THE EFFECT OF ADVISORY MESSAGES ON DRIVER BEHAVIOR DURING INCLEMENT WEATHER

A Thesis Presented

By

Desirée Dulcinéa Carron

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This research examines the effectiveness of advisory variable speed limit (VSL) and advisory variable message sign (VMS) messaging on reducing traffic speeds during inclement weather conditions. Regulatory variable speed limit infrastructure is costly to install, whereas advisory messaging enables state transportation departments to utilize existing infrastructure in an effort to slow traffic during winter storms and improve safety. This study utilized roadway sensor data in southern New Hampshire, roadway grip data obtained from a Road and Weather Information System (RWIS) station located in Derry, New Hampshire, and New Hampshire Department of Transportation (NHDOT) winter weather logs obtained from the Transportation Management Center (TMC). The data were used to determine the impact the advisory messages had on reducing traffic speeds as compared to the impact roadway grip has on speed reduction.

Overall, this analysis indicates that, while drivers do adjust their rates of speed based on the roadway grip value, the presence of both prescriptive and descriptive messages appears to cause them to reduce their rate of speed even further than they otherwise would, especially during storm events with large amounts of accumulating precipitation. Speed reductions were found to be more significant while prescriptive messages were displayed, although significant reductions in speed were also noted while descriptive messages were displayed. After controlling for the slowdown caused by a reduction in roadway grip, it was determined that the presence of prescriptive messages reduces the mean speed by 9.5 mph, and descriptive messages reduces the speed by 2.5 mph.
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<th>Definition</th>
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<td>CCTV</td>
<td>Closed Circuit Television</td>
</tr>
<tr>
<td>DOT</td>
<td>Department of Transportation</td>
</tr>
<tr>
<td>FHWA</td>
<td>Federal Highway Administration</td>
</tr>
<tr>
<td>GUI</td>
<td>Graphical User Interface</td>
</tr>
<tr>
<td>ITS</td>
<td>Intelligent Transportation System</td>
</tr>
<tr>
<td>KPH</td>
<td>Kilometers per Hour</td>
</tr>
<tr>
<td>MPH</td>
<td>Miles per Hour</td>
</tr>
<tr>
<td>MUTCD</td>
<td>Manual on Uniform Traffic Control Devices</td>
</tr>
<tr>
<td>NHDOT</td>
<td>New Hampshire Department of Transportation</td>
</tr>
<tr>
<td>QEW</td>
<td>Queen Elizabeth Way</td>
</tr>
<tr>
<td>RPU</td>
<td>Remote Processing Unit</td>
</tr>
<tr>
<td>RWIS</td>
<td>Road and Weather Information System</td>
</tr>
<tr>
<td>SWZ</td>
<td>Smart Work Zone</td>
</tr>
<tr>
<td>TMC</td>
<td>Transportation Management Center</td>
</tr>
<tr>
<td>VMS</td>
<td>Variable Message Sign</td>
</tr>
<tr>
<td>VSL</td>
<td>Variable Speed Limit</td>
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1. INTRODUCTION

1.1 BACKGROUND

Snowy conditions render navigation of an automobile difficult. Even the smallest amount of snow can wreak havoc when not properly treated, as was recently proven in Atlanta, Georgia in January 2014. An unexpected snowstorm in which a mere three inches of snow fell caused the roadways throughout the entire city of Atlanta and its surrounding suburbs to become completely gridlocked for more than eighteen hours (1). To avoid such catastrophic traffic-related occurrences from happening in the first place, state and city Departments of Transportation (DOTs) work tirelessly to clear the roads during winter storms to ensure the safest possible conditions for automobile operators. Still, snow and ice are not the sole contributors to vehicular crashes during winter storm events—human error and poor speed selection lead to disastrous outcomes. Speed plays a large role in causing drivers to lose control of their vehicles and as such, it is important that not only the snow or ice itself be addressed during winter storm events, but the speed at which drivers travel as well.

With the technological advancements made in the past two decades, Intelligent Transportation Systems (ITS) have improved over what they once were and are now promising be the future standard for safe roadway operations, especially during adverse weather conditions. Variable Speed Limit (VSL) signs are now able to automatically adjust the speed limit on a highway based on various measures such as weather conditions or congestion during peak hours. Variable Message Signs (VMS) warn drivers of dangers downstream or automatically relay the travel time through a section of roadway so they can better budget their time or seek an alternate route. Roadside devices are able to measure traffic metrics such as speed, occupancy, and volume as well as weather metrics such as precipitation type and intensity and the current roadway grip. These devices are each capable of relaying information to other ITS devices or to transportation dispatchers so the transportation personnel can better treat the roads and inform the public of the current conditions. ITS devices are becoming increasingly accurate and offer transportation agencies ever growing means to inform drivers of roadway conditions to actively prevent negative outcomes. Unfortunately, many northern states where snow and ice are concerns during winter months currently do not have substantial room in their operating budgets to install expensive ITS infrastructure to aid in improving safety conditions. States such as New Hampshire are therefore relying on the infrastructure that has already been installed as part of
previous transportation-related projects in an effort to reach out to the public, increase driver awareness during storms, and ultimately improve safety on roadways.

