Guidelines for the Use of

Variable Speed Limit Systems in Wet Weather

FHWA Safety Program

U.S. Department of Transportation
Federal Highway Administration

FHWA-SA-12-022

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Technical Report Documentation Page

1. Report No. FHWA-SA-12-022	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Guidelines for the Use of Variable Speed Limit Systems in Wet Weather		**5. Report Date** August 24, 2012 **6. Performing Organization Code**
7. Author(s) Bryan Katz, Cara O'Donnell, Kelly Donoughe, Jennifer Atkinson (SAIC) Melisa Finley, Kevin Balke , Beverly Kuhn (TTI) Davey Warren (Brudis and Associates)		**8. Performing Organization Report No.**
9. Performing Organization Name and Address Science Applications International Corporation 8301 Greensboro Drive McLean, VA 22101		**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.** DTFH61-10-D-00024
12. Sponsoring Agency Name and Address Federal Highway Administration U.S. Department of Transportation Office of Safety 1200 New Jersey Avenue, SE Washington, DC 20590		**13. Type of Report and Period Covered** **14. Sponsoring Agency Code**

15. Supplementary Notes

FHWA Project Manager – Guan Xu

FHWA Technical Reviewers – Richard Knoblauch, Ed Rice, Roemer Alfelor

16. Abstract

This report provides guidance on the use of variable speed limit (VSL) systems in wet weather at locations where the operating speed exceeds the design speed and the stopping distance exceeds the available sight distance. The use of VSLs during inclement weather or other less than ideal conditions can improve safety by decreasing the risks associated with traveling at speeds that are higher than appropriate for the conditions. By using VSLs, agencies can take into account traffic volume, operating speeds, weather information, sight distance, and roadway surface condition when posting speed limits.

This report provides guidelines for the design, installation, operation, maintenance, and enforcement of wet weather VSL systems. The guidelines presented in this report are intended for a broad range of audiences, from the transportation policy professionals who are considering whether or not their agency should use VSL systems to the engineers who are actually designing VSL systems for their jurisdictions. The information within this guidebook should be useful to anyone considering the implementation or development of a VSL system. This document also provides examples of the challenges, obstacles and issues that organizations have encountered when implementing VSL systems so that future implementers can develop practices that will increase their likelihood of success.

17. Key Words Variable Speed Limits, Wet Weather, Roadway Conditions, Pavement Conditions, Visibility, Sight Distance, Traffic Management Center	**18. Distribution Statement** No restrictions. This document is available to the public from: The National Technical Information Service, Springfield, VA 22161.

19. Security Clasif. (of this report) Unclassified	**20. Security Clasif. (of this page)** Unclassified	**21. No. of Pages** 40	**21. Price** N/A

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

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Chapter 1. Introduction

1.1 Background

The purpose of any speed limit sign is to inform drivers of the maximum acceptable and safe speed for normal travel conditions. However, if roadway conditions are less than ideal, such as during wet weather conditions, conventional static speed limit signs may not display an appropriate, reasonable, and/or safe speed limit for those conditions. The use of variable speed limit (VSL) systems during inclement weather or other less than ideal conditions can improve safety by decreasing the risks associated with traveling at speeds that are higher than appropriate for the conditions. By using VSLs, agencies can take into account traffic volume, operating speeds, weather information, sight distance, and roadway surface condition when posting speed limits. An example of a VSL sign is shown in Figure 1. Wet weather conditions are a contributing factor to many crashes throughout the United States. Between 2000 and 2009, 12.6 percent of fatal crashes occurred on wet pavement *(1)*. This chapter provides an introduction to VSLs and an overview of the important factors to consider when implementing a successful wet weather VSL system.

Figure 1: VSL Sign Installation in Pennsylvania
(Source: Bryan Katz)

After the investigation of a wet weather fatal crash on Interstate 35 near Hewitt, Texas on February 14, 2003, the National Transportation Safety Board (NTSB) issued five safety recommendations to the Federal Highway Administration (FHWA) for improving traffic safety under wet weather conditions. These safety recommendations are as follows:

1. H-05-12 – Issue guidance to your field offices describing the inadequate stopping sight distance that could occur when poor vertical geometries exist at locations with low coefficients of friction and speeds higher than the design speed, and work with States to inventory such locations.
2. H-05-13 – Once the locations in Safety Recommendations H-05-12 have been identified, assist the States in developing and implementing a plan for repaving or other roadway improvements.
3. H-05-14 – Issue guidance recommending the use of VSL signs in wet weather at locations where the operating speed exceeds the design speed and the stopping distance exceeds the available sight distance.
4. H-05-15 – Conduct research on commercial vehicle tire and wet pavement surface interaction to determine minimum frictional quality standards for commercial tires on wet pavement; once completed, 1) revise the tire requirements for commercial vehicles operating on wet pavement at highway speeds, and 2) develop minimum acceptable pavement coefficients of friction and maximum permissible pavement rut depths as part of roadway maintenance requirements, as appropriate.

5. H-05-16 – Review State programs that identify and eliminate locations with a high risk of wet weather accidents and develop and issue a best practice guide on wet weather accident reduction.

This project was conducted in response to recommendation H-05-14. The purpose of this project was to develop guidelines for using VSL systems in wet weather, particularly when operating speed exceeds design speed and stopping distance exceeds sight distance. The study team developed these guidelines after a thorough investigation of the state-of-the-practice of VSL installations in the United States and a complete review of the practices and procedures that States use when implementing and operating VSL systems. A table of the known VSL installations in the United States can be found in Appendix A.

This document also provides examples of the challenges, obstacles and issues that organizations have encountered when implementing VSL systems so that future implementers can develop practices that will increase their likelihood of success. These guidelines are intended for a broad range of audiences, from the transportation policy professionals who are considering whether or not their agency should use VSL systems to the engineers who are actually designing VSL systems for their jurisdictions. The information within this guidebook should be useful to anyone considering the implementation or development of a VSL system.

1.2 Roadmap to the Guideline Document

- Chapter 1 (this chapter) provides an introduction to VSL and the guidebook itself.
- Chapter 2 identifies driver, vehicle, and roadway characteristics affected by wet weather driving conditions.
- Chapter 3 provides design guidelines on setting appropriate speed limits and other recommendations related to the signage and development of algorithms to use for VSL systems in wet weather.
- Chapter 4 provides guidelines on the installation, operation, and maintenance of VSL systems in wet weather.
- Chapter 5 provides guidelines on coordinating VSL system installation with law enforcement and the judicial system.
- Chapter 6 describes case studies of agencies that have implemented successful VSL systems for wet weather conditions.

1.3 Design Speed, Operating Speed, and Maximum Safe Speed

The American Association of State Highway and Transportation Officials (AASHTO) defines design speed as the speed used to determine various geometric design features of a roadway. The design speed is based on various geometric features but it does not account for all types of inclement weather. Operating speed is defined by AASHTO as the speed at which drivers operate their vehicles during free-flow conditions *(2)*. Generally, the 85th percentile operating speed is used to calculate the posted speed of a facility. Although undesirable, in some cases the operating speed may exceed the design speed. The maximum safe speed is often independent of both the design speed on plans and the operating speed. Although the term "maximum safe speed" is referred to in several different ways in literature, a universally accepted definition does not exist. In this report, maximum safe speed refers to the speed beyond which driving conditions would be deemed unsafe for a particular vehicle and thus could potentially result in a crash. These driving conditions refer to the existing roadway geometry, pavement surface condition, or weather conditions such as rain, snow, or fog. The reason that the maximum safe speed depends on the specific vehicle is each type of vehicle has different characteristics that can result in a different maximum safe speed. For example, a truck's maximum safe speed on a horizontal curve under wet conditions will most likely be lower than a car's maximum safe speed under the same conditions.

VSLs can be beneficial when the operating speed exceeds the design speed. This situation can occur at locations where there is a change in alignment or roadway surface condition and motorists travel through a curve at a speed that exceeds the design speed. Additionally, VSLs are beneficial when the operating speed is greater than the maximum safe speed. Since the maximum safe speed is based on conditions such as wet weather, a VSL can display a speed that matches the maximum safe speed for a particular condition. It is important to recognize that there are several factors that contribute to determining the maximum safe speed, including: design plans, roadway geometry, AASHTO assumptions, pavement friction, braking friction, and reaction times based on the best performing drivers and vehicles.

1.4 Sight Distance and Factors Affecting Stopping Distance

As appropriate design speeds and maximum safe speeds are determined for a given roadway segment, it is important that the relationship between sight distance and stopping distance is also considered. A driver must be able to see the roadway ahead and have adequate time to come to a complete stop when required. Calculations can be made to determine the available sight distance on both horizontal and vertical curves. Visibility sensors can be used to determine appropriate sight distance under rain, snow, or fog conditions.

The design speed determines the required stopping distance under design conditions. The maximum safe speed can be determined under wet or other adverse conditions using various coefficients of adhesion, available sight distance, and roadway grade. The coefficient of adhesion will vary based on the pavement surface characteristics (both micro- and macro-texture), vehicle operating parameters, tire properties, and environmental conditions. Stopping distance calculations take into account both the distance traveled during a driver's reaction time as well as the braking distance required for the vehicle to come to a complete stop. VSL systems can be used to reduce operating speeds so that the stopping distance is equal to or less than the available sight distance under less than ideal conditions, such as during wet weather. This topic is discussed in more detail in Chapter 2 of this Guidebook, while additional information on safe speed calculations can be found in Chapter 3.

