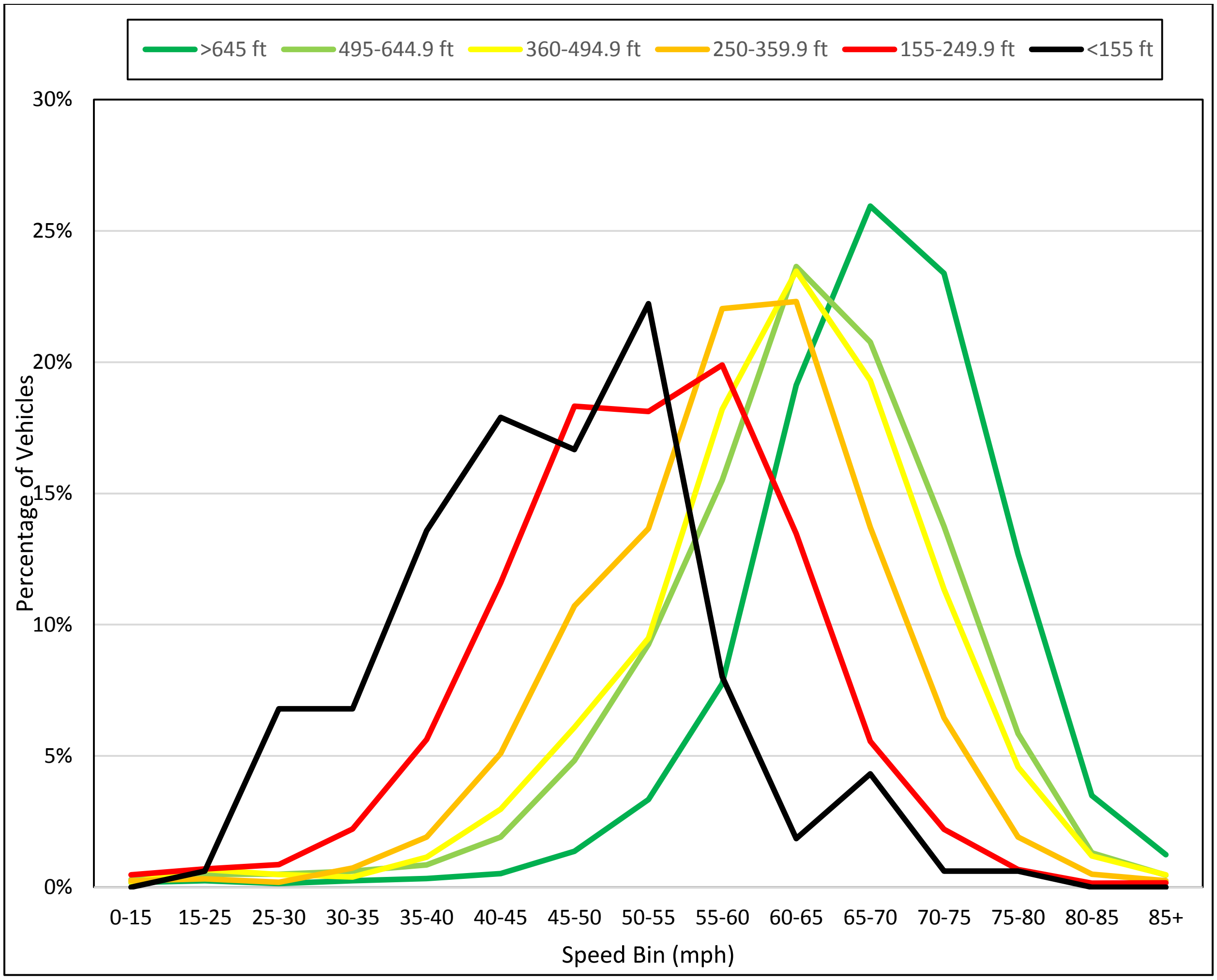


Figure 10. I-77 Speed Profiles

Speed/Visibility Models

Speed models were developed to relate the mean speed per 5 minutes to site characteristics. This was intended to provide an explanatory model that could be used to help illustrate how drivers reacted to lower visibilities before implementation of the VSL system on I-77 and was not intended to be transferable across sites. During the modeling process, several trends emerged:

- Mean speed was negatively correlated with the inverse of visibility distance.
- Volumes at the sites were typically far below capacity during fog events, and no significant relationships between speed and traffic volumes were detected.
- The day/night indicator variable typically showed slight reductions in mean speed during overnight hours.

- Site indicator variables were often significant, which captured specific geometric conditions at the location.

The final model for I-77 is shown by the following equation:

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

where

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

All variables selected were significant at $\alpha = 0.05$, and all other regression assumptions were met for the models. Since this model was intended simply to describe observed characteristics at the sites, 100% of the data were used for model development. Given the influence of site-specific variables, this model cannot be directly transferred to another location. That being said, the model does provide some important information about the relative sensitivity of driver speed choice to visibility on I-77.

Table 12 shows the model statistics. The p-values are less than 0.05 for all of the coefficients, indicating that they are significantly different than 0. Precipitation type, precipitation intensity, temperature, and factor interactions were also tested but were not found to be significant. It was also important to consider the practical significance of each coefficient to determine if the model made physical sense. The coefficient on the inverse of visibility variable is −4204. This sign and magnitude makes sense because as visibility decreases, driver speed also decreases. The inverse transformation of this variable affects the rate at which the speed increases or decreases with a change in visibility. The coefficient value of 1.13 on the day/night variable indicates that driver speeds were approximately 1 mph greater during the day than at night, which is intuitive. The coefficient value of 6.07 on the MP 6.6 site variable indicates that drivers were traveling approximately 6 mph faster at MP 6.6 than at MP 5.3 under the same visibility condition. The coefficient value of −2.67 on the MP 7.3 site variable indicates that drivers were traveling approximately 2.7 mph slower at MP 7.3 than at MP 5.3 under the same visibility condition.

Examination of the standardized coefficients helps show the relative importance of the different factors in generating the mean speed prediction. The standardized coefficient shows that the transformed visibility variable had the largest influence on the driver speed, as expected.

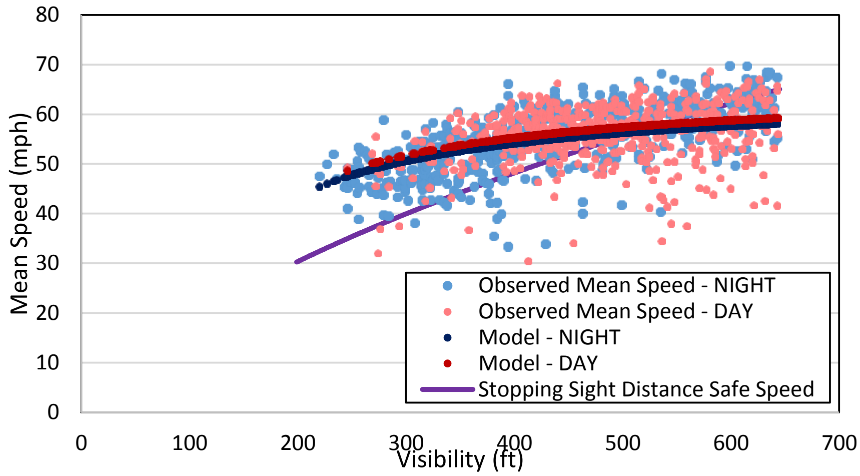
Table 12. I-77 Model Parameters

Model Element	Coefficients		*t*-statistic	*p*-value
	Unstandardized	Standardized		
Constant	64.6	N/A	259.46	0.000
Inverse Visibility	-4204	-0.752	-52.02	0.000
Day/Night	1.13	0.089	7.07	0.000
SB6	6.07	0.462	30.61	0.000
SB7	-2.67	-0.103	-7.70	0.000

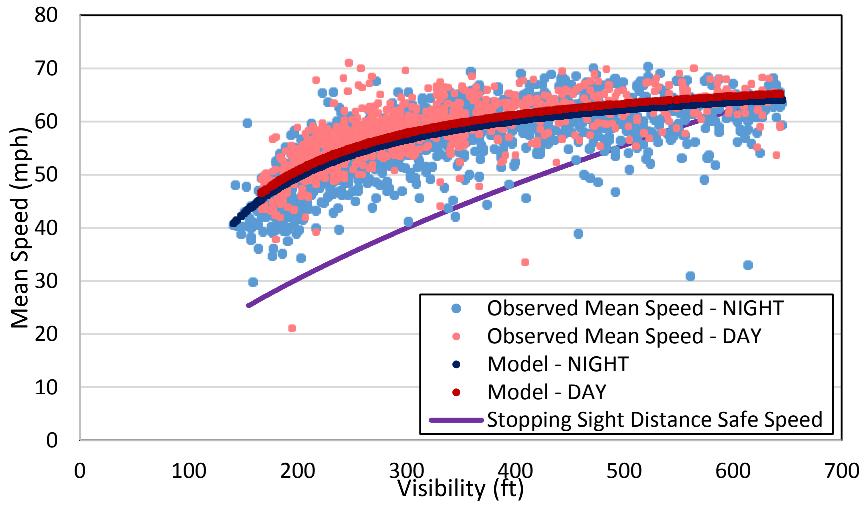
Figure 11 shows the raw data and the model estimates by site. The adjusted R^2 value for the model is 0.451. Although a better fit would be desirable, this R^2 value indicates that the model explains about 45% of the variation in the data. In this case, the wide dispersion in the model data adversely affected the model fit, although a clear relationship between visibility and speed was evident. The difference between the SSD safe speed and observed speeds is evident in Figure 11.