During winter ice and snow events since the 2012/2013 winter season, the New Hampshire Department of Transportation (NHDOT) has been posting advisory messages, including advisory VSL messages, to VMS located along the I-93 corridor in southern New Hampshire between the Salem and Manchester, New Hampshire. The hope of the NHDOT is that these messages will help to increase driver awareness of the roadway conditions and slow their rate of speed during ice and snowstorms to prevent crashes. The research presented within this thesis seeks to evaluate the effectiveness of this measure taken by the NHDOT during winter ice and snowstorms to improve roadway safety.

1.2 HYPOTHESIS

The objective of this research is to determine whether or not the advisory messages posted to VMS during ice and snow storms along the southern portion of I-93 in New Hampshire have an effect on reducing drivers' mean rate of speed, and if so, the magnitude of the measured reduction in speed. It is postulated that the advisory messages posted to the VMS do cause drivers to decrease their mean rate of speed beyond that which they otherwise would during ice or snow events. The null hypothesis is that the mean speed during winter ice and snowstorms is not lower than it otherwise would be during such events.

1.3 THESIS ORGANIZATION

This thesis is organized into five chapters. An appendix is also provided at the end of the report where all raw data can be found in the form of line graphs arranged by storm date.

Chapter One: Introduction offers a brief background on the topic of variable messaging and provides context to set up the rest of the thesis.

Chapter Two: Literature Synthesis outlines the existing literature relevant to variable speed limits and dynamic messaging, and driver response to these types of messaging. Within this chapter, the argument is made for why this further study is necessary on this topic to grow the academic body of knowledge on the topic of advisory messaging.

Chapter Three: ITS Architecture in New Hampshire provides details pertaining to the existing network of ITS devices the NHDOT currently uses during winter ice and snow events to gather
weather information and send advisory messages to the traveling public. The data measured by these devices were used as the means for this study.

Chapter Four: Data Synthesis explains the way in which data were captured and processed for the purpose of this study.

Chapter Five: Findings summarizes the data collected and explains the results from this study. This chapter explains in detail all observations made about the data that were collected and provides descriptive conclusions drawn from the processed data.

Chapter Six: Recommendation further summarizes the results from the study and explains how these results can be used in the future to better improve safety conditions on roadways during ice and snow storms.
2. LITERATURE SYNTHESIS

Many state DOTs have taken various measures to reduce the number of speed-related incidents on state-owned or federal roadways. Some states, such as Missouri and Washington State, have opted to install Variable Speed Limit (VSL) signs along major highways in order to allow the DOT to adjust the regulatory speed limit as is necessary (2,3). These dynamic signs replace conventional static signs and are compliant with the Manual on Uniform Traffic Control Devices (MUTCD) that outlines the types of pavement markings, roadway signage, and traffic signals permitted for use on highways in the United States. They are therefore enforceable by law.

VSL signs also happen to be much more expensive to install and maintain than conventional speed limit signs are, so many states have not had the means to install large systems of VSLs throughout their roadway networks. These budgetary shortfalls have led to situations such as the one currently being faced in New Hampshire. The NHDOT has invested in and installed a total of six VSLs throughout the entire state- and federally-owned highway network as part of their Intelligent Transportation System (ITS) initiative. Although New Hampshire is a small state, six VSLs are not enough signs to remotely comprise a cohesive network of dynamic signs. Additionally, these six VSLs have been installed at non-linked locations throughout the state, so as a safety measure, speed limits posted to these signs are not adjusted and remain fixed between 55 and 65 miles per hour at most locations based on the surrounding static signs on the roadway.

Effectively, these six signs are merely more expensive static signs with a digital face, but this clearly was not the DOTs ultimate intention when these signs were first installed. The NHDOT installed these signs as part of transportation projects where funding was available in the budget for ITS devices with the intention of eventually replacing all static signs on all major highways with dynamic ones as part of future transportation projects. In 2012, a master plan was drafted proposing the eventual replacement of all static speed limit signs with VSL, but no definitive timeline has been laid out for the plan. In the meantime, the NHDOT has sought cost-effective means to advise the public and combat speeding during winter ice and snow events by utilizing the existing VMS and weather detection infrastructure. They are seeking to evaluate the effectiveness of the advisory messages being posted during winter storms.

A wide cross-section of published studies was discovered relating to the topic of advisory messaging and VSL within the United States and Europe. Variable messaging is still relatively
new to the transportation field in the United States, and a significant level of interest surrounds its safe implementation for applications ranging from winter storm management to improving safety conditions through live work zones. The following sections summarize the pertinent findings from the existing literature available in the academic realm.