1.5 When to Consider Variable Speed Limit Systems

Wet weather VSL systems should be considered in locations where there is a history of adverse weather conditions, where crash rates are higher than expected, where safe speeds are reduced more than 10 miles per hour (mph) below the posted speed limits, and where stopping distances exceed the available sight distance. The FHWA's ENTERPRISE Pooled Fund Study provided four warrants to consider when deploying regulatory VSL systems *(3)*. While the ENTERPRISE Pooled Fund Study suggests that maximizing capacity and work zone safety are two reasons for considering VSLs, there are also warrants for safe stopping distance and safe travel speeds under adverse weather conditions. However, these warrants do not consider the situations when the stopping distance exceeds the sight distance. The warrants have been modified and simplified in Chapter 3.

There are many cases where static speed limit signs are effective in providing an appropriate driving speed for motorists.   When wet weather conditions occur, drivers will typically adjust their speed in a manner that is safe for conditions. However, there are times, particularly when ideal conditions do not exist, when VSL systems should be considered in order to communicate appropriate speed limits based on real-time information. The most common implementations include locations with frequent adverse weather conditions, congestion, traffic incidents, and/or work zones.

Drivers typically have the ability to select safe speeds accurately under wet weather conditions on a straight roadway section with good pavement quality and adequate sight distances. However, if ideal conditions do not exist, and the roadway does not meet the driver's expectations, there is a greater chance that a driver error could result in a crash. For example, drivers typically cannot determine simply from driving on a pavement surface that their braking distances are increased due to poor available friction. Additionally, an unfamiliar motorist may not be aware of sight distance issues related to a horizontal curve until he or she enters the curve and has to apply the brakes suddenly. In situations such as these, VSLs may be an appropriate solution to communicate a safe driving speed to motorists. However, to be credible and effective, VSLs should be set for the average vehicle and driver and adjusted for actual weather and pavement conditions.

1.6 Other Countermeasures to Consider

In considering when and where to deploy VSL as a weather-responsive traffic management strategy, agencies should also consider other countermeasures prior to installing a VSL system. These countermeasures can include installing "Slippery When Wet" signs, fluorescent yellow sign sheeting for enhanced conspicuity on signs, flashing beacons, and skid-resistant surface treatments, which could increase the critical speed to above the operating speed. In the vicinity of reduced sight distance due to horizontal curves, dynamic curve warning systems, horizontal signing, and optical speed bars may be considered. Further information on these and other countermeasures can be found in the following resources:

- Engineering Countermeasures for Reducing Speeds. U.S. Department of Transportation, Federal Highway Administration, Washington, D.C. Available at http://safety.fhwa.dot.gov/speedmgt/ref_mats/eng_count/. Accessed on April 17, 2012.
- McGee, H.W. and F.R. Hanscom. Low-Cost Treatments for Horizontal Curve Safety. FHWA-SA-07-002. U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., December 2006. Available at http://safety.fhwa.dot.gov/roadway_dept/horicurves/fhwasa07002/. Accessed on July 3, 2012.

Chapter 2. Driver, Vehicle, and Roadway Characteristics Related to Driving in Wet Weather

2.1 The Driving Task

A driver is continuously balancing three main tasks: control, guidance, and navigation. Control refers to all activities involved in the driver's interaction with the vehicle. The driver receives control information from the vehicle's displays, from the "feel" of the vehicle, and from the roadway. Control also involves the driver maintaining a safe speed and keeping the vehicle on the proper path *(4, 5)*.

Guidance of the vehicle is how the driver interacts with other vehicles, the roadway, and the surrounding environment to guide the vehicle safely down the roadway. As drivers travel along the roadway, they receive information (e.g., alignment, grade, hazards, traffic, traffic control devices, etc.) from various sources and use their judgment to adjust the vehicle's speed and path appropriately *(4)*.

Navigation is how the driver is going to get from their origin to their destination. Navigation involves both pre-trip and in-trip decisions. Pre-trip navigation can include planning a route, receiving instructions, mapping a route, etc. In-trip navigation includes using route guidance and landmarks en-route to get from the origin to the destination *(4)*. Drivers may also use electronic navigation devices or global positioning system (GPS) units to obtain navigation information en-route.

At any given time, a driver is receiving and processing information that contributes to decisions being made regarding one or more of these tasks. Drivers continuously use information from a number of real-time sources as well as their experiences and general expectations to make driving decisions. Drivers "juggle" these multiple sources of information by giving any one piece of information a short amount of attention before moving onto the next piece of information. Drivers should prioritize the relative importance of the information being received. Importance is assigned based on the consequence of not paying attention to an information source. Information with the highest importance should be addressed first. Obviously, among the main driving tasks, control is the most important, followed by guidance and navigation. Thus, under less than ideal conditions, such as wet weather, drivers tend to pay more attention to the control of the vehicle and less attention to less critical information *(4)*.

2.2 Sight Distance

For the safe and efficient operation of vehicles, drivers need to be able to see the roadway ahead and any potential hazard soon enough to react to it. Sight distance is the length of roadway ahead that is visible to a driver. Sight distance is comprised of driver perception-reaction time and the time to complete the maneuver safely. The driver perception-reaction time includes the time to perceive the condition (e.g., an object in the roadway), time to complete cognitive functions to understand the condition (e.g., recognize the object and decide if and how to respond), and time to initiate the desired maneuver (e.g., take foot off accelerator and step on brake). The driver perception-reaction time varies based on the distance to and nature of the object, the visual performance of the driver, the cognitive capabilities of the driver, the atmospheric visibility, and the roadway environment. The time to safely complete the maneuver is primarily impacted by the roadway condition and the vehicle's performance capabilities, especially tire-pavement friction, road-surface conditions (e.g., wet), and downgrades *(6)*.

In general, sight distance should be sufficient to allow a driver traveling at or near the design speed to stop before reaching a stationary object in the travel path. Stopping sight distance is the distance traveled from the instant the driver sees and recognizes a hazard to the instant the brakes are applied (brake reaction time) plus the distance actually needed to stop the vehicle (braking distance). *A Policy on Geometric Design of Highways and Streets (2)* provides a thorough explanation of stopping sight distance as well as the design values and stopping sight distances for various design speeds based on assumed conditions on level roadways. The design values are determined using values for a predetermined design driver and design vehicle under a predetermined set of circumstances. However, the stopping distance can vary based on factors, including (but not limited to) driver reaction times, vehicle deceleration rates (which are different for each type of vehicle), braking efficiency, coefficient of adhesion, and roadway grade. The coefficient of adhesion refers to the frictional force between the tires and the pavement. Thus, the coefficient of adhesion is lower under poor tire conditions and poor pavement conditions than it would be for good tire conditions on dry pavement. A decrease in the coefficient of adhesion will result in an increase in stopping distance. Using longer distances increases the margin for error for all drivers, especially during wet weather conditions. However, as discussed in Chapter 1, there are roadway environments where the operating speed is greater than the design speed and the safe stopping distance is greater than the available sight distance.

2.3 The Driver

In 2010, there were more than 210 million drivers in the United States. Approximately half of these drivers were male and half were female. Almost three-quarters of these drivers (71 percent) fall into the 25 to 64 age range, with younger drivers (24 or less) comprising 13 percent of the driving population and older drivers (at least 65) representing 16 percent of the driving population *(7)*. However, it is expected that the older driving population will double over the next 30 years *(8)*. The changing demographics of the driving population are important to recognize when considering the impacts of wet weather on the driving task. Typically, drivers with more experience are less risk tolerant than younger drivers. Driver experience and maturity impacts decision-making, especially under less than ideal conditions, such as wet weather. For example, in wet weather conditions, younger drivers may tend to devote less attention to control of the vehicle than they should. Brake reaction times can vary between drivers from as low as 0.64 seconds for alerted drivers to over 3.5 seconds for un-alerted drivers when simple signals are used in research tests *(2)*.

2.4 The Vehicle

In 2010, an estimated 242 million motor vehicles were registered in the United States *(7)*. These motor vehicles consist of passenger cars, light trucks and vans, motorcycles, recreational vehicles, buses, and commercial vehicles, all of which have different design and operational characteristics. Thus, the amount of control needed to drive a vehicle safely varies based on the type of vehicle. For example, it is less demanding to control a passenger vehicle with an automatic transmission than it is to control a commercial vehicle with multiple gears and clutches. Even so, most control activities, once mastered, are performed automatically with little conscious thought *(4)*. A vehicle's design and maintenance also impact a driver's ability to control the vehicle, especially during wet weather. Anti-lock brakes reduce wheel lock-up under braking, which reduces the likelihood of skidding on slippery pavement. Vehicle maintenance items include, but are not limited to, properly working windshield wipers, proper tire pressures, adequate amount of tread on tires, and maintenance of the brake system. AASHTO suggests that although most drivers decelerate at rates greater than 14.8 ft/s^2 when an unexpected object is encountered in the roadway, 90% of drivers decelerate at rates greater than 11.2 ft/s^2, and thus 11.2 ft/s^2 is used as a design value *(2)*.