A particularly interesting finding from the I-77 model was related to the coefficients of the site dummy variables. The coefficients suggest that compared to speeds at MP 5.3, speeds were about 6 mph faster at MP 6.6 and 2.5 mph slower at MP 7.3 when visibility was held constant. This is interesting because all three sites are on downhill grades and separated by short distances.

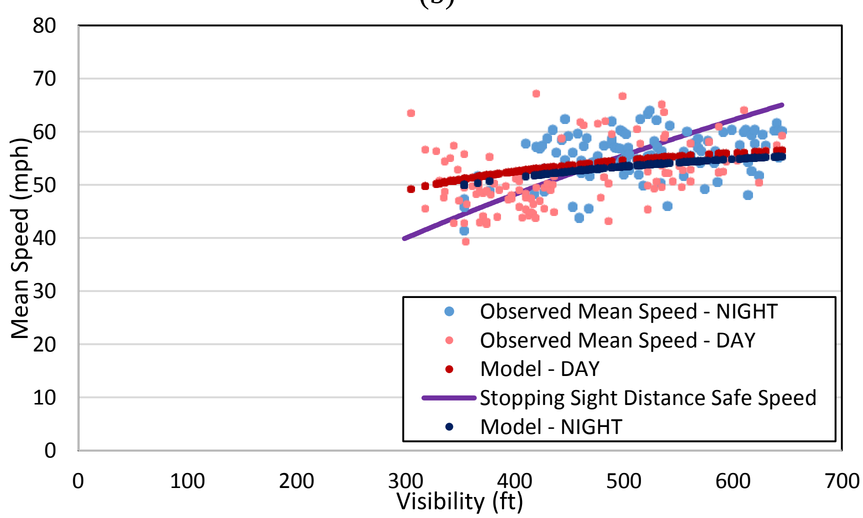
To understand this relationship better, individual low visibility events were plotted in time to see how speeds changed by site, as shown in Figure 12. Visual analysis of the individual events showed that driver speeds were fairly consistent from site to site, both on clear days and on foggy days, but that the visibility varied from site to site, with the worst visibility typically occurring at MP 6.6. Therefore, the compliance with safe speed appears better at MP 5.3 and MP 7.3 simply because visibility was better relative to MP 6.6. This accounts for the difference in magnitude of the coefficient on the site indicator variables. Because there were not additional speed detectors upstream of MP 7.3, it is not known what the visibility was when the drivers were choosing the speed they maintained throughout this corridor. Thus, the data appear to indicate that drivers did not necessarily alter their speed much as visibility changed as they proceeded through the corridor. This implies that the MP 6.6 model represents the critical case for driver behavior on the corridor.



(a)



(b)



(c)

Figure 11. I-77 Models: (a) MP 5.3, (b) MP 6.6, (c) MP 7.7

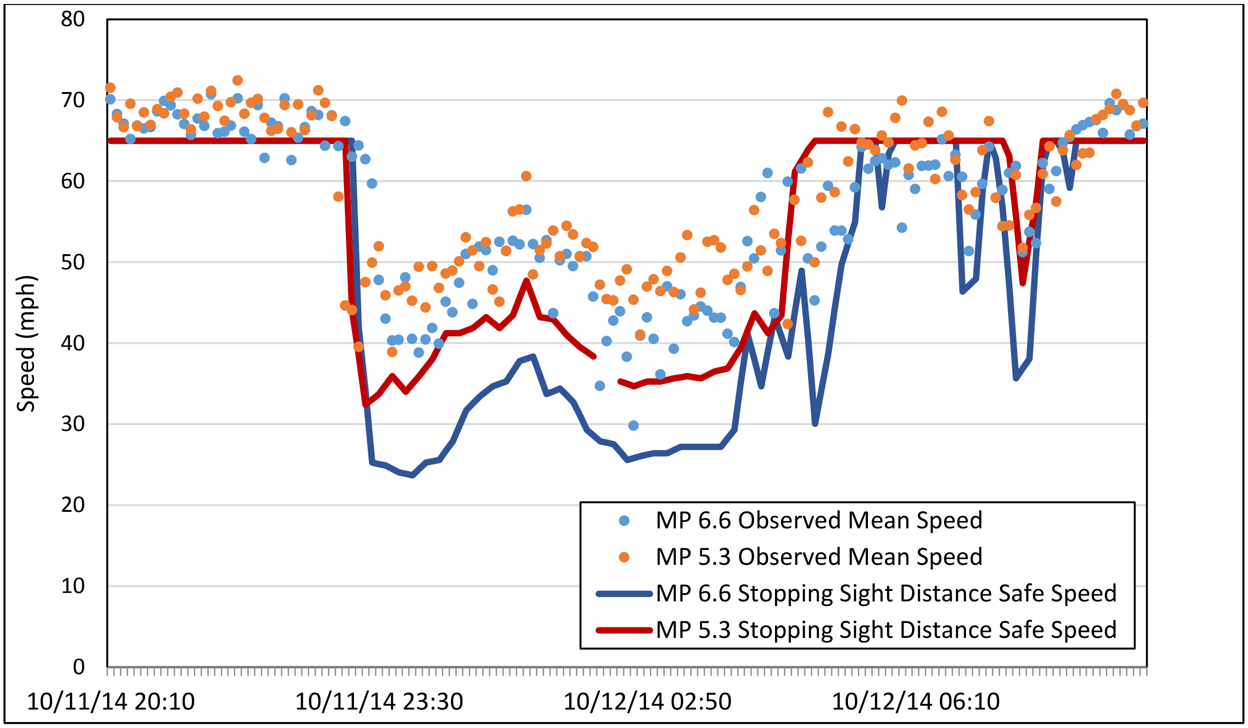


Figure 12. I-77 Low Visibility Event

I-64 in Afton

Visibility Profiles

Low visibility was observed on 77 days between July 1, 2014, and December 31, 2014, on I-64. Figure 13 shows the visibility profile for the I-64 study section using all data from this period. The purple line shows the percentage of time the RWIS sensor was reporting reduced visibility once invalid readings were removed from the analysis. Figure 13 shows that the distribution of fog varied spatially along the corridor. The worst visibility occurred at MP 99.9, which had reduced visibility for more than 10% of the collection period. Since data were available for only 6 months in 2014, the frequency distribution data cannot be directly compared to that for I-77.