2.1 European Studies

2.1.1 VSL and Advisory Messaging Field Research in Finland

Pirkko Rama has conducted extensive research on the impact of regulatory variable speed limits during the winter season in Finland. Speed limits across Finland are reduced by 20 kph (approximately 12.5 mph) along all major highways during the winter season generally spanning between November and April for safety purposes. Although the roadways are clear of ice and snow for the majority of the winter season, and speed reductions are only required during storm events, the country permanently reduced the speed limit historically for all time periods during the winter season as a safety precaution. The emergence of VSL technology enabled the Finland transportation department to easily reduce the speed limits only during storms, thus improving traffic operations under normal conditions without a reduction in safety during adverse weather. VSL technology also enabled the DOT to reduce the speed limits by more than 20 kph whenever icy conditions necessitated it.

In 1997, Rama and Luoma investigated whether or not drivers accepted the implementation of weather-controlled road signs (4). The study, which was a follow-up survey, was conducted on individuals who drove on a 14-kilometer stretch of roadway in Finland's southern coast where rapid weather changes occur throughout the winter season. Throughout the study area, thirty-six VSL signs and five VMS were installed to warn drivers of potential hazards and adverse weather. The VSL signs used standard fiber optic displays, and the VMS displays consisted of two modules stacked vertically with the upper one capable of displaying one of three warning images including one for slippery road conditions, hazards ahead, and construction ahead, and the lower one displaying text. Signs were updated based on weather station data and were left blank when no message was necessary.

In an effort to determine driver acceptance of the weather-controlled road signs, the researchers interviewed drivers who had stopped at a rest area approximately 0.2 miles from the end of the study area. A total of 590 drivers were interviewed three, four, eleven, and thirteen months after the implementation of these signs in this region, and it was found that the majority of individuals
(95%) felt that the variable signs were useful. 81% of the individuals believed the posted speeds were appropriate. It was also found, however, that the majority of individuals interviewed stated that the slippery road condition or temporary temperature values displayed on the signs did not affect their behavior as drivers. This study was purely a subjective survey that did not include the collection of any objective data to validate the responses provided by those surveyed. The authors conclude by stating that although the results from this survey show that the public is open to the use of VSL during adverse weather conditions, further objective studies are required to verify whether or not the messages and signs do affect driver behavior.

In 1999 and 2001 Rama further studied the effects of weather controlled VSL and warning signs on driver behavior in Finland using quantitative data (5,6). For this study, symbolic images indicating slippery conditions along with warning messages indicating minimum advisable headways, temperature readings and speed limits were posted to VMS in addition to the speed reductions posted on VSL (Figure 1). VMS and VSL signs were updated automatically using a network of sensors installed along the roadways studied, although signs could also be manually updated as needed by the transportation department staff. Driving speeds and headways were measured using loop detector based traffic monitoring stations both before drivers could see the signs as well as 360-1,000 meters downstream from the signs. The traffic monitoring stations were placed at positions in the roadway where the road slightly curved.

It was found that a decrease in the posted speed limit of 20 kph (approximately 12.5 mph) during winter events led to a reduction of 3.4 kph (2.1 mph) in the average free flow speed. This reduction was in addition to a mean free flow speed reduction of 6.3 kph (3.9 mph) that would have otherwise occurred as a result of poor roadway conditions regardless of whether or not an advisory message were posted. This means that an overall reduction of 9.7 kph (6.0 mph) was observed. Furthermore, the mean speed did not increase significantly when the signs were blackened with no message displaying. These reductions in speed and standard deviation were found to be statistically significant and the test was deemed a success, although it was pointed out that it might not be socioeconomically advantageous to permanently implement the system of VSL signs and VMS throughout the study area because the cost of installation would potentially outweigh the impact the system would have to society.
2.1.2 **Multivariate Empirical Research in Sweden**

Research was conducted in Sweden to determine the impact of advisory variable speed limits on roadway capacity and level of service on the E4 motorway in Stockholm, Sweden (7). This study was one of the first to examine the effectiveness of VSL empirically using multivariate performance models by comparing "before" and "after" scenarios. The authors found that no significant reduction in speed was observed both immediately after the VSLs were installed and several months later. The data for this study were admittedly small in size: only one day of data taken in May 2004 was available for the "before" condition, and only a total of six days’ worth of data were taken in May and September 2005 for the "after" condition. Furthermore, these data were taken on days where the roadway and weather conditions were dry with no rain, rather than during stormy days, leading one to question whether or not the lack of compliance with the speed reductions was due to the fact that drivers did not deem it necessary to slow down based on roadway conditions, or if the noncompliance with the VSLs was general in nature and would translate across all roadway and weather conditions.
2.1.3 Driver Simulator Study in Italy

In 2012, a study was conducted in Italy with the objective of evaluating the effectiveness of variable message signs information through a driving simulation (8). Individuals taking part in the study were placed inside a stationary vehicle in a test lab that had screens placed around the exterior of the vehicle to simulate driving conditions. As part of the simulation, individuals were asked to operate the simulation vehicle as though it were a real vehicle traveling down a highway with a low average daily traffic flow and a high rate of crashes. Variable message signs were placed at various intervals along the simulation roadway that displayed a number of messages on them. The messages displayed comprised a combination of pictograms and text with varying levels of complexity. The messages used on the signs were selected by the European Commission DG-TREN under the European program Easy Way and ranged from way finding messages to cautionary messages.