The previously mentioned stopping sight distances are typically based on passenger cars, so they do not explicitly consider commercial vehicles. In general, commercial vehicles need longer stopping sight distances than passenger cars. However, because commercial vehicle drivers are positioned higher above the pavement, they can generally see further down the road than a driver of a passenger car. Thus, commercial vehicle drivers typically have more time to perceive and react to a potential hazard, somewhat making up for the increased braking distances. So, separate stopping sight distances for different vehicle types are not typically used in highway design. One exception includes locations where horizontal sight restrictions exist on downgrades, especially at the end of long downgrades where commercial vehicle speeds are similar to or exceed passenger car speeds. Under such conditions, it is desirable to provide stopping sight distances longer than those provided for passenger cars *(2)*. Another situation where commercial vehicle drivers may not be able to see further than passenger car drivers is during rain. Under these conditions, the intensity of the rain may limit the view of the roadway and surrounding environment of all drivers.

2.5 The Visual Scene

Wet weather reduces the visibility of potential hazards and traffic control devices, making them more difficult for drivers to detect. The distance at which a driver can see a non-illuminated, non-reflective object is dependent upon a variety of factors, including the vehicle's headlights, the driver's visual capabilities, and the driver's expectation of seeing a hazard. While many traffic control devices are retroreflective, rain can reduce the retroreflective materials' ability to perform and decrease the visibility of the device. Under wet weather conditions, internally illuminated traffic control devices may provide better visibility.

As discussed, under normal driving situations drivers have the ability to process information from multiple sources, but as conditions deteriorate, they begin shedding information sources in order to attend to the primary driving functions of control and guidance. Traffic control devices (e.g., speed limit signs) have to compete for the driver's attention; therefore, it is critical that they be placed where drivers can see them and quickly obtain information.

2.6 The Pavement

As mentioned, the time to safely stop once a hazard is detected and the driver applies the brakes is dependent upon road surface conditions and available tire-pavement friction. Pavement conditions that may contribute to an increase in wet weather crashes include *(9)*:

- Rutting or wheel path channelization.
- Build-up on shoulder edges that causes ponding on the road surface.
- Bleeding of pavements.
- Drainage issues that result in water on the pavement.
- Geometrics (grades and curvature).

Water on the pavement can significantly reduce tire-pavement friction. Even as little as 0.002 inches of water on the pavement can reduce the coefficient of friction by 20 to 30 percent *(10)*.

Rutting, build-up on the shoulder, or drainage issues can result in relatively thick water films on the pavement surface. The coefficient of friction for a vehicle tire sliding on wet pavement decreases exponentially as the water film thickness increases. The effect of the water film thickness is influenced by tire design and condition, with worn, smooth, and "bald" tires being most sensitive. At low speeds (less than 20 mph), the effect of water film thickness on friction is minimal; however, at higher speeds (greater than 40 mph), the effect is more pronounced. When relatively thick water films are present and vehicles are traveling at higher speeds, hydroplaning can occur *(9)*.

Obviously, the deceleration maneuver is impacted by wet pavement. *A Policy on Geometric Design of Highways and Streets (2)* recommends 11.2 ft/s^2, a comfortable deceleration rate for most drivers, as the deceleration threshold for determining adequate stopping sight distance. Such deceleration corresponds to the braking friction on packed snow and thus is within the driver's capability to maintain control of the vehicle during braking maneuvers on wet pavement. Also, most vehicle braking systems and the tire-pavement friction levels on most roadways, even under wet conditions, are capable of providing a deceleration rate of at least 11.2 ft/s^2.

Previous research has shown that under emergency conditions, mean deceleration rates are the same between good and poor visibility conditions, but differ among good and poor traction conditions (17.7 ft/s^2 and 13.8 ft/s^2, respectively). However, the 85th percentile values are the same (12.1 ft/s^2). On wet pavement with vehicles without an anti-lock braking system, the mean and 85th percentile deceleration rates are about 13.8 ft/s^2 and 12.2 ft/s^2, respectively (54% and 47% of the pavement's coefficient of friction, respectively). On wet pavement with anti-lock brakes, the mean and 85th percentile deceleration rates are about 17.1 ft/s^2 and 14.5 ft/s^2, respectively (66% and 56% of the pavement's coefficient of friction, respectively) *(6)*.

2.7 Speed Zoning

All States follow the same basic approach to formulate speed regulations. This approach specifies that drivers should not exceed speeds that are safe and prudent for existing conditions, even if the posted speed limit indicates that a higher speed is allowable. Thus, a driver is responsible for considering the roadway environment and potential hazards when selecting a speed. This includes weather, visibility, traffic, and roadway characteristics *(5)*.

A safe and reasonable speed limit is typically based on a statutory speed limit or traffic engineering study. Speed zones established based on these studies may change the basic speed limits set by law. Speed zones can either be regulatory or advisory. Regulatory speed limits are enforceable, whereas advisory speed limits are generally not enforceable, although drivers could be cited for violating the basic speed rule that requires drivers to drive at an appropriate reduced speed when necessary *(5)*.

In most cases, the establishment of a speed zone is predicated on the assumption that most drivers operate their vehicles in a safe, reasonable, and prudent manner. The speeds that the majority of drivers choose to travel on a given roadway segment are considered an indication of safe and reasonable speeds. The 85th percentile speed of free flowing vehicles, the speed at which 85% of drivers travel at or below at a given point on the roadway, is commonly taken to determine the posted speed for that segment. This driver-defined maximum safe speed can then be adjusted slightly, if necessary, based on site-specific factors, including sight distance restrictions, pavement conditions, etc. A speed limit to the nearest 5 mph increment of that maximum safe speed is then typically posted *(5, 11)*.

Even though the speed limit may be based on the 85th percentile speed, many studies have reported that the posted speed limit is usually significantly lower than the measured 85th percentile value. For example, the Institute of Transportation Engineers (ITE) found that for roadways with posted speed limits of 45 mph and below, most of the measured speeds are higher than the posted speed limit *(12)*. When the posted speed limit is 55 mph or more, about half of the measured speeds are above the posted speed limit. This may be due in part to the difficulty in predicting operating speeds (and thus the speed limit) based on the roadway geometry and roadside features.

As discussed previously, all basic State speed laws typically require drivers to adjust their speed to existing road conditions; thus, the primary responsibility for adjusting speed to adverse conditions, such as wet weather, rests with the driver. Nevertheless, in an attempt to improve safety, some jurisdictions have decided to reduce speed limits at specific locations during adverse weather conditions.

A VSL is one that changes with changing conditions. The use of this operational strategy is by no means new; dating back more than 60 years, agencies have modified speed limits on a temporary basis for a variety of reasons. School zones and work zones are some of the more common applications of VSLs. Modern VSL systems use technology to adjust speed limits in real-time. Speeds may be modified based on traffic conditions, adverse weather conditions, road surface conditions, or work zones to better control operating speeds within the monitored section of roadway. VSLs not only work to maintain safe driving speeds, but also to warn drivers of changing road conditions. However, when wet weather conditions get too bad, the speed limit displayed on the VSL could still be "faster" than what drivers feel is a speed at which they can comfortably control and guide their vehicle. This can be problematic because drivers trust VSL systems to provide them with the maximum safe speed for the conditions.

As noted, driver behavior varies during adverse weather events based on experience and risk tolerance. Therefore, some drivers may slow down when they encounter wet weather, but others may maintain or even increase their speeds. The result of this varying behavior may be a significant speed differential between slower and faster vehicles on the roadway. It is generally accepted that an increase in speed differential increases the potential for conflicts between vehicles, which in turn increases the potential for crashes. VSL systems based on weather conditions can work to reduce the speed differential under unpredictable events and encourage more uniform speeds. However, there is still the potential for speed differentials to occur immediately upstream of the rain event and reduced speed limit (i.e., as drivers enter the reduced speed limit zone).

Chapter 3. Guidelines for the Design of Wet Weather Variable Speed Limit Systems

This chapter provides design guidelines on setting appropriate speeds and other details related to speed limit signage and the development of algorithms for the use of VSL systems in wet weather. This chapter includes guidelines for determining the appropriate type of VSL system to use, setting appropriate speed limits for VSLs, and determining the display and locations of VSL signs.

3.1 Determining the Appropriate Type of Variable Speed Limit System to Use

Guideline 1: Conduct an analysis to determine if a wet weather variable speed limit system is appropriate.

Figure 2 depicts a decision-making process for assessing whether a Wet Weather VSL is appropriate for a given location. If a location is not appropriate for a VSL system, then other countermeasures may be appropriate (refer to section 1.6).

Whether or not a Wet Weather VSL system should be considered is dependent on an area experiencing adverse weather conditions that impact traffic, a higher crash rate than expected for similar segments, a regularly occurring speed requirement that reduces operating speeds 10 mph less than the typical posted speed limit, and conditions where stopping distance for average drivers and vehicles exceeds the available sight distance, based on the physical condition of the road. These conditions might exist due to alignment changes or weather conditions such as snow, rain, or fog.