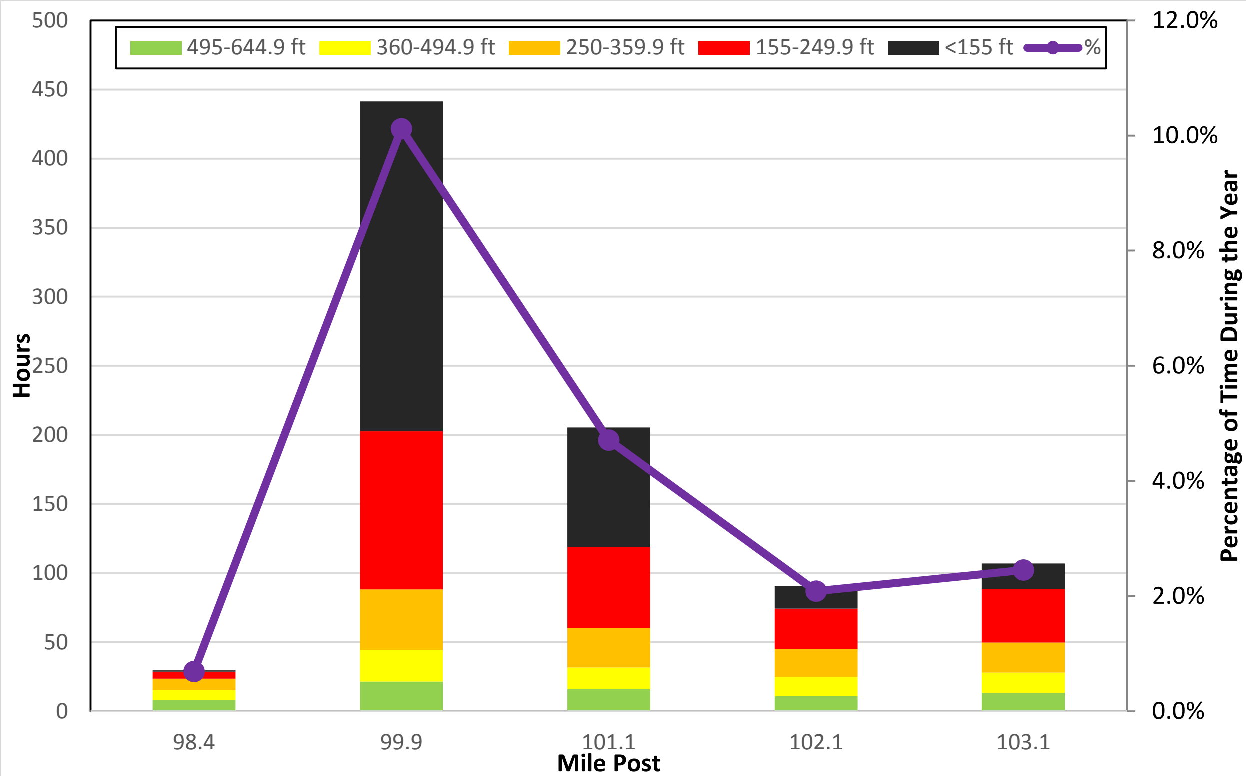


Figure 13. I-64 Visibility Profile, July-December 2014. The purple line shows the percentage of time the RWIS sensor was reporting reduced visibility once invalid readings were removed from the analysis.

Crash Analysis: Crash Frequency

Police crash reports were used to analyze crashes from July 1, 2014, to December 31, 2014, in conjunction with the visibility measurements. A review of these reports revealed 27 total crashes between MP 97 and MP 103, with 1 crash being coded as having occurred in fog. The remaining crash dates were cross referenced with a list of dates during the collection period that had fog to determine if any other crashes occurred in low visibility. The process revealed that 10 crashes occurred during periods of fog, again indicating inconsistency between visibility measurements and police judgment of weather conditions. The 10 crashes occurred on 7 different days spread evenly throughout 6-six month period. Nine of the crashes occurred between MP 97 and MP 99 and were nearest the RWIS station at MP 98.4.

A closer examination of the visibility on the corridor when each of the crashes occurred revealed that the visibility at MP 98.4 was clear while the sensors at adjacent station MP 99.9 recorded severe low visibility. Five of these crashes occurred in the WB direction. Although the visibility at the crash site may have been clear, the vehicle had recently traveled through a foggy area if it was traveling in this direction. Eight of the 10 crashes were fixed object–off road collisions. The remaining 2 crashes occurred when a driver struck a bear in the roadway and a second vehicle struck the bear carcass. This crash type breakdown does not align with the findings of Hamilton et al. (2014) as none of these crashes was a rear-end crash, none involved multiple vehicles, and none resulted in any injuries. This was likely due to the small sample size.

Although visibility data were not available, police reports were examined for all crashes from 2010 to 2014. Between MP 97 and MP 103, there were 148 crashes. Six crashes were coded as occurring during fog by the responding officer. A review of the crash descriptions written by the officer found 1 additional crash that was coded as occurring in rain but was described as occurring in foggy/rainy conditions. Icy road conditions played a role in 5 of the 7 crashes. Four crashes were fixed object–off road collisions, 1 was an angle crash, 1 was a sideswipe–same direction, and one was a rear-end collision. Approximately 4.7% of the crashes occurred during fog based on the police coding and descriptions. This percentage was lower than the proportion of fog crashes on I-77 (approximately 11%). Possible explanations for this are discussed later.

Driver Behavior

Speed Analysis

The mean speeds at each station by visibility bin are shown in Table 13. The N column represents the number of 5-minute speed observations included in each bin. Table 13 shows an overall trend that speeds decreased as visibility decreased but that speeds were often far greater than the SSD safe speed, particularly for the lowest visibility bins. Hypothesis testing at $\alpha = 0.05$ revealed that the mean speed for each low visibility bin was statistically different than the mean speed during clear conditions for all cases.

For each 5-minute speed observation, the lane speed differential was calculated by subtracting the right lane speed from the left lane speed. The differentials were aggregated in the same manner as the mean speeds and are shown in Table 14. Hypothesis testing at $\alpha = 0.05$ revealed that the mean speed differential for each low visibility bin was not statistically different than the mean speed differential for clear conditions at MPs 98.4 EB, 98.4 WB, and 99.9 EB. This suggests that at these locations the potential for conflict between vehicles in adjacent lanes did not increase as visibility decreases. The speed differentials for all low visibility bins were found to be statistically different from those for clear conditions at MP 101.1 EB and MP 102.1 WB. At MP 99.9 WB, speed differentials for visibility bins less than 495 feet were found to be different from those for clear conditions. At MP 101.1 WB only, speed differentials for the lowest visibility bin (<155 feet) was found to be different than that for clear conditions. At each of these locations, reduced visibility below a certain value increased the potential for conflict between vehicles in adjacent lanes compared to clear conditions. At MP 102.1 EB, speed differentials for three of the low visibility bins were found to be statistically different and two were not.

Table 13. I-64 Mean Speed by Visibility Bin

Visibility Bin	I-64 Eastbound								I-64 Westbound							
	MP 98.4		MP 99.9		MP 101.1		MP 102.1		MP 98.4		MP 99.9		MP 101.1		MP 102.1	
	N	Speed (mph)	N	Speed (mph)	N	Speed (mph)	N	Speed (mph)	N	Speed (mph)	N	Speed (mph)	N	Speed (mph)	N	Speed (mph)
≥645 ft	48891	67.0	40753	66.5	41732	72.5	48678	70.5	48717	64.5	40658	63.5	44257	63.4	48031	69.4
495-644.9 ft	100	60.1	250	61.4	155	67.8	119	67.9	100	60.2	251	59.6	178	60.8	129	66.4
360-494.9 ft	84	60.9	267	62.6	158	67.8	161	66.7	84	61.3	266	60.0	170	60.9	169	65.1
250-359.9 ft	100	61.1	516	61.8	295	67.7	230	64.7	99	60.6	517	59.4	307	60.8	242	64.9
155-249.9 ft	59	57.4	1341	59.5	563	65.8	351	62.8	59	58.5	1340	57.4	616	59.8	351	64.0
<155 ft	13	49.4	2730	54.0	705	60.4	196	59.7	13	51.0	2721	53.0	849	55.7	196	62.4

Table 14. I-64 Lane Speed Differential by Visibility Bin

Visibility Bin	I-64 Eastbound								I-64 Westbound							
	MP 98.4		MP 99.9		MP 101.1		MP 102.1		MP 98.4		MP 99.9		MP 101.1		MP 102.1	
	N	Speed (mph)	N	Speed (mph)	N	Speed (mph)	N	Speed (mph)	N	Speed (mph)	N	Speed (mph)	N	Speed (mph)	N	Speed (mph)
≥645 ft	48891	7.4	40753	5.1	41732	-0.2	48678	5.9	48717	7.9	40658	7.8	44257	6.5	48031	4.8
495-644.9 ft	100	7.2	250	5.2	155	1.2	119	6.2	100	8.4	251	7.5	178	6.4	129	5.4
360-494.9 ft	84	8.0	267	5.2	158	2.4	161	6.5	84	8.7	266	7.3	170	6.8	169	5.8
250-359.9 ft	100	7.7	516	5.2	295	1.8	230	6.6	99	8.7	517	7.2	307	6.7	242	5.7
155-249.9 ft	59	8.1	1341	5.2	563	1.3	351	6.4	59	8.8	1340	7.4	616	6.7	351	5.6
<155 ft	13	7.9	2730	5.0	705	2.3	196	6.5	13	9.2	2721	7.2	849	6.2	196	5.9

As with the I-77 dataset, the coefficient of variation may be a better measure of the dispersion of speed data since it accounts for the amount of variation relative to the mean speed. The coefficient of variation increases as visibility worsens, particularly for visibility less than 250 feet.

Figure 14 shows the speed profiles for the sites at MPs 98.4 and 102.1. Visually, it is obvious that speeds at the MP 102.1 sites, particularly in the WB direction, were not sensitive to changes in visibility. The curves representing each visibility case are a similar shape and do not shift to the left much as visibility decreases. At MP 98.4, there is more variation in the curves. The curve for each worsening visibility bin is clearly shifted to the left. The curves for the lowest visibility bins are also flatter than the curves representing clear conditions.

Table 15 shows that at least 78% of drivers were exceeding the SSD safe speed at both MP 98.4 sites. In the lowest visibility bin, 100.0% of the vehicles were exceeding the SSD safe speed. This is consistent with the speed profile for I-77 at MP 6.6. At MP 102.1, a different trend emerged. At the MP 102.1 WB site, more than 99% of vehicles were traveling faster than the SSD safe speed in even the highest visibility bin. At MP 102.1 EB, at least 96% of vehicles were exceeding the SSD safe speed in all low visibility bins.