The researchers found that the drivers reduced their speeds by approximately 5% when they approached a sign displaying a message they did not understand, such as confusing way finding messages directing them to "Francavilla Ortona." They maintained a stable speed if the message they were approaching was easily understandable, such as "Look out" or "Employ Ongoing Attention". The messages displayed did not necessarily instruct the drivers to reduce their speeds, and as such, the reduction in speed measured in the lab could potentially create a safety hazard in the roadway. If drivers unexpectedly reduce their speed within the mainline of a highway to comprehend a complex sign, and following distances are too close due to congestion or carelessness, a potential for collisions is created. The essential conclusion made from this study is that the information presented on the signs must be simple and easily comprehended by drivers approaching them at high rates of speed in order to achieve the largest benefit from the signs without decreasing driver safety.

2.2 Field Studies in the United States

Few states in the United States have elected to install comprehensive VSL systems along their major roadways. Those states that have opted to install VSL systems include Washington, Missouri, Maine, and Minnesota, among others. All of these installations have been used as pilot studies for potential further expansion of the networks. VSL technology is not as widely used in the United States as it is in Europe because much hesitation surrounds the implementation of this technology, and as a result, these DOTs have chosen to install devices on a trial basis with the
intention to study their effectiveness. This section summarizes the key findings made in the studies conducted in the United States.

2.2.1 WASHINGTON STATE

Washington State DOT has opted to install a system of VSL signs along a portion of I-90 running east-west across the state (3). High crash rates are present on I-90 during the winter months, which are the result of poor roadway geometry, large volumes of heavy vehicles (22%), and recreational travelers who are not familiar with the roadway. Washington State DOT calculated that crash rates during January were 12% higher than they were during July. To try to reduce the number of crashes during adverse weather conditions where fog, snow, and/or ice are present on I-90, Washington State DOT has opted to install a system of VMS and VSL signs along a 40-mile section of the interstate. A central computer utilizes algorithms to process data collected by roadside sensors to calculate safe travel speeds and speed limit reductions during poor weather conditions. This information is then relayed to the system operator, who makes the decision of whether or not to accept the suggestions made by the central computer and activate the VSL and VMS to display the recommended messages regarding weather advisories, required vehicle equipment (i.e. tire chains), reduced speed limits, and the reason for a reduction in speed limit. The system operator has the ability to adjust VSL messaging by direction and roadway segment.

Improvements in traffic operation have been noted since the installation and implementation of the VSL networks. The DOT determined the VSL messaging does cause drivers to reduce their rate of speed during inclement weather. They also found that the messaging caused a reduction in speed variance, reducing stop-and-go traffic and creating more uniform traffic flow.
Another study was performed on a portion of I-270/I-255 in St. Louis, Missouri where a VSL system was implemented as part of a trial to determine whether or not such a system would be successful in the United States for congestion management. A team of researchers evaluated qualitative driver perceptions of the VSL system over the first two years after the system was installed to determine the level of resistance to innovation in the implementation of a dynamic traffic management system (2). This research brings an important light to the existing literature on this topic because, unlike the vast majority of other findings available from various studies, the findings presented in this study were based on reactions from both the general public as well as from law enforcement officers who conducted details within the study area.

Missouri DOT installed a network of sensors along a portion of I-270/I-255 in St. Louis as a planning study for further VSL deployment in the state. These sensors collected speed, occupancy, and traffic volume data that were used to develop VSL protocols for the purpose of improving safety and increasing traffic throughput during peak periods. The DOT utilized the press and social media as part of their public outreach educational program relating to VSL technology and how it works before installing the network of VSL signs. The VSL signs were used during congested periods and were automatically updated based on roadside sensor data, with speed limits ranging between 40 mph and 60 mph. Speed limits upstream from congestion were reduced to prevent traffic flow breakdown and improve overall operations. The values were overridden as necessary by operations staff.

A continuous online survey was used to evaluate the public perceptions regarding the VSL system. Both quantitative and qualitative questions were used in the survey utilizing both numeric ratings and essay responses. Fifteen law enforcement officers were also surveyed using
a double-sided paper survey. The law enforcement officers were surveyed twice during the study: once at the beginning of the study, and another 18 months later.