When all guidelines are met, a Wet Weather VSL installation would be justified. If the rest of the guidelines are met and there are no conditions where the stopping distance exceeds the available sight distance, a Wet Weather VSL may still be considered, based upon traffic engineering judgment.

Guideline 2: A regulatory variable speed limit system is preferable over an advisory variable speed limit system.

It is important to recognize that a regulatory system can be enforced, while an advisory system typically cannot. A regulatory system is preferable, especially for longer segments, because it usually results in a much higher compliance rate. However, it also requires a larger responsibility to display accurate real-time data and to be credible to most drivers. This is particularly important when using VSLs in wet weather,

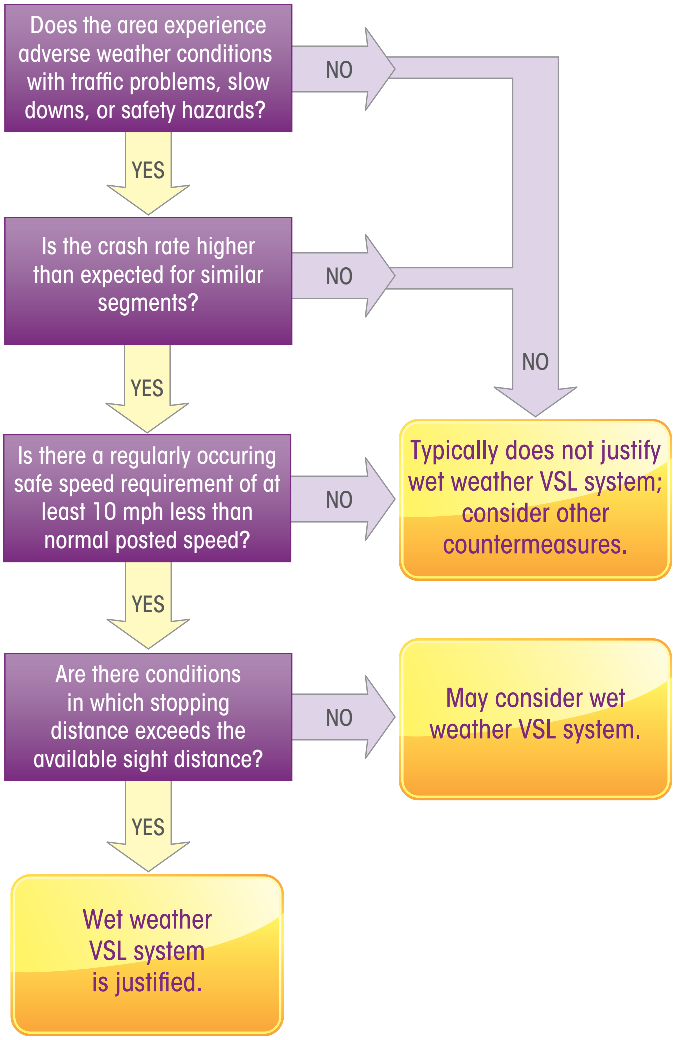

Figure 2: Wet Weather Variable Speed Limit Flowchart

because a regulatory system displaying speeds that are not based on real-time weather conditions can result in inappropriate speed recommendations. Figure 3 illustrates a decision tool for determining whether a system should be regulatory or advisory. The majority of VSL systems currently active in the United States are regulatory and therefore enforceable. Examples of regulatory and advisory VSL signs are shown in Figure 4. The main consideration for a regulatory versus advisory speed limit should be whether or not the area under consideration is a stretch of road and not an isolated location.

Another consideration the highway agency must take into account is the legal authority that its State has for posting variable speed limits. It is important in order to ensure that the agency has legal authority to set and enforce VSLs. This is elaborated upon in 5.2 Guideline 18: Determine the legal authority to post variable speed limits.

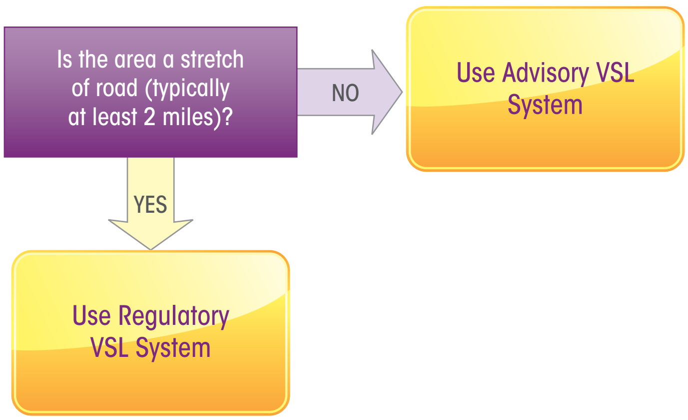

Figure 3: Regulatory Versus Advisory VSL Flowchart

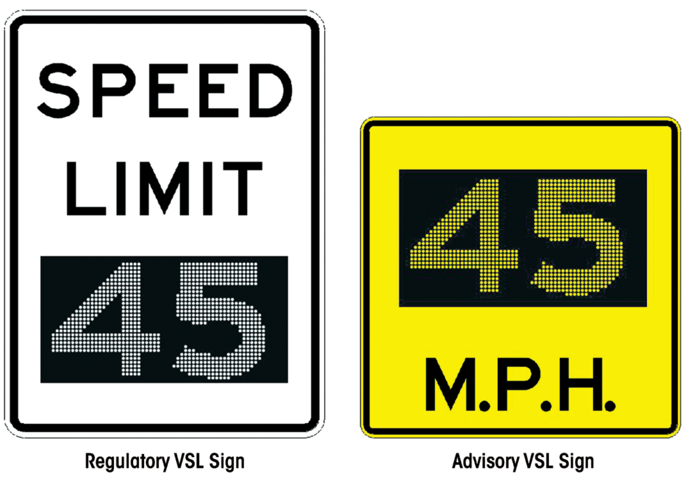

Figure 4: Example Regulatory and Advisory Variable Speed Limit Signs

Some States choose to use advisory VSL systems for specific reasons. For example, Missouri's VSL system was unresponsive to changing conditions, which resulted in a lack of compliance and acceptance by drivers and law enforcement, so the system was changed to advisory. Minnesota uses an advisory system because a regulatory system would have required changes to State statutes, and the advisory system could be more readily deployed.

Guideline 3: Consider a semi-automated or automated approach for variable speed limit systems.

Automated and semi-automated speed limit systems use an algorithm that determines what the maximum safe speed is based on real-time field conditions. With semi-automated systems, the traffic management center (TMC) operator is notified of what the algorithm-recommended speed is, at which point the operator has the option of approving or rejecting it. The systems can be designed so that the speed limit will be automatically displayed if the operator does not respond within a certain period of time. If an automated system is being used, it is important that the credibility of the speed limits be checked and modified frequently — annually, at a minimum.

If it is necessary to operate a VSL in a manual setting, it is important to determine who is responsible for activating the speed limits. Although it is not necessary for this responsible party to be TMC personnel, that is often the case. Whoever the chosen responsible party is should set and change speed limits based on real-time field and weather conditions. It is also important that law enforcement officers and other authority figures such as supervisory maintenance personnel have the ability to suggest a speed change. This is important because less than ideal conditions may exist on the roadway that the system controller, who may be located remotely, is not aware of.

3.2 Determining Speed Limits for Variable Speed Limit Systems

Guideline 4: Incorporate weather responsive decision support into existing variable speed limit algorithms to determine the displayed speed limit.

As discussed in the previous chapters, sight distance and stopping distance are the primary factors to consider when setting speed limits. If drivers cannot see the roadway ahead, they may not have time to avoid a potential hazard. Drivers traveling at or near the speed limit should have time to make an emergency stop before reaching the potential hazard in their driving path.

A weather responsive algorithm that uses information from traffic, pavement, and weather sensors should be used to determine the maximum safe speed limit, based on real-time conditions, which should be displayed on the VSL system. The sensor data should provide the algorithm with sufficient information to determine a speed limit that will allow for safe sight and stopping distances under the current conditions. It is particularly important for a VSL to display speeds that are representative of the conditions, especially during less than ideal weather conditions, because drivers trust the VSL to do so.

At present, there are no generally accepted, comprehensive algorithms for determining appropriate speeds for VSLs in wet weather conditions when there are sight distance concerns. For informational purposes, an untested sample algorithm is provided in Figure 5 to demonstrate the inputs and the calculations that need to be performed, using standard, accepted roadway design equations, as detailed in the rest of this section. The Western Transportation Institute is currently performing research for the Oregon Department of Transportation (DOT) under the study "Evaluation of a Variable Speed Limit System for Wet and Extreme Weather Conditions" to determine a wet weather algorithm. The first phase of this research has been completed, which included evaluation of a sensor system to measure the road surface state and depth of precipitation on the roadway. This system has proved successful in consistently identifying the roadway condition as dry, moist, wet, snowy or icy on both asphalt and concrete.