In all reduced visibility bins, at least 74% of drivers were exceeding the SSD safe speed. In the lowest visibility bin, nearly every vehicle was exceeding the SSD safe speed. The same trend was apparent with the percentage of vehicles traveling within 10 mph of the SSD safe speed. In fact, for safe speeds of 45 mph or less, more than 90% of vehicles were exceeding the SSD safe speed and more than 71% were traveling more than 10 mph above the SSD safe speed.

Modeling Speed

The same trends from the I-77 model emerged during the modeling for I-64:

- Mean speed was correlated with the negative inverse of visibility distance, although it was less sensitive than on I-77.

- Volumes at the sites were typically far below capacity during fog events, and no significant relationships between speed and traffic volumes were detected.

- The day/night indicator variable typically showed reductions in mean speed during overnight hours. Reductions were larger on I-64 than on I-77, possibly showing the result of larger commuter traffic volumes.

- Site indicator variables, which captured specific geometric conditions at the location, were often significant.

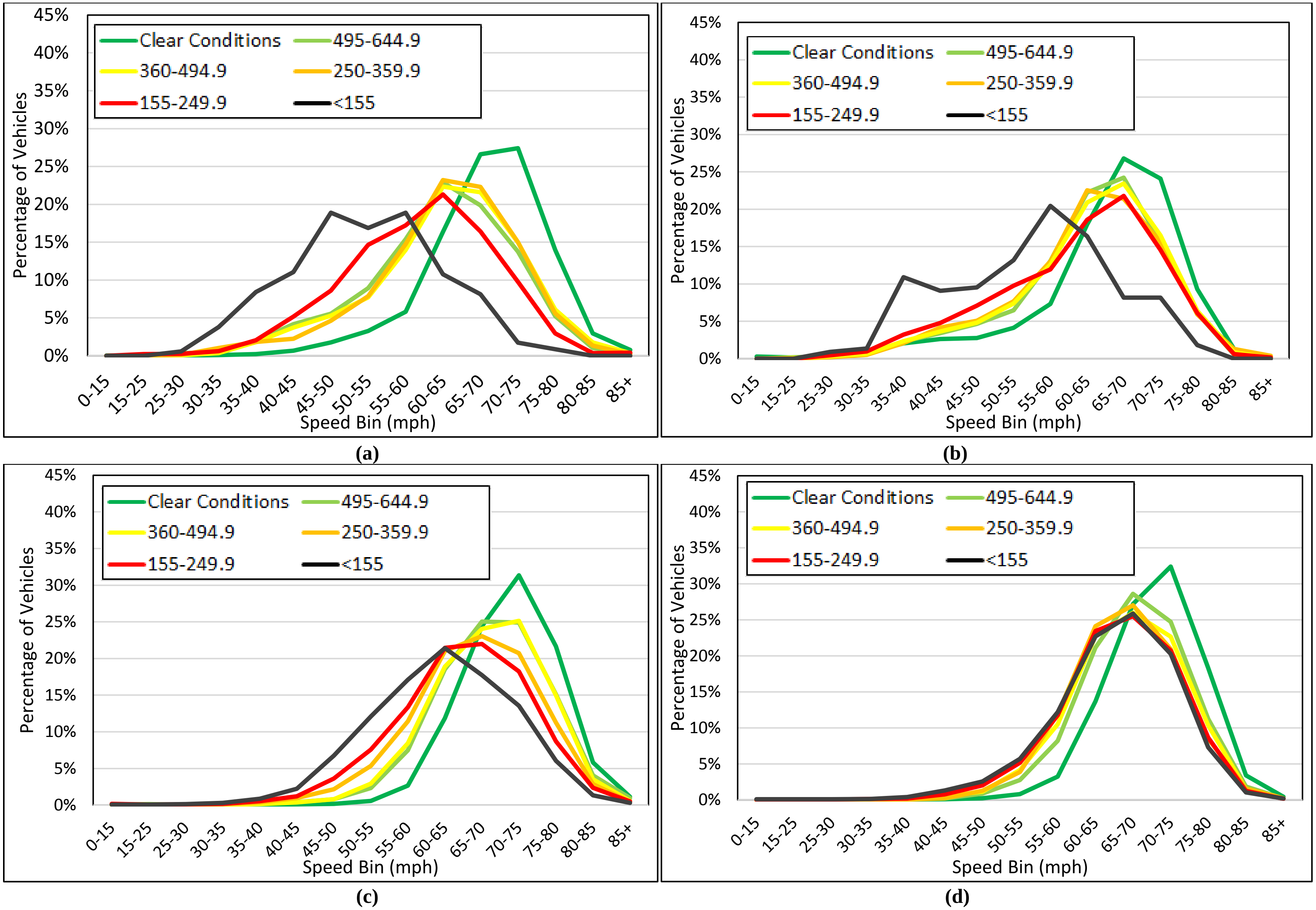


Figure 14. I-64 Speed Profiles: (a) MP 98.4 EB; (b) MP 98.4 WB; (c) MP 102.1 EB; (d) MP 102.1 WB

Table 15. I-64 Speed Profile Characteristics

Site	Visibility Bin	SSD	N (No. of bins)	Volume (No. of vehicles)	Mean Speed (mph)	Standard Deviation (mph)	Coefficient of Variation	Pace Speed (mph)	% Vehicles		
									In Pace	>SSD	>SSD + 10
MP 98.4 EB	≥645 ft	65	48,896	3,052,823	67.0	7.7	0.11	65-75	54.0%	N/A	N/A
	495-644.9 ft	55	100	4,493	60.1	8.0	0.13	60-70	42.8%	78.5%	40.2%
	360-494.9 ft	45	84	3,795	60.9	8.0	0.13	60-70	43.9%	94.1%	81.1%
	250-359.9 ft	35	100	4,608	61.1	8.2	0.13	60-70	45.5%	98.9%	94.8%
	155-249.9 ft	25	59	1,938	57.4	8.6	0.15	55-65	38.5%	99.8%	98.9%
	<155 ft	<25	13	344	49.4	7.5	0.15	45-55	35.8%	100.0%	100.0%
MP 98.4 WB	≥645 ft	65	48,773	2,878,396	64.5	9.0	0.14	65-75	50.9%	N/A	N/A
	495-644.9 ft	55	100	4,529	60.2	9.1	0.15	60-70	46.5%	82.0%	46.7%
	360-494.9 ft	45	84	3,606	61.3	9.2	0.15	60-70	44.0%	93.0%	80.3%
	250-359.9 ft	35	100	3,846	60.6	9.2	0.15	60-70	44.4%	99.0%	93.0%
	155-249.9 ft	25	59	1,340	58.5	9.2	0.16	60-70	40.4%	100.0%	98.6%
	<155 ft	<25	13	220	51.0	9.3	0.18	55-65	36.8%	100.0%	100.0%
MP 102.1 EB	≥645 ft	65	48,868	2,908,852	70.5	6.5	0.09	65-75	55.8%	N/A	N/A
	495-644.9 ft	55	119	8,696	67.9	7.2	0.11	65-75	49.9%	96.0%	70.0%
	360-494.9 ft	45	161	9,374	66.7	7.1	0.11	65-75	49.2%	99.3%	95.6%
	250-359.9 ft	35	230	12,086	64.7	7.5	0.12	60-70	44.1%	99.6%	98.3%
	155-249.9 ft	25	351	20,138	62.8	7.6	0.12	60-70	43.4%	99.8%	99.5%
	<155 ft	<25	196	10,675	59.7	7.5	0.13	60-70	39.2%	99.9%	99.9%
MP 102.1 WB	≥645 ft	65	48,070	2,981,776	69.4	5.9	0.08	65-75	59.6%	N/A	N/A
	495-644.9 ft	55	129	9,308	66.4	6.4	0.10	65-75	53.3%	99.6%	66.6%
	360-494.9 ft	45	169	10,307	65.1	6.6	0.10	60-70	48.7%	99.9%	98.1%
	250-359.9 ft	35	242	14,028	64.9	6.5	0.10	60-70	51.2%	99.9%	99.3%
	155-249.9 ft	25	351	23,114	64.0	6.8	0.11	60-70	49.0%	99.9%	99.7%
	<155 ft	<25	196	12,666	62.4	7.3	0.12	60-70	48.6%	99.9%	99.8%

SSD = stopping sight distance.

The final model for I-64 is shown by the following equation:

$$S = 62.2 - \frac{1089}{Vis} + (5.25 \times \; DayNight) - (1.52 \times W99) + (5.84 \times E101) + (4.13 \times E102) + (4.65 \times W102)$$

where

S = mean speed per 5 minutes (mph)
Vis = visibility distance (feet)
DayNight = day or night dummy variable, with 1 indicating day
WB99 = dummy variable, with 1 indicating MP 99.9 WB
EB101 = dummy variable, with 1 indicating MP 101.1 EB
EB102 = dummy variable, with 1 indicating MP 102.1 EB
WB102 = dummy variable, with 1 indicating MP 102.1 WB.