The researchers found that, unlike the findings presented from previous research conducted in Finland, an overwhelming dissatisfaction was present among those participating in the study. Both the general public and law enforcement thought the system was a waste of taxpayer funds and found that most drivers were not abiding by the reduced speed limits presented on the VSL signs. Law enforcement found the VSL impossible to enforce because the public was confused about the rate of speed they were legally supposed to be traveling at, and a significant portion of the population was not adhering to the reduced speeds. An officer stated that an advisory VSL (rather than regulatory VSL) would perhaps be more beneficial due to the impracticality of enforcing the variable speed limits. Overall, this test run of the VSL system in Missouri left a bad taste in most everyone's mouth for one reason or another.

VSL systems are new to American drivers, many of whom do not fully understand the theory used to design the operation of the VSL systems, and they therefore are intrinsically resistant to the implementation of these devices in general. The researchers pointed out that a better marketing strategy upon implementation of the system would have greatly helped to improve the public's awareness and understanding of the functionality of the system and its economic and societal value, therefore improving the success of the system in general.

2.2.3 MAINE

Advisory VSL messages have been used in Maine on the Maine Turnpike and Maine Interstate since at least 2006 (9). These advisory VSL are used during winter storms in an effort to slow speeds during icy and snowy conditions. They are also used during emergency situations such as crashes, fires, and floods and as a congestion mitigation tool during special events such as concerts. During the winter seasons spanning between the years 2006 and 2008, a study was conducted to evaluate the effectiveness of the advisory VSL at reducing driver speeds. Instantaneous speeds were captured in two-hour intervals using radar guns during several winter storm events of varying intensity with a wide range of roadway surface conditions. Speeds were averaged over the two-hour intervals, and the 85th percentile speed was also determined for each interval. Based on the data captured, the researchers determined that the VSLs did not appear to have any significant impact on the drivers' rate of speed. It was found that even with poor roadway conditions where packed snow and ice was visible on the roadway and the VSLs active,
the average and 85th percentile speeds were still higher than they would otherwise be had the drivers been adhering to the advisory speed limit.

The authors note that the VSLs remained active during periods of time that did not warrant a reduction in speed along the roadway, which may have led to the lack of adherence to the advisory speeds. They point out that by leaving the VSL signs active during clear conditions, drivers are lead to believe that the signs are not reliable and are thus conditioned to regard the advisory messages posted as being unnecessary to adhere to.

2.2.4 MINNESOTA

The use of VSL in active construction work zones has also been a topic of interest to state DOTs in an effort to improve safety to both drivers as well as the construction workers. Research was conducted on VSLs located within work zones along I-494 in Twin Cities, Minnesota (10). The morning peak traffic hours between 6:00 and 8:00 a.m. were evaluated to determine driver compliance with the reduced speed limits posted to the VSLs, which were not regulatory. Speeds were measured both upstream and downstream from VSL signs using Doppler radar sensors. Traffic volumes were measured using five sets of radar sensors. The advisory speed limit was set to vary every one minute in 5 mph increments.

The study found that the maximum average speed measured during this study decreased by 25-35%, which was found to be significant, while the VSL signs were displaying reduced speed limits, and during the 6:00-7:00 a.m. hour, a 7% increase in throughput volume was measured, which was also significant. Although the throughput volume did also increase during the 7:00-8:00 a.m. hour, this increase was not found to be statistically significant. It was concluded from this research that drivers did comply with the advisory speed limits through the work zones; however, the estimated level of compliance fell into a wide range of 20-60% driver compliance depending on a number of variables present. This range of driver compliance means that, depending on the variables present, anywhere between the 20% and 60% of the drivers actually adhered to the advisory speed limit posted to the VSL. The study found that the level of compliance with the VSL decreased as the difference between the posted speed and the speed level of the approaching traffic increased.
2.3 THEORETICAL STUDIES

Theoretical studies have been conducted relating to VSL technology using two different means: microsimulation and a driver simulator. The microsimulation studies utilized the traffic software package, PARAMICS, to model traffic flow with speed adjusted by VSL. The driver simulator study utilized a machine comprised of a physical vehicle complete with steering wheel surrounded by television screens that simulated realistic driving conditions where VSL and advisory messaging are used. The following summarizes these studies and their impact on the body of knowledge regarding driver behavior when VSL are implemented.

2.3.1 MICROSIMULATION STUDIES

2.3.1.1 PARAMICS Studies- I-4 in Orlando, Florida

The software package PARAMICS was used for a study that evaluated VSL strategies to improve highway safety once a high potential of a crash is detected (11). The study area that was used in the simulation included a section of I-4 in Orlando, Florida that spans 20 miles between downtown Orlando and a northern suburb. The authors developed statistical models to determine the real-time crash potential in the simulated roadway network. It was found that the benefits of VSL in an ideal (simulated) situation include not only slowing the flow of traffic, but also reducing hazards at targeted locations. This study showed importantly that the implementation of a VSL system can improve safety and positively impact drivers' travel times during all hours of operation, not just during the peak traffic periods, assuming drivers comply with the reduced speed limits. A decrease in crash risk as large as 122% was measured at one study location within the network, and network travel times were measured to decrease by as much as 467 minutes.