The sample algorithm assumes that all speed limits should be set to the next lowest 5 mph increment and that the selected speed limit will be no higher than the maximum allowable posted speed and no lower than the minimum predetermined speed. It is also assumed that an algorithm may be used on its own or may be used as part of an algorithm for VSL systems that are specially designed for other purposes. The sample algorithm begins with obtaining speed and pavement condition data and determining if the roadway is wet. If the roadway is not wet, the sample algorithm stops and the lesser of the 85th percentile operating speed or design speed should be displayed. If the roadway is wet, the sample algorithm continues. It is recommended that site-specific coefficients of roadway adhesion be measured for a variety of weather conditions, although the sample algorithm can be used whether or not the pavement quality is known. Although different studies have shown a variety of values for the coefficient of adhesion, if the actual values are not known, one can assume a coefficient of adhesion value, μ, of 0.6 for rain conditions and 0.25 for snow or ice for maximum braking on poor pavement, based on past research *(13)*. Once sight distance, S, is determined from a field study or from visibility sensors in inclement conditions, the sight distance can be used to calculate the displayed VSL speed, V, using μ, S, and G, where V_1 indicates the vehicle speed in feet per second, g refers to the gravitational constant of 32.2 ft/s^e, η_b refers to the braking efficiency as a decimal percentage, μ indicates the coefficient of road adhesion, and G is equal to the roadway grade in percent expressed as a decimal (i.e. a downhill grade of -3% is -0.03). This relationship is based on an accepted sight distance equation *(14)* and is expressed as:

$$S = \frac{V_1^2}{2g(\eta b \mu \pm G)}$$

where
S = sight distance (ft),
V_1 = displayed VSL speed (ft/s),
g = gravitational constant (32.2 ft/s^e),
η_b = braking efficiency (decimal percentage),
μ = coefficient of road adhesion (unitless),
G = roadway grade (percent expressed as a decimal).

When converting the initial speed V1 from feet per second to miles per hour, setting the gravitational constant g equal to 32.2 ft/s^2, assuming a value of 1.0 for a vehicle's braking efficiency factor since antilock braking systems are more prevalent on today's vehicles, and adding in the distance traveled during perception-reaction time using the accepted value of 2.5 seconds, the following equations are derived:

$$S = \frac{0.03V^2}{\mu \pm G} + 3.67V$$

$$\text{OR} \quad \frac{\left(-3.67 + \sqrt{13.47 + \frac{0.12}{\mu \pm G} * (S)}\right)}{\frac{0.06}{\mu \pm G}}$$

Once the VSL display speed is calculated, it can be compared to the current 85th percentile speed to determine whether the calculated displayed VSL speed, the current 85th percentile speed, or the design speed should be displayed. If the calculated speed is less than the 85th percentile speed, the lesser of the calculated speed or design speed should be displayed. If the calculated speed is not less than the 85th percentile speed, the lesser of the 85th percentile speed or design speed should be displayed. All

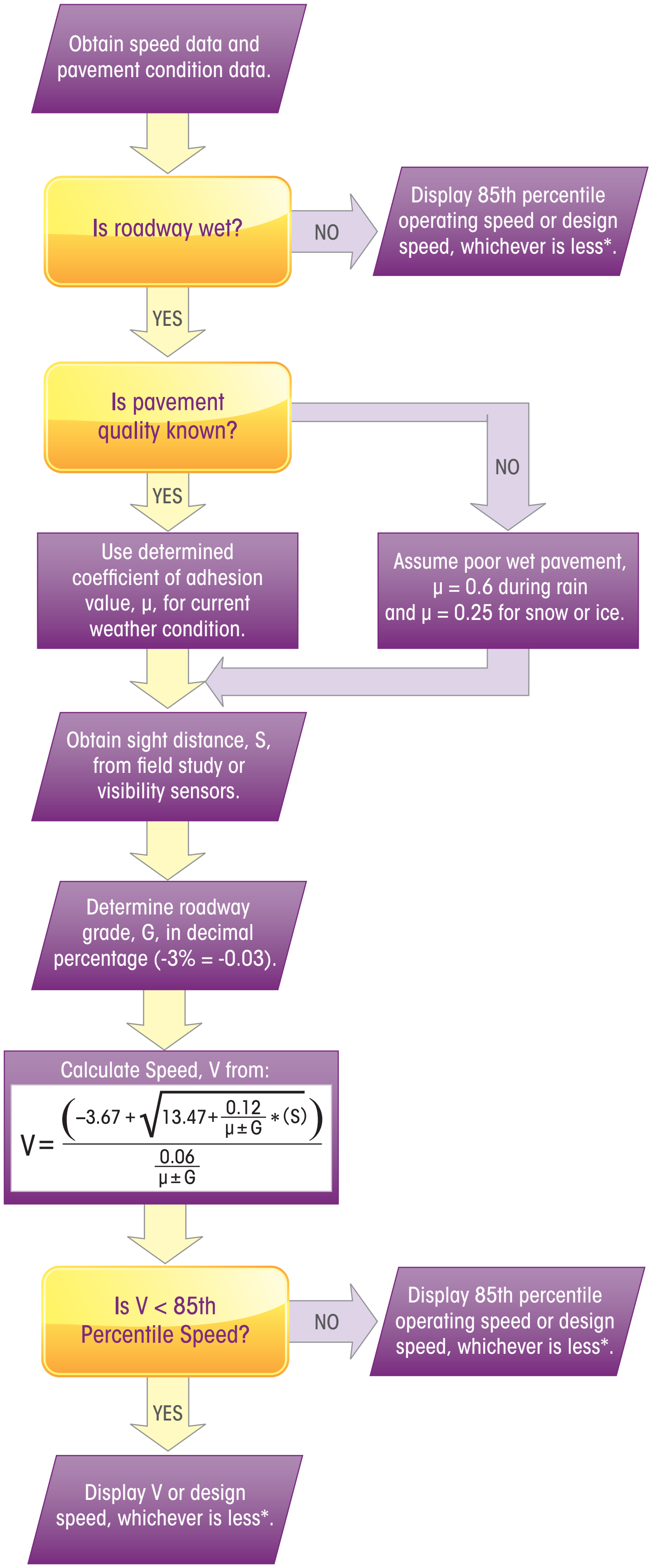

Figure 5: Example VSL Algorithm for Wet Weather

speed limits should be set to the next lowest 5 mph increment, but no higher than the maximum allowable posted speed limit and no lower than the minimum pre-determined displayed speed (for more details, see Guideline 6: For freeways, set a minimum speed limit of not less than 30 mph for regulatory systems or not less than 15 mph for advisory speed systems.

It is important to recognize that there are many variables that can be used for determining an appropriate speed based on sight distance. The example equation above uses very conservative values; however, since it is very important for a speed limit to be credible, it is necessary to develop and use an algorithm that results in reasonable speed limits that motorists will both find credible and respect. Therefore, it is critical to adjust the various values for braking efficiency, coefficients of adhesion, and perception-reaction times to those appropriate for each specific site. Conditions are rarely the same as those used in the sample algorithm above.

In addition to algorithms that calculate an appropriate speed limit to be displayed, some VSL systems use a pre-determined speed reduction for wet weather or poor surface conditions. This speed reduction can either be one pre-set speed that the system displays any time conditions are less than ideal, or it can be a range of speed limits that the system can display. The latter is recommended in order to incorporate adjustments for varying weather conditions.

Guideline 5: All speed limit algorithms and manual display calculations should be approved by a traffic engineering professional.

Algorithms and manual display determinations should be established based on a traffic engineering study, even if speed limits are manually adjusted by a TMC operator. It is not acceptable for a TMC operator to change and set VSLs arbitrarily.

Guideline 6: For freeways, set a minimum speed limit of not less than 30 mph for regulatory systems or not less than 15 mph for advisory speed systems.

It is important to pre-set a minimum speed limit on a VSL system. Many international agencies use a minimum speed limit of 30 mph for VSL systems, whereas some State agencies within the United States have set a minimum speed limit of 40 mph, or no more than 20 mph under the normal posted speed limit. Advisory VSL speed limits have been used in the United States with minimum displayed speeds of 15 mph.

Guideline 7: Use speed limits in 5 mph increments.

It is advisable that VSL systems be designed with 5 mph speed increments. The majority of the existing VSL systems are currently successfully using 5 mph hour speed increments. Speed increments smaller than 5 mph will likely confuse drivers, as speed limits are always posted in multiples of 5 mph. Increments greater than 5 mph will not provide drivers with an accurate, safe speed limit.

3.3 Determining Display and Location of Variable Speed Limit Signs

Guideline 8: Display variable speed limit changes for at least 1 minute.

Speed limits should be updated frequently enough that they represent real-time conditions, but not so frequently that they confuse or overwhelm drivers. For automated systems, speed recommendations should be generated and sent to the VSL operator at intervals of 60 seconds or less so that the system is generating speed recommendations based on current conditions. However, for all VSL systems, speeds should be displayed for at least 1 minute so that approaching drivers are not confused by seeing more than one speed limit change.

Guideline 9: Do not display reduced speed limits more than 1 mile upstream from the section of roadway where the reduced speed is desired.