All variables selected were significant at $\alpha = 0.05$, and all other regression assumptions (such as homoscedasticity and normal distribution of residuals) were met for the models. Since this model was intended simply to describe observed characteristics at the sites, 100% of the data were used for model development. Given the influence of site-specific variables, the model cannot be directly transferred to another location. That being said, the model does provide some important information about the relative sensitivity of driver speed choice to visibility on I-64.

Table 16 shows the model statistics. Again, the *p*-values are less than 0.05 for all the coefficient values, indicating that they are significantly different than 0. The coefficient on the transformed visibility variable is −1089. Compared to the I-77 model, the sign is the same but the magnitude is smaller, indicating that changes in visibility had a smaller influence on speed on I-64 than on I-77. The coefficient value of 5.25 on the day/night variable indicates that driver speeds were more than 5 mph greater during the day than at night, which is much larger than was determined for I-77 (1.13). The site-specific variable for MPs 98.4 EB, 98.4 WB, 99.4 EB, and 101 WB do not show up in the model, indicating that data for the speed-visibility relationship at sites were not significantly different and can be represented by the same curves. The coefficient value of −1.52 for the MP 99 WB site variable indicates that drivers were traveling approximately 1.5 mph slower at MP 99 WB than at MPs 98 EB, 98 WB, 99 EB, and 101 WB, holding visibility constant. The coefficient value of 5.84 for the MP 101 EB variable indicates that drivers were traveling approximately 6 mph faster at MP 101 EB than at the four base sites, which shows the influence of traveling downhill versus uphill. The coefficient values for the MP 102 EB and WB sites are 4.13 and 4.65, respectively. Despite these site-specific coefficients, the standardized coefficients still reveal that the inverse of the visibility distance exerted the single strongest influence on the model.

Table 16. I-64 Model Parameters

Model Element	Coefficients		*t*-statistic	*p*-value
	Unstandardized	Standardized		
Constant	62.18	-	538.176	0.000
Inverse Visibility	-1089	-.432	-77.152	0.000
Day/Night	5.25	.341	62.787	0.000
E101	5.84	.239	41.984	0.000
W102	4.65	.149	26.326	0.000
E102	4.13	.130	23.094	0.000
W99	-1.52	-.091	-15.632	0.000

Figures 15 through 19 show the raw data with the model predictions by site. The adjusted R^2 value for this model was 0.500, which is comparable to that for the I-77 model. Again, there was a large amount of dispersion in the observations, particularly at low visibility levels, which negatively affected model fit. Examination of the figures showed that in this case the observed speeds were relatively insensitive to changes in visibility as compared to what was observed for I-77, perhaps because of the commuter driving population and the fog lights at these sites. Speed reductions were observed at lower visibility ranges, but the magnitude of the change was inconsistent.

The speed-visibility relationship in time at adjacent sites was analyzed in the same way as for I-77. A review of multiple low visibility events did not reveal any speed relationship that was masked by the model coefficients, as with the I-77 dataset. One observation from the time plots was the inconsistency in the RWIS visibility data. A sample plot of a low visibility event for I-64 Westbound is shown in Figure 20. As noted earlier, the effects of grade on I-64 were different depending on whether traffic was going uphill or downhill, so speeds along the route were influenced by geometric as well as visibility factors. Figure 20 shows that the visibility readings at MP 101 often fluctuated significantly, with no corresponding change in mean speed. It is unclear whether these fluctuations are a result of sensor data quality limitations or true changes in visibility. No validation dataset was available to assess the underlying quality of the visibility measurements.