Abdel-Aty continued his research into congestion mitigation using VSL along I-4 in Orlando, Florida with a further study that also utilized PARAMICS (12). This study sought to examine the use of VSL as a means of reducing freeway crash risks, namely rear-end and lane-change crashes, dynamically in real-time. Three different vehicle loading conditions were used to establish the level of congestion on the highway: 60% vehicle loading, 80% vehicle loading, and 90% vehicle loading. It was found that variable speed limits could be most effective under free flow and pre-congestion conditions (60% and 80% vehicle loading), but not under congestion (90% vehicle loading). Under heavy congestion, vehicle speed is controlled by surrounding traffic conditions, which is why the VSL were ineffective under this condition. It was found that the crash risk...
throughout the study area deceased with the use of VSL as the level of congestion increased. The use of VSL under increasing levels of congestion did not significantly increase travel times.

Both of these studies indicate that VSL can have a positive impact on safety assuming that drivers would comply with the reduced speed limits. Microsimulation software lacks the ability to determine whether or not the drivers would actually comply with the VSL in a real-life situation. These models indicate that speed reduction can improve safety conditions during special circumstances; however, they are unable to indicate whether or not these improvements would actually take place in the field because the human element is not present in the model.

2.3.1.2 PARAMICS Study- QEW Canada

Hellinga and Mandelzys also used PARAMICS microscopic traffic simulation software to evaluate the sensitivity of the safety and operational impacts of VSL to driver compliance (13). A 10-kilometer portion of the Queen Elizabeth Way (QEW) in Canada was modeled in PARAMICS using actual geometry and traffic volume data. A base model was calibrated to existing conditions without VSL. The VSL system used in the PARAMICS models was comprised of 13 signs spaced approximately 500-600 meters apart. The system was set to select an appropriate speed limit based on 20-second intervals of speed, occupancy, and volume data.

This study showed that the level of driver compliance was the driving factor in the impact of the VSL system. In this study, both regulatory and advisory VSL were investigated. The researchers found a positive correlation exists between the level of compliance and the level of safety throughout the study area, while a negative correlation was found between level of safety and travel time. They further found that the level of influence the VSL system had on traffic operations was a direct resultant of the strategy used to increase or decrease the speed limits displayed in addition to the method by which the VSL were enforced. These findings indicated that regulatory VSL would possibly be more widely accepted and adhered to by drivers than advisory VSL would be, although further research must be conducted to fully support this theory.

2.3.2 DRIVER SIMULATOR STUDY

In 2008, a study was published that used a driving simulator to measure the effects of warning messages and variable speed limits on driver behavior (14). The driving simulator used in this study comprised a realistic automobile complete with an operational steering wheel surrounded by screens on which a roadway was projected such that the driver "felt" as though they were truly driving a vehicle. A total of 86 individuals (48 male and 38 female) participated in the study,
driving a 5-mile portion of a theoretical freeway in the simulation. The participants were shown three types of warning messages on VMS that warned of speed limit changes ahead, permutated to produce a total of twenty-four unique scenarios. Drivers' reactions to these scenarios were monitored to determine what effect these messages have on driver behavior both under free flow and congested conditions.

Under congested conditions, drivers were observed to begin driving at a high rate of speed (approximately 60 mph) and gradually reduce their speed until reaching the congestion, where they abruptly reduced their speed before increasing their speed to 45 mph. Rates of speed within the congested areas tended not to vary greatly due to the close spacing of vehicles. The original speed of 60 mph was regained after the congestion cleared and they passed a VSL displaying "55 mph." Speeds exceeded 60 mph once they passed the sign displaying "65 mph."

Under uncongested conditions, speeds were observed to be typically uniform. No abrupt drop in speed occurred once the drivers encountered a congested area, as had been the case under congested conditions. Even though the VSL displayed the same speed reductions under uncongested conditions as they had under congested conditions, only minor changes in speed were observed, and the return to free flow speed was not as noticeably abrupt as it was under congested conditions.

The researchers also noted that the drivers' response at any given sign depended on their response at the previous signs they passed on the roadway, and drivers were likely to drive with more caution when an advisory message posted to the VMS ahead of the reduced VSL related to safety. A driver was not likely to ignore the speed limit posted on one VSL sign but then adhere to the next one. The researchers point out that while the study subjects typically followed the speeds posted on the VSL signs, the mechanics of a vehicle force a time lag between the observance of a sign and the physical reduction in vehicular speed, which should be kept in mind in the field. Although the results from this study offer insight into driver behavior with variable speed limits, it was conducted in a simulator and, as the authors point out, individuals may adhere more strongly to the posted speed limits while under observation than they otherwise would under real world conditions because they know their actions are being carefully scrutinized, and they receive no travel time benefit from speeding.
2.4 The Need for Further Research

Though the existing literature on the topic of driver behavior regarding VSL and VMS messaging indicates that the systems are not necessarily well adhered to by drivers in the field, nor are they well accepted by drivers or law enforcement, most studies have shown that they do increase safety and/or traffic throughput while at least moderately reducing traveling speeds. The research conducted by Rama in Scandinavia showed that drivers did indeed reduce their speeds slightly as a result of the VSL in place, and no researchers found that a reduced speed limit caused drivers to increase their speeds above what they otherwise would be traveling at. Additionally, the theoretical studies conducted using computer modeling software, PARAMICS, found that many operational benefits such as reduced congestion are achievable through implementation of VSL systems, assuming driver adherence to the speed limits is present.