Figure 6: Variable Speed Limit System on the New Jersey Turnpike (Source: Bryan Katz)

If the distance between the display and the speed reduction is too short, drivers will not have enough time to react. On the contrary, if the distance between them is too long, motorists will likely resume normal speeds before they reach the area where speed reduction is necessary. Credibility and responsiveness are the keys to a successful VSL system. VSL signs should be spaced at regular intervals where conditions are likely to vary. In Figure 6, a VSL system has been in place on the New Jersey Turnpike for decades that is capable of showing reduced speed limits due to ice, snow, fog, construction, accidents, or congestion. A replacement plan is currently in place to replace the signs, but changeable message signs will still be used with VSLs to adjust for various roadway conditions. If the congestion warning shown in the figure with the reduced speed limit of 45 mph is shown too far upstream of the congestion, motorists will begin to ignore the signs and will likely accelerate.

Guideline 10: Where variable speed limit signs are closely spaced, do not allow speed differentials of more than 15 mph without advance warning.

When VSLs are used in a corridor, it is important for there to be multiple displays throughout the corridor. These signs should not all automatically display the same speed; each speed displayed should be based on the real-time conditions at that location. This may require additional sensors, but it is an important design factor because rain intensity can vary greatly throughout a long corridor. However, it is important for VSLs that are less than 1 mile apart to not display speeds that are drastically different unless advance warning is provided of the reduced speed ahead. In the United States, one agency will not allow two consecutive VSLs to differ by more than 15 mph.

Guideline 11: Use Changeable Message Signs (CMS) to communicate reasons for speed reduction.

When possible, any additional data that can increase the credibility of the system should be included on a CMS, either attached to the VSL itself or nearby. If there are CMSs located near the VSL system, they should be used to communicate reasons for the reduced speeds. Some examples of messages to be displayed include "CAUTION RAIN AHEAD," "SLOW TRAFFIC AHEAD," "STOPPED TRAFFIC AHEAD," "XX MPH TRAFFIC AHEAD," or "REDUCED SPEED LIMIT AHEAD." For further information about acceptable messages to display on CMSs, refer to Chapter 2L of the MUTCD *(11)*. Legislation in some States may require a message sign indicating the reason for a speed change. Another good use for a CMS in coordination with a VSL system is to warn drivers entering the roadway that VSLs are being used. Figure 7 shows an example from Wyoming on Interstate 80 of how a sign can be used to warn of changing road conditions.

Figure 7: Changeable Message Sign in Wyoming Used to Communicate Speed Reduction Warning (Source: Bryan Katz)

Guideline 12: As with static speed limit signs, variable speed limit signs should be placed at all entrances to the roadway.

Additional speed limits should be installed beyond intersections and interchanges to remind users of the speed limit as well as to provide information to traffic entering from other roadways.

Additional information and guidance on communicating road weather messages, including VSL displays, can be found in http://ntl.bts.gov/lib/33000/33000/33047/rev_final_hf_analysis_road_weather.pdf.

Chapter 4. Guidelines for the Design, Installation, Operation, and Maintenance of Wet Weather Variable Speed Limit Systems

This chapter provides guidelines for developing a comprehensive concept of operations for a VSL system, determining where weather sensors are appropriate, ensuring that all necessary equipment is incorporated in the requirements, and developing an operations and maintenance plan.

4.1 Guideline 13: Develop a comprehensive concept of operations for the variable speed limit system.

Once the decision has been made that a VSL is appropriate for a location, the first step in the design process should be to develop a concept of operations. A concept of operations is a document that helps ensure that the system contains all required features. This document will describe the characteristics of the proposed system and may involve the full system engineering process for developing it. FHWA's *Systems Engineering Guidebook for ITS* can be used as a guide in this process *(15)*. In the operational concept, it is important to keep issues related to system operations and maintenance in mind and not to lose sight of the primary purpose of a VSL system, which is to reduce speed variance and avoid accidents caused by drivers traveling at an unsafe speed.

4.2 Guideline 14: Install appropriate weather sensors or use accurate weather data at problem locations.

It is important to determine the data needs of a VSL system, which data sources should be used to meet these needs, and when they should be used to ensure that adequate data is collected. The data that should be collected for wet weather VSLs are traffic, weather, and pavement conditions. Either real-time traffic cameras or sensors can be used to collect traffic data, but data on weather conditions can be collected in a variety of ways, including video, pavement sensors, weather radar, and sensors for rain and fog. Additionally, it is important for personnel on the ground, such as law enforcement, first responders, and other incident management personnel, to be able to request speed reductions based on their observations in cases where there are weather conditions that the system operator is not yet aware.

4.3 Guideline 15: Ensure that equipment required in the design process is incorporated into the installation requirements.

In order to avoid potential issues, there are a variety of details that need to be considered when designing any VSL system. These details include sensors, communications, power, operator confirmation and override, and a police notification process. When designing a VSL system, it is important to have adequate speed and visibility sensor coverage in the vicinity of the VSL sign. The most cost-effective time to add these sensors is when power and communication are being added at the beginning of the design phase. Although sensors may be costly to begin with, they are even more expensive to add after the system is designed. It is important to budget for and include a reasonable number of sensors in advance.

The communications and power for a VSL system should be designed in conjunction with other nearby devices that use similar technology, such as Closed Circuit Television (CCTV). If running landline communications and power is cost prohibitive, wireless communication and solar power may be more cost-effective options. However, it is important to consider overall power requirements and whether solar energy will provide enough power to the entire system. Additionally, cost and maintenance of batteries should be considered since battery life may be reduced in harsh environments. Additional technology that should be included in the design of a VSL system are speed detectors, rain sensors, Bluetooth detectors, and a method to provide police notifications. It is crucial for police officers to be aware of the speed limit that a VSL is displaying at any given time. Because police officers typically take their communications gear with them when shifts change, it is important that the notifications are broadcast and not sent directly to individual officers.

Another important detail to ensure is that the system outputs information into a log of all actions that the system makes. Regardless of whether changes in the system are made automatically or by the operator, it is extremely important to maintain a log. Any changes made to the speed display should be logged, as should the source of the change. This log should be designed in a way that ensures the data will be archived and backed up.

4.4 Guideline 16: Develop an Operations and Maintenance Plan.

A plan for operating and maintaining the VSL system should also be included in the process. It is easy for maintenance to be overlooked when budgets are being created, but it is a necessary element. To maintain both driver safety and driver trust in the system's accuracy, it is important that a VSL system operate properly and reliably. Agencies should develop plans in advance for regular cleaning, checking, and calibration, not just of the signs, but of all the equipment, including road weather and traffic sensors, cameras, and communications. This should be at least a 5-year plan and include information on funding requirements. Additional studies should be completed after the VSL has been implemented in order to measure the effectiveness of the system. If these studies show that the VSL system is not operating effectively, changes may need to be made regarding either the system itself or related enforcement efforts. Guidance for developing operations and maintenance manuals can be found in FHWA's *Systems Engineering Guidebook for ITS (16)*.

Important elements that are relevant to VSLs and should be clearly addressed in the plan include:

- Identification of the personnel responsible for operation and maintenance;
- Identification of the human resources and facilities, including tools, needed for operation and maintenance;
- Identification of funding sources for on-going operation and maintenance;

- Descriptions of the operation and maintenance activities to be performed;
- Descriptions of the checks to be made, and the data to be collected, for system health and performance monitoring;
- Necessary training for operators and maintenance personnel;
- Identification of other documents used in operations and maintenance, such as relevant policy directives, system configuration documentation, and operation and maintenance manuals;
- Preventive as well as reactive maintenance activities; and
- Life expectancy of the system and end-of-life replacement or upgrade processes.

Chapter 5. Guidelines for the Enforcement of Wet Weather Variable Speed Limit Systems

The following guidelines pertain to coordinating regulatory VSL system installation and operation with law enforcement and the judicial system. This includes guidance on coordinating and collaborating with law enforcement, determining legal authority, and maintaining a system log for evidence of potential violations.

5.1 Guideline 17: Coordinate and collaborate with law enforcement before deploying a variable speed limit system.

The State highway and law enforcement agencies should work together closely to determine how the VSL system will operate and be enforced. An interagency agreement should be developed that specifies the standard operating procedures to be followed and the respective responsibilities of the agencies. The agreement should address items such as:

- Delegation of authority for setting and changing the VSL;
- How the VSL will be set, including minimum and maximum speeds to be posted;
- How often the speed limit can change;
- How the VSL will be enforced;
- How best to communicate speed limit changes to patrol officers; and
- How law enforcement can access VSL sign displays and logs.

For any VSL to be successful in effectively managing speed and reducing crash risk, there must be a clear vision of how the system will operate and be enforced, and all participants must share this vision. Engineers, police, and the courts must know their roles and responsibilities as they relate to VSL. The potential benefits of this coordination and collaboration are as follows: a coordinated approach that supports the integrity of enforcement; an enforcement threat that deters inappropriate speeds and encourages compliance with VSL; speed violations successfully adjudicated; and increased safety for officers writing citations.

A map-based web page, text messages, email, or other methods could be used to notify patrol officers of current speed limits as well as the date and time of last change. A grace period should be allowed after each speed limit change before commencing enforcement of lower speed limits to ensure that the speed limit at time of the violation was seen by passing motorists.

5.2 Guideline 18: Determine the legal authority to post variable speed limits.

The highway agency will need to identify all jurisdictions responsible for speed enforcement in the zone with VSLs. This is important in order to ensure that the agency has legal authority to set and enforce VSLs so that speed violations can be successfully adjudicated. The State highway agency and State police must work with State legislators and council members in local jurisdictions to ensure that the necessary statutes are enacted or revised, as needed, to make VSLs enforceable.