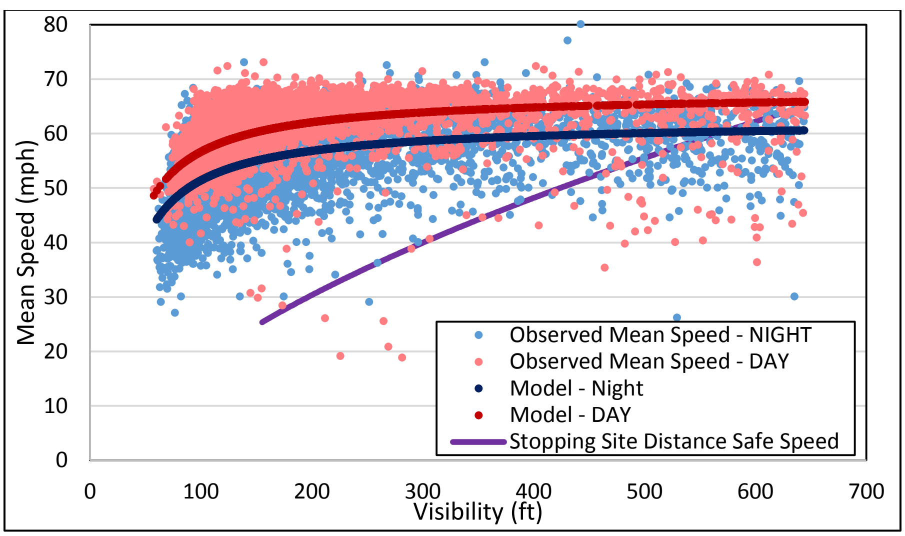


Figure 15. I-64 Models for MPs 98.4 EB, 98.4 WB, 99.9 WB, and 101.1 EB

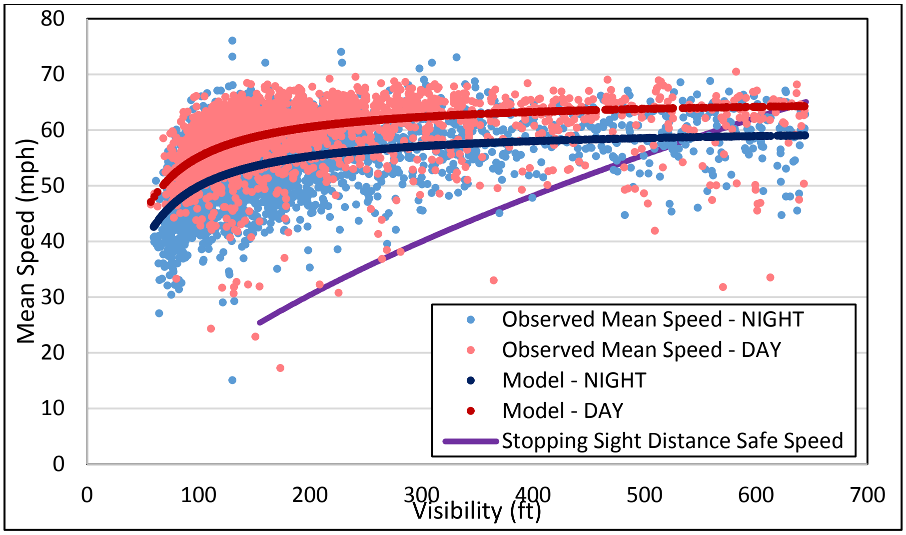


Figure 16. I-64 Model for MP 99.9 EB

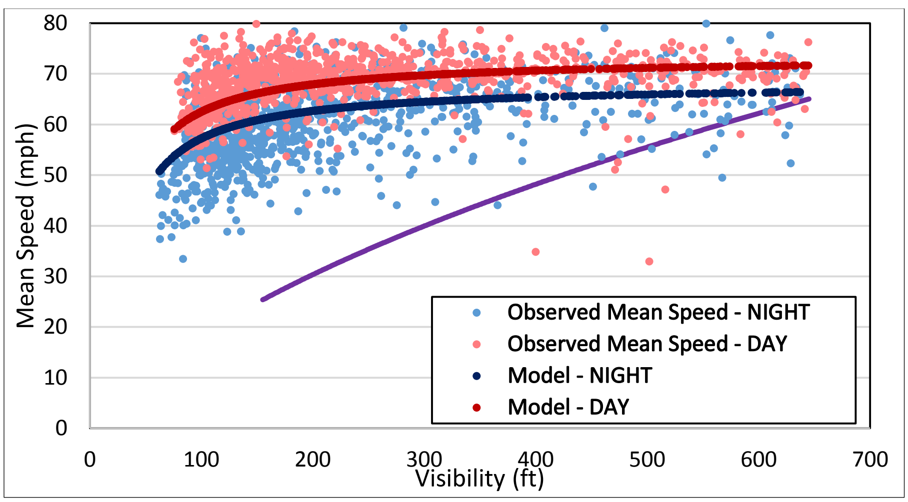


Figure 17. I-64 Model for MP 101.1 EB

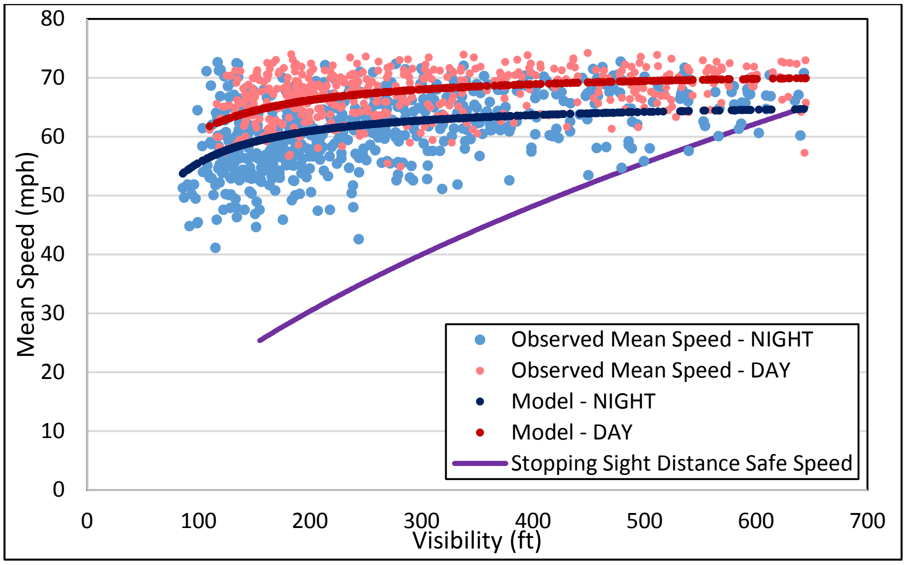


Figure 18. I-64 Model for MP 102.1 EB

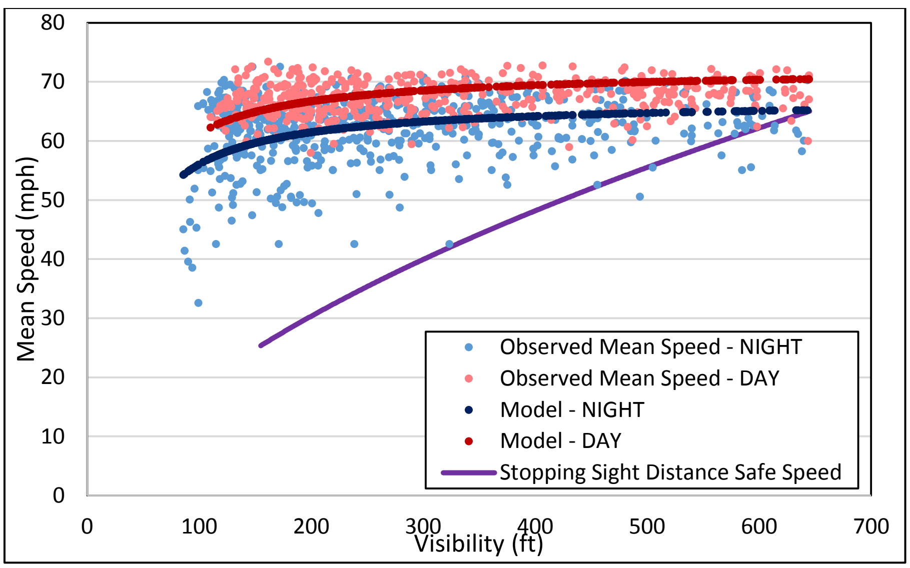


Figure 19. I-64 Model for MP 102.1 WB

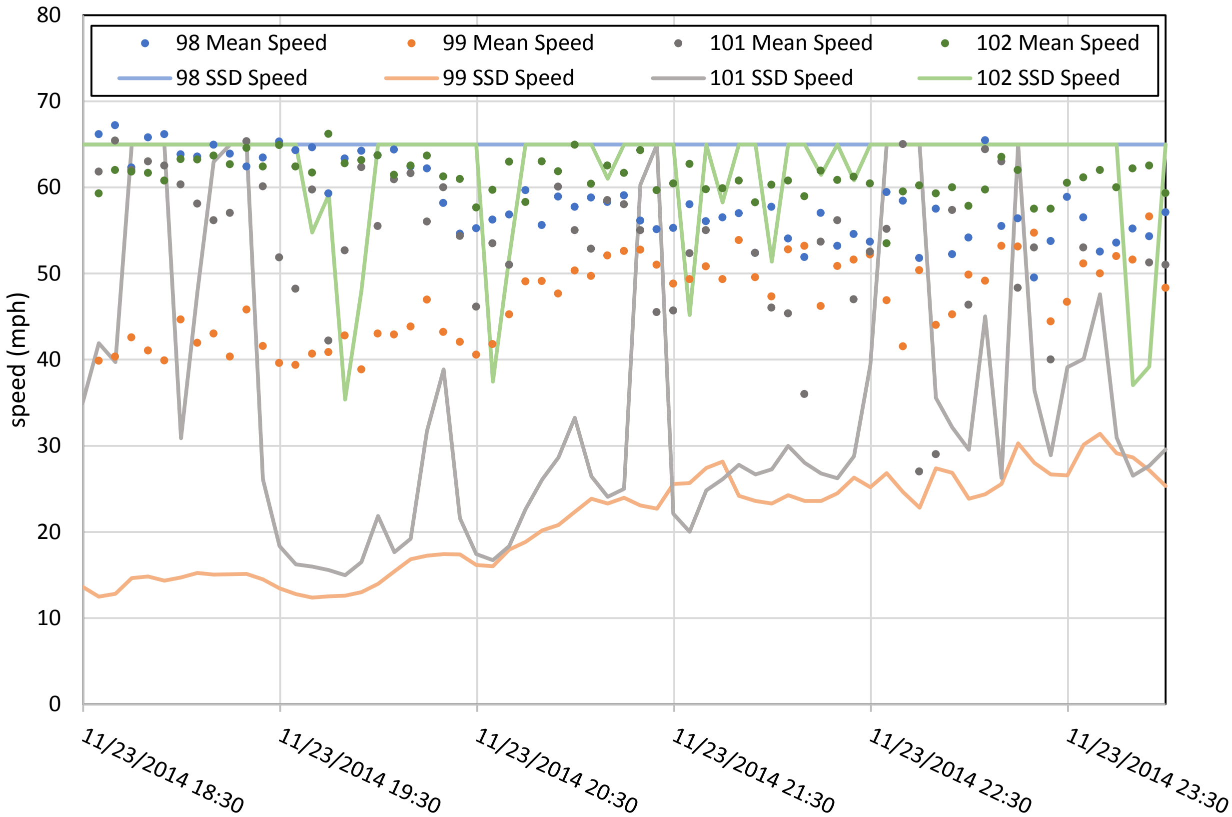


Figure 20. I-64 WB Low Visibility Event. SSD = Stopping Sight Distance.

Generalized Linear Model

Despite having a better fit than the model for I-77, the I-64 model showed a lack of sensitivity as a function of visibility. Visual inspection of the I-64 models revealed that the mean speed curves were very flat except in the very low visibility cases. To understand the relationship between mean speed and visibility better, a generalized linear model was developed using the I-64 dataset. The analysis of variance (ANOVA) table revealed that all variables and all interaction variables were significant (Table 17).

Pairwise comparisons using Tukey's Least Significant Difference test by visibility bin and site were performed to determine the relative sensitivity of mean speeds. The results are shown in Table 18. The last column shows which bins had mean speeds that were significantly different from all of the other bins at that site. The analysis revealed than at all sites except MP 102 WB, mean speeds for the lowest visibility bin were significantly different than mean speeds for all other visibility bins. In general, only visibility less than 155 to 250 feet shows a statistically significant reduction in vehicle speeds versus clear conditions. As a result, it appears that drivers on Afton Mountain were less sensitive to changes in visibility than drivers on I-77.

Table 17. ANOVA Table for I-64 Generalized Linear Model

Model Element	Sum of Squares	Degrees of Freedom	Mean Square	F	Sig.
Corrected Model	465201	77	6041.583	193.051	0.000
Intercept	9068790.790	1	9068790.790	289781.095	0.000
Visibility Bin	15583.088	4	3895.772	124.484	0.000
Site	80655.654	7	11522.236	368.178	0.000
Day/Night	16559.309	1	16559.309	529.131	0.000
Vis Bin * Site	6672.511	28	238.304	7.615	0.000
Vis Bin * Day/Night	3186.189	4	796.547	25.453	0.000
Site * Day/Night	1807.503	7	258.215	8.251	0.000
Vis Bin * Site * Day/Night	1215.994	26	46.769	1.494	0.051
Error	531144.095	16972	31.295	-	-
Total	59486486.57	17050	-	-	-
Corrected Total	996345.985	17049	-	-	-