What has not been extensively studied, however, is whether or not drivers adhere to advisory speed limit reductions during winter months under ice and snow conditions in the United States. Regulatory VSLs have been studied in Washington State and Missouri, with improvements in traffic operations observed in Washington. The study conducted in Missouri determined that VSLs were not well received by both the public and law enforcement alike. VSLs were determined to be successful in decreasing speeds while also increasing throughput through work zones in Minnesota. In Maine, winter advisory VSL messaging very similar to that which the NHDOT utilizes on their roadways in winter was studied, but it was found that the messages posted during storms were left posted long after the roadway conditions were no longer icy. This caused drivers to assume the messages were not useful and to ignore them.

Messages posted to the VMS by NHDOT are removed once the district maintenance and/or state police request their removal, meaning the messages are removed from the signs once the weather and roadway conditions return to normal non-icy operations. This faster removal of the messages may contribute to a stricter driver adherence to the advisory speed limits. The research presented within this paper will address this gap in the existing literature to determine whether or not advisory speed limit messaging is effective in reducing the rate of speed traveled during winter storms, and whether this form of VSL would be a wise safety measure for other state DOTs to adopt.
3. ITS ARCHITECTURE & DATA IN NH

State DOTs have been in search of a method to improve safety during the winter season, and reducing speeds on major roadways during storm events using the VMS infrastructure that they likely already have installed is a simple safety measure, if it indeed is effective. Reducing the speed limits using advisory messages posted to VMS eliminates the need to install new regulatory VSL signs, which come at a large cost when compared to static regulatory signs.

The infrastructure is in place in New Hampshire to evaluate whether or not the advisory signs posted to the VMS are truly impacting driver behavior by decreasing the free-flow speed along the roadway network (Figure 3). Along the 18-mile southern portion of I-93 in New Hampshire between Manchester and Salem, roadway sensors have been installed by NHDOT that collect speed, occupancy, and volume data in five-minute intervals. A Road and Weather Information Station (RWIS) is also located to the side of I-93 at mile 11.0 in Derry, New Hampshire that collects, among other meteorological data: real-time roadway grip, precipitation type, and precipitation intensity data using infrared technology.

The effectiveness of the posted advisory speed limit signs will be analyzed using the available historic data from the roadway traffic sensors and RWIS. It will be determined whether or not drivers observe the advisory speed limits presented on the variable message signs, which is being evaluated. If so, it will be determined whether or not the decrease in speed is a function of the message or of driver awareness. This section outlines the means by which data were collected and analyses were performed.
The NHDOT installed and calibrated a total of 26 solar powered trailer mounted roadway sensors on I-93 between Manchester and Salem, NH in 2006 (Figures 4-6). The sensors are assigned a label consisting of the letter “q” followed by a two digit number for inventory and record keeping purposes. The sensors are trailer mounted to enable them to be moved as needed; however, they have mostly been kept stationary along the I-93 corridor since 2006. These sensors use infrared technology to measure speed, volume, and occupancy across all lanes of travel. A Remote Processing Unit (RPU) mounted along with the sensor records the values and compiles them into 5-minute intervals. Five minute summaries are sent to the NHDOT Transportation Management Center (TMC) in Concord, NH. The data are accessible to the NHDOT TMC staff through a web browser-based Graphical User Interface (GUI) that updates every fifteen minutes, and the background data can also be accessed from this website.

Archived data are maintained at the NHDOT TMC in an Oracle database. All 5-minute summaries compiled by the RPUs are archived by the TMC and easily accessible in spreadsheet format. Personnel at the TMC create weekly and quarterly reports from the data for record keeping and goal setting purposes. Standard reports can also be created per request of an engineer or contractor in the field with nearly real-time data.
Figure 4  Portable Roadway Traffic Sensor (18)
Figure 5  NHDOT ITS Network Manchester-Derry, NH
This 18-mile portion of I-93 has been in the process of being widened from two lanes per direction to three lanes (four lanes in some areas) since 2006, with project completion expected in 2016 (15). The New Hampshire/Massachusetts state border is one of the most widely crossed borders in the entire nation for commuting to work, and I-93 being the main route connecting Manchester, NH to Boston, MA experiences heavy congestion during commuting periods. NHDOT decided, after evaluating all possible alternatives, to fully reconstruct the entire portion.
of I-93 running between Manchester and Salem, adding one to two lanes in either direction to increase capacity to meet demand and geometrically realigning the roadway to improve safety and comply with current federal highway design codes. Construction is being staged in phases such that one interchange at a time is being reconstructed, leaving much of the corridor untouched by construction at any given time.