Most, if not all, States have a speed zoning statute that delegates to the DOT the power to establish or change speed limits on the basis of an engineering investigation. The States that have implemented VSLs have done so mainly under the broad authority provided in this speed zoning provision of State Law or through a special provision in its vehicle code to allow for VSL systems.

Speed limits are established by statute or on the basis of an engineering study. Section 11-803 of the Uniform Vehicle Code *(17)* also includes the following provision:

> *Such a maximum speed limit may be declared to be effective at all times or at such times as are indicated upon the said signs; and differing limits may be established for different times of day, different types of vehicles, varying weather conditions, and other factors bearing on safe speeds, which shall be effective when posted upon appropriate fixed or variable signs.*

This provision specifically supports the setting of VSLs and should be incorporated into the State speed zoning statute. Also, the *Judicial Enforcement of Variable Speed Limits* report addresses legal considerations for implementing and enforcing VSLs and should be referred to for more detailed information on this topic *(18)*.

5.3 Guideline 19: Maintain system log for evidence of speed limit violations.

A system log should be maintained that provides evidence of the speed limit posted at time of the offense, as well as the prevailing traffic speeds, environmental conditions, or other reasons for any speed limit change. A copy of the engineering study documenting the decision logic and need for VSL at a particular location should be readily available to law enforcement and the courts.

For speed violation to be successfully adjudicated, the State should provide certifiable evidence of the speed limit posted at time of the violation and the reason the speed limit was changed. Speed limits that differ from the general statutory speed limit must be based on an engineering investigation. The potential benefits of maintaining a system log are as follows: successful adjudication of speed violations; fair and reasonable speed management system, as perceived by drivers; greater respect for law enforcement; and enforcement targeted at drivers that disproportionately contribute to crash risk. The system logs could also be used as part of a continuous ongoing evaluation to monitor and determine the effectiveness of the VSL system and changes needed to improve its effectiveness.

Chapter 6. Weather-Related Variable Speed Limit Case Studies

In order to provide an in-depth analysis of the VSL systems and to obtain additional information on their use in wet weather and issues related to sight distance and stopping distance, various States with active VSL systems were interviewed. These States were chosen from the list of known U.S. installations of VSLs, which can be found in Appendix B, based on their relevance to the purpose of this guide, the level of experience each governing agency had with VSL systems, and the agency's willingness to share detailed information about their systems. The States below have VSL systems that currently incorporate weather conditions in their speed-setting criteria.

6.1 Alabama

Alabama DOT (ALDOT) currently operates a VSL system on a 7-mile section of Interstate 10 in Mobile, Alabama. The section of roadway where the VSL system is implemented previously had a very high number of vehicle accidents due to visibility issues caused by fog. Following a very severe crash in 1995 involving 193 vehicles, ALDOT chose to deploy this low visibility warning system.

The VSL system collects data from remote vehicle detectors, fog detection devices, and visibility sensors. The visibility sensors use forward-scatter technology and are installed roughly every mile. The data is reviewed by the TMC operators, who then manually change the speed limit based on the existing weather and traffic conditions. The operators use charts that detail what the posted speed limit should be based on driver visibility. The speed limits are changed in increments of 10 mph within the range of 35 to 65 mph. The system controls a total of 24 VSL signs, but is divided into six zones, in which the speeds in each zone can be set independently. Table 1 below shows the speeds and other strategies based on visibility distance *(19)*.

Table 1: Alabama DOT Low Visibility Warning System Strategies

Visibility Distance	Speed Limits and Other Strategies
Less than 900 feet (274.3 meters)	Speed limit at 65 mph (104.5 kph)
Less than 660 feet (201.2 meters)	Speed limit at 55 mph (88.4 kph)
Less than 450 feet (137.2 meters)	Speed limit at 45 mph (72.4 kph)
Less than 280 feet (85.3 meters)	Speed limit at 35 mph (56.3 kph) and street lighting extinguished
Less than 175 feet (53.3 meters)	Road Closure by Highway Patrol
Source: *Best Practices for Road Weather Management*, Version 2.0, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., May 2003, http://ops.fhwa.dot.gov/weather/best_practices/CaseStudiesFINALv2-RPT.pdf (accessed May 31, 2012).	

The system is set up to notify local and State law enforcement immediately of any changes to the conditions and speed limits on I-10. The system allows the TMC to notify the public of the existing conditions and the appropriate speed limit. The public perception of the system is positive because ALDOT has taken steps toward dealing with the issues with fog. There are plans to extend the corridor farther on I-10 and onto I-65.

6.2 Delaware

Delaware DOT (DelDOT) currently operates a VSL system on Interstate 495 that changes speed limits based on weather conditions. The speed limits are varied by DelDOT operators at the TMC either by decision of the Chief Traffic Engineer, delegated to the TMC Manager, or at the request of the Delaware State Police (DSP) for extreme weather conditions and poor roadway surface conditions.

Real-time traffic conditions such as speed, volume, and occupancy are collected at count stations along the roadway, and weather data is obtained from cameras and personnel in the field. Speed reductions of 5 to 20 mph can be made for any of the following conditions: traffic incidents, extreme weather conditions (heavy precipitation, high winds, reduced visibility due to precipitation, fog, or smoke), and poor roadway surface conditions (ice and/or snow covered pavement, "black ice" patches on pavement material, and object spills on the roadway pavement or roadsides). Speed limits are not adjusted for ozone action days, as was initially envisioned. The concern was that motorists cannot perceive a reason why they need to slow down, so using the VSL system on ozone action days may actually create speed differential issues along the roadway.

The VSL system is regulatory, but the DSP maintains the authority to issue tickets to drivers when the issuing officer believes they are traveling too fast for conditions, regardless of the posted VSL. As per Delaware code, drivers have a responsibility to adjust their speeds based on the prevailing conditions regardless of the static signing. The same speed limit is typically displayed throughout the entire corridor, but it is possible for the signs to display different speeds.

The VSL system has been very favorably received by police, emergency services, and DelDOT personnel involved with maintenance or construction projects along the roadway. Other than some initial reliability issues with communications, DelDOT has received no negative feedback on the signs. Over time, their goal is to install similar systems along all of the interstates and limited access facilities.

6.3 South Carolina

South Carolina DOT (SCDOT) launched its VSL project in 2009 as the result of a Road Safety Audit (RSA) that determined that a VSL system was necessary to decrease the number of speed and wet weather related crashes on US 25 in Greenville County. According to SCDOT, 85 percent of accidents between 2003 and 2007 occurred during wet weather conditions, and speed was a contributing factor in 62 of these 71 accidents *(20)*. The system covers a 2-mile rural segment of the roadway that has a 55 mph speed limit and a 6 percent downgrade. The project was delayed due to power issues, but the system has been operational since mid-2011.

The system automatically reduces the speed limit to 45 mph if non-ideal roadway conditions are present. Currently this is determined based on the amount of precipitation, which is collected by a standard weather station installed nearby. Sensors are installed in the pavement to read barometric pressure and determine if ice is forming on the pavement. Cameras are linked to the central system so that SCDOT can watch the VSLs. The VSL signs are supplemented by overhead variable message signs that display standard messages based on the type of weather condition being experienced.

6.4 Washington

Washington State DOT (WSDOT) currently has several VSL systems in place on the following roadways: I-5 Northbound into downtown Seattle, I-90 between the City of Bellevue and Seattle, SR 520 between the City of Bellevue and Seattle, US 2 over the Stevens Mountain Pass, and I-90 over the Snoqualmie Mountain Pass. All of the speed limits posted on VSL systems in Washington are regulatory and enforceable. The VSLs in the urban areas are set automatically based on speed and occupancy sensors correlated to an 85th percentile speed, so wet conditions only affect speed selection if traffic is driving slowly because of the conditions.

However, the speeds in the mountain passes are set manually based on environmental sensor information.

WSDOT implemented this speed management system on I-90 through Snoqualmie Pass, a popular tourist destination, in response to a high crash rate brought about by the rain and fog of summer and the snow and ice of winter. The system collects data from 6 environmental sensor stations (ESS) and 22 radar vehicle detectors. The ESS detect a variety of environmental information, including air temperature and humidity, precipitation, wind speed, and pavement temperature and condition.

All of the data is sent to a central control computer that calculates the suggested safe speed limit based on the strategies provided in Table 2. If the system operators agree with the suggested speed, the VSL signs are activated to display the reduced speed limits and the CMSs are activated to display the reason for the reduced speeds and the road weather advisories. The roadway is broken down into sections by direction, so that the operators can modify the speeds in each section independently from the others. The speed limits can vary between 35 mph and 65 mph in 10 mph increments *(19)*.

A study conducted by the University of Washington found that the speed management system reduced the average vehicle speed by up to 13 percent. Speed variance increased slightly, but the overall roadway safety has improved as drivers are required to decrease speed during non-ideal weather and roadway conditions *(19)*.