Table 18. I-64 Generalized Linear Model Pairwise Comparisons of Mean Speeds

Site	Visibility Bin	Mean	Std. Error	95% Confidence Interval		Significantly Different From
				Lower Bound	Upper Bound	
98 EB	495-644.9	60.493	.610	59.296	61.689	<155
	360-494.9	61.516	.660	60.222	62.810	<155
	250-359.9	61.905	.630	60.670	63.140	<155
	155-249.9	59.419	2.012	55.475	63.363	<155
	<155	49.375	1.552	46.333	52.416	All Others
98 WB	495-644.9	61.243	.610	60.047	62.440	<155
	360-494.9	61.888	.660	60.594	63.182	<155
	250-359.9	61.682	.631	60.445	62.920	<155
	155-249.9	63.563	2.012	59.619	67.507	<155
	<155	50.986	1.552	47.944	54.027	All Others
99 EB	495-644.9	61.507	.358	60.805	62.209	155-249.9, <155
	360-494.9	62.521	.342	61.850	63.192	155-249.9, <155
	250-359.9	61.793	.246	61.310	62.276	155-249.9, <155
	155-249.9	59.701	.153	59.401	60.002	All Others
	<155	54.570	.109	54.356	54.784	All Others
99 WB	495-644.9	59.742	.357	59.041	60.442	155-249.9, <155
	360-494.9	59.999	.343	59.326	60.671	155-249.9, <155
	250-359.9	59.391	.246	58.909	59.873	155-249.9, <155
	155-249.9	57.573	.153	57.272	57.874	All Others
	<155	53.540	.109	53.326	53.754	All Others
101 EB	495-644.9	67.362	.460	66.461	68.264	155-249.9, <155
	360-494.9	67.538	.448	66.660	68.416	155-249.9, <155
	250-359.9	67.591	.326	66.952	68.229	155-249.9, <155
	155-249.9	65.799	.236	65.337	66.261	All Others
	<155	60.858	.212	60.443	61.274	All Others
101 WB	495-644.9	60.213	.431	59.367	61.058	<155
	360-494.9	60.619	.433	59.770	61.467	<155
	250-359.9	60.698	.319	60.072	61.324	<155
	155-249.9	59.821	.225	59.379	60.262	<155
	<155	55.890	.192	55.513	56.267	All Others
102 EB	495-644.9	67.479	.529	66.442	68.515	250-359.9, 155-249.9, <155
	360-494.9	66.929	.445	66.057	67.801	250-359.9, 155-249.9, <155
	250-359.9	65.048	.373	64.316	65.780	All Others
	155-249.9	62.913	.299	62.328	63.499	All Others
	<155	61.364	.442	60.497	62.231	All Others
102 WB	495-644.9	65.850	.509	64.852	66.849	155-249.9, <155
	360-494.9	65.416	.434	64.566	66.266	<155
	250-359.9	65.257	.366	64.541	65.974	<155
	155-249.9	64.094	.299	63.508	64.679	495-644.9
	<155	63.653	.442	62.786	64.520	495-644.9, 360-494.9, 250-359.9

Discussion

Crash Analysis

The crash analysis for I-77 supported the finding by Hamilton et al. (2014) that crashes in low visibility are more likely to be severe and involve multiple vehicles. In general, the crash results for I-77 revealed that the presence of any fog that restricts visibility below the SSD has an effect on safety, as there was a change in crash characteristics between clear conditions and the highest visibility bins. It also appears that crash characteristics changed further when visibility decreased below 360 feet. The proportions of rear-end crashes and multi-vehicle crashes increased, and crash rates were also extremely high in the 155 to 250 feet visibility range.

Unfortunately, because of the limited visibility data for I-64, a detailed crash analysis was not performed. Qualitative analysis of the crashes during the 6 months of available visibility data did not reveal the same crash trends as for I-77. Although it is difficult to draw many conclusions because of the small sample size for I-64, it is possible that the fog lights decreased the likelihood of rear-end and multi-vehicle crashes in low visibility, thus improving safety. Similarly, the regular commuter traffic may have had a role in the crash history, as the regular commuters are accustomed to driving in low visibility.

Although the differential between safe speed and observed speed implies that driver behavior in low visibility was less safe on I-64 than I-77, the crash analysis suggested that this was not the case. The crash analysis for I-64 using a limited sample of data from July 1, 2014, to December 31, 2014, did not reveal the same crash trends as found for I-77. The crash history for I-77 supported previous studies that showed crashes in low visibility were more likely to be severe and involve multiple vehicles. It is possible that the fog lights and commuter driving population played a role in these differences, but more visibility data are needed to ensure that visibility and crash trends are sustainable over a longer period on I-64.

Driver Speed Choice

Mean speed and modeling at all sites revealed that there was a relationship between speed and visibility such that as visibility decreased, mean speed also decreased. The exact nature of this relationship was different for each site. At all sites, there was a large differential between mean speed and safe speed during low visibility, particularly in the most severe visibility reductions.

The speed analysis for I-77 revealed that mean speeds exceeded safe speeds for all low visibility bins. Means speeds were in excess of 45 mph when the safe speed was less than 25 mph. At MP 6.6, where visibility was most limited, more than 75% of vehicles exceeded the safe speed for all low visibility bins, with 98% exceeding the SSD safe speed in visibility below 360 feet. At MP 6.6, the mean speed differential between lanes for all low visibility bins was statistically different from differentials for clear conditions, suggesting that there is a higher potential for conflict between vehicles in adjacent lanes. Hypothesis testing on the standard deviation of speeds for each visibility bin found that no standard deviation for reduced visibility was statistically different from that for clear conditions. This indicates that speed variance did not increase as visibility decreased.

The speed analysis for I-64 also showed that mean speeds exceeded safe speeds for all low visibility bins. Observed mean speeds on I-64 were less sensitive to changes in visibility than mean speeds on I-77. At MP 101.1 EB, speeds were greater than 60 mph when the safe speed was less than 25 mph. Results from the lane differential analysis were mixed for I-64. At MP 98.4 EB and WB and MP 99.9 EB, the mean speed differential by lane in low visibility was not statistically different than the differential in clear conditions; at the other sites, speed differentials for at least one low visibility bin was statistically different from clear conditions. It is possible that differing grade played a role in accounting for the difference between sites. For all reduced visibility bins, at least 74% of drivers exceeded the SSD safe speed. For the lowest visibility bin, nearly every vehicle exceeded the SSD safe speed. The speed standard deviation for every low visibility bin was not statistically different from that for clear conditions at MP 98.4 EB and WB, which is consistent with the findings for I-77 that speed variance did not increase as visibility decreased. Results differed at MP 102.1: the standard deviations for speed were different from clear condition for nearly every low visibility bin.

Speed choice behavior differed between the I-77 and I-64 sites, with larger deviations between observed and safe speed on I-64. One theory to account for this difference concerns the presence of the fog lights installed on I-64 to delineate the edge of pavement during periods of low visibility. It is possible that the improved delineation provided by these lights may have resulted in drivers reducing speed less during fog. A similar phenomenon occurred with the application of permanent raised pavement makers (Behar et al., 2004). A human factors review of permanent raised pavement markers on two-lane roads and multi-lane freeways found that as the driving workload was decreased because of the improved delineation of the roadway, the drivers compensated by increasing speed (Behar et al., 2004). It is possible that a similar compensation is happening on I-64 because of the fog lights. Despite this, the available crash data from Afton Mountain did not reveal any significant safety issues during fog as compared to I-77.

Another hypothesis is that the difference in speed choice could be due to the differing driver populations on the two routes. According to VDOT's regional operations staff, the I-64 site contained a higher proportion of regular commuters who were familiar with the recurring low visibility conditions on the corridor and might drive with a heightened sense of confidence compared to the motorists on I-77, who might be traveling the road for the first time. A simulator study found that in low visibility conditions, driver behavior could be categorized into two groups: drivers who chose not to maintain visual contact with the vehicle ahead and drivers who maintain visual contact with a lead vehicle (Broughton et al., 2007). Although the sample size for the study was small, analysis found that 75% of the drivers chose to maintain visual contact with the lead vehicle, even if the speed and headway associated with this following behavior compromised safety (Broughton et al., 2007). It is possible that this behavior is more prevalent in regular commuting traffic, supporting the higher speeds for the I-64 model. The higher speeds during low visibility on I-64 indicate that implementing a VSL system may be more challenging at this site. Motorists on I-77 appear to be reducing speed more than motorists on I-64, making this site an easier pilot site for the VSL system although there is still a large disparity between the speed driven by current drivers and the SSD safe speed.

CONCLUSIONS

- *At both sites, observed speeds during fog events typically far exceeded the SSD safe speeds.* Drivers often were traveling more than 20 mph over the SSD safe speed during dense fog. This indicates that drivers often could not correctly determine an appropriate travel speed during fog. Drivers on I-77 typically altered their speed during fog events more than drivers on I-64.

- *Both crash severity and frequency were negatively affected by fog events on I-77, particularly when fog was very dense.* Findings from I-77 mirrored national research results, with crash severity and frequency increasing during fog. Rear-end and multi-vehicle crashes also became more common.

- *Crash trends for the I-64 site differed from those for I-77, but limited visibility data were available.* Despite the fact that traffic on I-64 showed smaller speed changes as a function of visibility than traffic on I-77, limited data analysis showed fewer crashes on I-64. Possible explanations for the difference include the effect of the fog lights and differences in driving population. These findings were based on 6 months of data, so more analysis is needed.

RECOMMENDATIONS

1. *VDOT's SWRO with assistance from VTRC should monitor driver response to the I-77 VSL after its activation to determine the degree to which drivers are complying with the speed limit.* The modeling showed significant differences between the SSD safe speed and the actual operating speeds on the roadway. The VSL algorithm proposed in the "Benefits and Implementation" section that follows attempts to identify an intermediate speed between the current operating speed in fog and the desired safe speed. Driver speed choice should be monitored after system activation to determine whether the system is positively affecting driver behavior. Lane differentials and the standard deviation should also be monitored to determine the effects of the VSL system on speed variance.

2. *VDOT's SWRO should be prepared to modify the proposed VSL algorithm depending on how drivers respond to the VSL speed limits posted during fog events*. The VSL control algorithm that is being deployed incorporates the model that represents driver behavior without any speed guidance. After the system is activated, new models should be developed to represent driver behavior with guidance from VSL signs. With a regular commuter population, the algorithm may need to be adjusted through an iterative process until driver behavior is near the SSD safe speed. It may not be possible to influence behavior as much with non-commuters who are unfamiliar with driving in low visibility or VSL systems, but the

algorithm should be adjusted if changes in behavior are identified. It is recommended that at least 100 hours of data during reduced visibility conditions be collected prior to the development of new driver behavior models. These 100 hours should contain at least 25 hours of visibility less than 250 feet to ensure a minimum number of observations of driver speeds in the lowest visibility bins. This should provide sufficient data to create stable models.

3. *VDOT's SWRO should carefully monitor safety during the worst visibility conditions.* Results from this research shows that the most critical safety concerns occur when visibility is less than 250 feet. For this reason, crashes, crash severity, and speeds should be monitored when visibility is below this threshold to determine the effects of the VSL system on safety. Some of the visibility-controlled VSL systems that were reviewed for this report will shut the highway down when visibility falls below a certain threshold. If the VSL system does not improve safety when visibility is below a given threshold, then SWRO may want to develop guidelines for facility closures.

4. *When designing new VSL systems, VDOT's regions should co-locate visibility and speed sensors, harmonize data aggregation intervals across data sources, and consider collecting and archiving individual vehicle–level data, at least initially.* For the most part, the evaluation in this study relied on existing sensor systems that were present on both corridors. Although speed and visibility sensors were often located in close proximity, this was not always the case. There were sometimes mismatches between the data aggregation intervals (e.g., 5 minutes versus 10 minutes) used by visibility and speed sensors, which created the need to interpolate data. These factors introduce possible error into the analysis since data must be extended or interpolated. Likewise, using aggregate data makes it impossible to look at microscopic behavioral trends such as speed compliance by vehicle type or headway by vehicle type. It is recommended that the regions consider archiving individual vehicle–level data, at least during the initial system activation, so that more detailed driver behavior analyses can be performed.

5. *VDOT's regions should incorporate knowledge of current driver behavior to increase the likelihood of compliance with future visibility-controlled VSL deployments.* The models and mean speeds showed that although there is a natural tendency for drivers to reduce their speeds in low visibility conditions, they still drive much faster than the SSD safe speed. For the VSL system to improve safety, it is crucial that drivers respect the speed limit; otherwise, speed variance could be an issue. Designers of future visibility-controlled VSL systems should consider the lessons in driver behavior from in this study and use them as they create their own algorithms.

6. *VTRC in conjunction with VDOT's NWRO should expand the analysis of I-64 at Afton Mountain to include more low visibility data and consider operational issues related to the geometrics of the site.* Only 6 months of speed and visibility data were analyzed in this study. Given the differences in driver behavior between I-77 and I-64, analysis of additional data could help further verify whether these differences were sustained long term. This would also permit further examination of the effect of the fog lights. In addition, the NWRO has indicated an interest in examining operational and safety issues related to the lack of

truck climbing lanes at the site. A follow-up study that assesses safety during limited visibility, as well as operational and safety issues related to congestion, should be performed to support a possible future active traffic management system that addresses both congestion and safety.

7. *If the I-77 VSL system is found to reduce the frequency and severity of crashes, improve speed compliance, and reduce speed variance, VDOT's NWRO should consider deploying VSLs on Afton Mountain.* The I-77 ATSMS is serving as a pilot for weather-controlled VSL systems in Virginia. This study showed that the fog on Afton Mountain is more severe but speeds are less sensitive to changes in visibility than on I-77. Although the crash history for Afton Mountain is not as severe as for I-77, the speed data showed that the potential exists for severe multi-vehicle crashes to occur. Because of the speed insensitivity to visibility reductions, there is even more concern that motorists will not respect reduced speed limits at Afton Mountain. As a result, careful monitoring could be even more critical on I-64.

BENEFITS AND IMPLEMENTATION

Given that the I-77 VSL system had not been activated as of July 2016, the benefits of implementing the VSL system cannot be quantified. As a result, only the implementation of the recommendations is discussed here. Much of the implementation of the recommendations hinges on a follow-up study that will evaluate the effectiveness of the I-77 VSL system.

1. *VTRC initiated a new study to conduct an ongoing evaluation of the safety impacts of the I-77 VSL system once it is activated.* Recommendations 1, 2, and 3 all relate to the need to have ongoing performance monitoring of the system and to create a feedback loop for continuous improvement of the system. VTRC recently initiated this second phase study to address these recommendations, and continuous feedback to VDOT's SWRO is planned as fog events occur. The evaluation is planned to end in the spring of 2018.

2. *VDOT's SWRO has already incorporated information related to driver speed choice in the I-77 VSL control algorithm.* This relates to Recommendation 5 and has already been implemented. The existing driver behavior on the corridor in low visibility was reviewed by VDOT's VSL technical advisory committee, and the VSL algorithm incorporates a model of pre-ATSMS driver behavior. The algorithm divides visibility into three cases: SSD safe speed between 50 and 65 mph (Case 1), SSD safe speed between 40 and 49.9 mph (Case 2), and SSD safe speed less than 40 mph (Case 3). For Case 1, the model speed is used if the mean speed of traffic is greater than the model speed. Otherwise, the algorithm outputs whichever is greater: the SSD safe speed or the mean speed of traffic. The same process is used for the other cases; however, Case 2 replaces the model speed with the model speed minus 5 mph, and Case 3 replaces the model speed with the model speed minus 10 mph. This helps bridge the gap between SSD safe speed and model speed. A visual representation of this is shown in Figure 21. As Figure 21 shows, the initial algorithm essentially splits

the difference between observed pre-VSL driver behavior and desirable speeds based on the SSD.

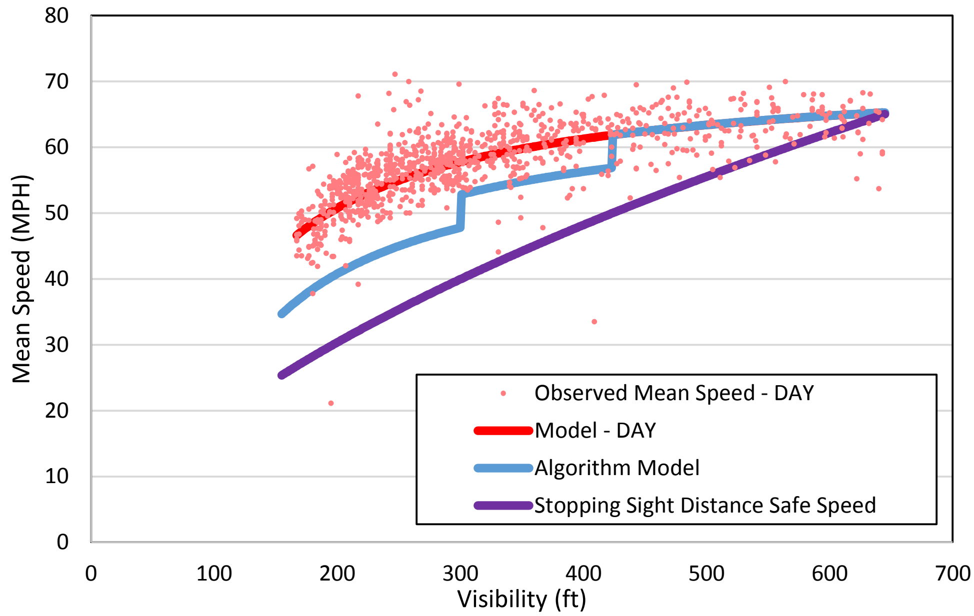


Figure 21. VSL Control Algorithm for I-77

3. *VTRC will work with VDOT's NWRO to develop and initiate a new study of I-64 over Afton Mountain within the next year.* Recommendations 6 and 7 relate to the need for further study at Afton Mountain and potential future actions should the I-77 VSL prove to be beneficial. VTRC is currently in discussions with NWRO about the scope of this study. Recommendation 7 cannot be implemented until after the I-77 Phase 2 evaluation is completed.

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