Table 2: Washington State DOT Speed Management Control Strategies

Weather Conditions	Pavement Conditions	Control Strategies
• Light to moderate rain • Visibility distance greater than 0.5 mi. (0.80 km)	• Dry • Wet	• Speed limit remains at 65 mph (104.5 kph) • No tire regulations
• Heavy rain • Fog • Visibility distance less than 0.2 mi. (0.32 km)	• Slushy • Icy	• Speed limit reduced to 55 mph (88.4 kph) • Traction tires advised
• Heavy rain or snow • Blowing snow • Visibility distance less than 0.1 mi. (0.16 km)	• Shallow standing water • Compacted snow/ice • Deep slush	• Speed limit reduced to 45 mph (72.4 kph) • Traction tires required
• Freezing rain • Heavy rain or snow • Blowing snow • Visibility distance less than 0.1 mi. (0.16 km)	• Deep standing water • Deep snow/slush	• Speed limit reduced to 35 mph (56.3 kph) • Tire chains required
Source: *Best Practices for Road Weather Management*, Version 2.0, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., May 2003, http://ops.fhwa.dot.gov/weather/best_practices/CaseStudiesFINALv2-RPT.pdf (accessed May 31, 2012).		

6.5 Wyoming

In February 2009, Wyoming DOT (WYDOT) implemented a VSL system along the Elk Mountain Corridor, which is located in southwestern Wyoming on Interstate 80 between Laramie and Rawlins. This corridor is used by both private citizens and commercial carriers, and several stretches experience severe winter weather. The corridor was previously equipped with weather stations and CMS. The original system was equipped with 20 VSLs and was expanded by 8 additional VSLs during the 2009–2010 winter seasons. Weather conditions and visibility are monitored by cameras and road and wind sensors, surface and atmospheric conditions are collected at the weather station located in the middle of the corridor, and speed is monitored by sensors in the pavement and markers alongside the highway.

The VSL system currently consists of 140 miles in four segments that cover approximately 35 percent of Interstate 80. The Wyoming Highway Patrol, maintenance foremen, and TMC operators are responsible for speed selection. Visibility, surface conditions, and vehicle speeds are used to determine appropriate speed limits. Wyoming Highway Patrol visually inspects conditions and reduces speed limits as deemed appropriate. The maintenance foreman can also lower speeds if the Wyoming Highway Patrol is not available. If the average vehicle speed drops 15 mph from the standard speed and no one else is on the corridor to confirm conditions, then the TMC Operator has the authority to reduce speed limits. Also, if there is a drop in visibility or a change in surface conditions, the TMC Operator has the authority to set the speed limits based on the criteria provided in Table 3 *(21)*.

Table 3: Wyoming DOT Speed Management Strategies

Reported Condition	***Wet or Dry***	***Slick Spots***	***Slick***
Speed Limit (mph)	**Visibility (feet)**		
75	>950	>1625	
65	735-950	1225-1625	>1700
50	475-725	750-1225	1025-1700
35	<475	<750	<1025

Source: "Wyoming Department of Transportation Policy Memorandum: Variable Speed Limit," Wyoming Department of Transportation, GIS/ITS, Cheyenne, WY, February 16, 2011.

In urban areas, the system primarily monitors incidents and vehicle speeds; however, in rural areas, the system monitors visibility, weather, and pavement conditions. There is no limit to how often speed limits may be changed or how long the speeds must be displayed.

Legislation for WYDOT's VSL system went into effect in July 1, 2008. This legislation grants authority to set speed limits based on "vehicle or weather emergency." The legislation also states that speed limits can vary by time of day, vehicle type, weather conditions, and other factors, which can be posted on fixed and variable signs.

6.6 Discussion

Although several VSL systems are currently being used or have been used in the past in the United States, enhancements can be made in decreasing speed limits for wet weather conditions. Many States base their VSLs on current vehicle speeds, so wet weather does not affect speed changes unless traffic is driving slowly because of the conditions. For example, in Washington, environmental sensor information is considered when making speed decisions in the mountain passes, but not in the urban areas. In Minnesota, the possibility of incorporating rain sensor data and other weather condition information into their algorithm is being researched, but the algorithm is currently based on difference in speed along the corridor. Missouri has not explicitly considered rain and snow in their speed selection process, except in very extreme circumstances where a specific hazard is known. Typically, the system responds to weather conditions based on real-time traffic conditions.

These examples show the common theme that exists among most VSL systems, reflecting a need for wet weather enhancements. Because of this, the NTSB issued safety recommendation H-05-14, requesting that guidance be issued recommending the use of VSL signs in wet weather at locations where the operating speed exceeds the design speed and the stopping distance exceeds the available sight distance. In response to this NTSB recommendation, this document provides guidelines developed from a thorough investigation of the state-of-the-practice of VSL installations in the United States and a complete review of the practices and procedures that States use when implementing and operating VSL systems. This document also provides examples of the challenges, obstacles and issues that organizations have encountered when implementing VSL systems so that future implementers can develop practices that will increase their likelihood of success.

Appendix A. References

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Appendix B. VSL Installations in the United States

Known installations of VSLs in the United States are presented below. For each installation the following information is provided: location, type of activation (manual, automated, hybrid), total length, type (regulatory, advisory), number of VSL signs, type of sensors, and current status. The installations are sorted first by current status, beginning with the active installations, and then by alphabetical order of the State in which the installation resides.

Known U.S. Installations of VSLs

Location	Type of Activation	Total Length	Type	Number of VSL Signs	Type of Sensors	Current Status
I-10, Mobile, Alabama	Manual	7 mi	Regulatory	24	Visibility, CCTV	Active
I-70, Colorado	Manual	19 mi	Regulatory	8	Loops, Radar, Temperature, Precipitation, Wind speed	Active
I-70, Colorado	Manual	1 mi	Regulatory	4		Active
Delaware	Manual	4 bridges	Regulatory	5–8	Speed, Volume, Occupancy, Environmental (weather)	Active
I-4, Florida	Hybrid	10.5 mi	Regulatory	20	Loop detectors, Side-fire radar (volume, speed, occupancy), Weather visible by CCTV	Active
I-95, Maine	Manual	~195 mi	Advisory	65 total (solar powered)	Some have cameras, Radar (to read speed of traffic)	Active
I-295, Maine	Manual	50 mi	Advisory		Some have cameras, Radar (to read speed of traffic)	Active
I-35W, Minneapolis	Automated	15	Advisory	174	Single loops	Active

Location	Type of Activation	Total Length	Type	Number of VSL Signs	Type of Sensors	Current Status
I-270, St. Louis, Missouri	Hybrid	38 mi	Advisory	70 (all solar powered)	Speed, Occupancy	Active
Turnpike, New Jersey	Manual	~148 mi	Regulatory	164	Speed (Environmental sensors are inactive due to lost connection)	Active
Turnpike, Pennsylvania	Manual	10 mi	Regulatory	18	Speed, Environmental, CCTV	Active
Bridges/ Tunnels, Virginia	Manual	4 bridge-tunnels	Regulatory	50	CCTV	Active
I-75, Tennessee	Manual	19 mi	Regulatory	10	Speed, Environmental (fog)	Active
I-90, Washington	Manual	28 mi	Regulatory	14	Speed, Environmental	Active
US 2, Washington	Manual	23 mi	Regulatory	8	Speed, Environmental	Active
Seattle Metropolitan Area, Washington (I-5, I-90, SR 520)	Automated	Unknown	Regulatory	Unknown	Speed, Environmental	Active
I-80 Wyoming	Manual	140 mi	Regulatory	Approx. 42	Speed, Environmental	Active
I-84, Idaho	Manual	105 mi	Advisory	5	Vehicle, Environmental	Test Site
I-94, Minneapolis	Automated	8 mi	Advisory	110	Single loops	Under construction

Location	Type of Activation	Total Length	Type	Number of VSL Signs	Type of Sensors	Current Status
I-77, south of I-81, Virginia	Hybrid	20 mi	Regulatory	40	TBD	Planned
Turnpike/I-595, Florida	Automated	2-lane off-ramp	Advisory	1	Moisture	Removed
I-10/I-310, Louisiana	Manual	Unknown	Advisory	Approx. 12	Visibility, Speed	Removed
I-695, Maryland	Automated	3 mi	Regulatory	4	Speed, Queue	Removed (temporary installation)
I-96, Michigan	Automated	8 mi	Regulatory	7	Speed	Removed (temporary installation)
I-494, Minnesota	Automated	2.5 mi	Advisory	3	Speed	Removed
I-80, Nevada	Manual	2–3 mi	Regulatory	4	Visibility	Removed (technical issues)
I-40, New Mexico	Automated	3 mi	Regulatory	3	Speed, Environmental	Removed
I-526, South Carolina	Manual	2 mi	No speed change	8	Fog	Removed
I-80, Utah	Manual	6 mi	Regulatory	2	Day/Night automatic	Removed (temporary installation)
I-215, Utah	Manual	2 mi	Regulatory	2	Speed, Environmental	Removed
I-95, Virginia (work zone at Woodrow Wilson Bridge)	Hybrid	1 bridge	Regulatory	Unknown	Speed, Queue length	Removed

For More Information:
http://safety.fhwa.dot.gov

FHWA, Office of Safety
Guan Xu
guan.xu@dot.gov
202-366-5892

FHWA-SA-12-022