The roadway sensors were installed at the beginning of this construction project as part of a Smart Work Zone (SWZ) that includes a series of cameras, variable message boards, and roadway sensors. These devices were installed on a test bed as temporary devices to monitor traffic operations during each stage of construction. The sensors are also used to create quarterly traffic reports for the I-93 corridor and can be used to create daily reports for project managers or field engineers per request of the TMC. The ultimate goal of this trial installation was to examine the benefit these sensors can provide to project managers, engineers and construction crew in the field. The TMC would like to install permanent roadway sensors at key locations on major highways in New Hampshire in the future. They are also pushing to make roadway sensors standard devices installed as part of Smart Work Zones throughout the state on future roadway projects.

3.2 Road and Weather Information System (RWIS) Network

As part of the expanding Intelligent Transportation System (ITS) network throughout the state of New Hampshire, Road and Weather Information System (RWIS) stations have been installed in critical locations along the major highways. This network was expanded in response to the Federal Highway Administration (FHWA) Clarus initiative, which was a multi-year effort to develop an integrated weather observation system for transportation to create a Nationwide Surface Transportation Weather Observing and Forecasting System. The intention of this system is to supply location specific information to the National Weather Service for improved weather predictions and models, and to create a cohesive network of weather stations that are maintained by a number of different agencies and organizations (16).

While the National Weather Service would be able to provide general information for a region regarding the total amount of snow that fell during any given storm, or the general weather events that took place on a given day, such a service is not able to provide such detailed information for localized areas as an RWIS station does. The information collected by the RWIS located within the study area was therefore used as the basis for weather information for this study because the information provided is local to the area, providing more accurate information for the study.
One RWIS has been installed along the southern portion of I-93 at mile 11.0 in Derry, New Hampshire (Figures 5&7). This station has the ability to measure, among other weather information: roadway grip (a measure of how slippery the roadway surface is), precipitation type, severity and accumulation, and roadway surface temperature. The RWIS is also equipped with a Closed Circuit Television (CCTV) camera that relays a real-time video feed back to the TMC. This video footage is displayed on a large wall-mounted screen in the TMC headquarters in Concord, NH that can be seen by both TMC and State Police personnel. It is also displayed on the TMC staff’s individual work stations for roadway monitoring purposes and as a visual check to ensure the RWIS data being relayed back to the TMC is valid.

*Figure 7 Road and Weather Information System (RWIS) Station (16)*
Data measured by the RWIS are collected and stored in an onboard computer system and sent to an Oracle database that is maintained by the NHDOT TMC. The data are accessible with an approximate 15-minute time delay to TMC staff via a web browser user interface that also acts as a warning system to alert TMC staff of adverse roadway conditions during storm events. The GUI is set up in a spreadsheet broken down by location with data compiled into 5-minute intervals. An algorithm is built into the system that visually alerts operators when conditions become potentially hazardous in the field by color-coding rows based on recorded precipitation type: "dry" is not colored, "moist" or "wet" is colored blue, "frost"/"snow"/"ice"/"slush" is colored red. Using the data collected by the RWIS, the TMC staff is able to take measures such as manually posting warning messages to VMS to inform the public of adverse roadway conditions or dispatching personnel to roadways in need of maintenance.

The most widely used data from the RWIS for the purpose of this study was that of roadway grip during the entire duration of each storm. The roadway grip information provides a numerical representation of how much traction the roadway is able to provide during any given five-minute interval at the specific location in the roadway where the sensor is located. The roadway grip values should not be confused with the coefficient of friction, as the roadway grip values are determined solely based on roadway conditions, and tire conditions are not taken into account in the calculation of the roadway grip as would be required to provide a coefficient of friction.

The roadway grip values are measured using a remote surface state sensor that is integrated into the RWIS software system (17). The remote surface state sensor uses an eye-safe laser to visually detect changes in the roadway surface condition that result in a change in roadway grip. The sensor measures the thickness of the layer of rain/snow/ice on the roadway surface and extrapolates from that thickness the level of grip present on the roadway. The sensors are capable of measuring water/ice depths in the range of 0.00-2.00 mm, with an accuracy of +/-0.1 mm in the range of 0.00-1.00 mm. These sensors have a resolution of 0.01 units and are able to measure roadway grip values in the range of 0.01 to 1.00.

Under optimal dry pavement surface conditions, the typical values of roadway grip throughout the study area range between 0.80 and 0.82 (Table 1). Under snowy or icy conditions, the roadway grip value drops to approximately 0.10 at worst. Rain can cause the roadway grip value to fall between 0.60 and 0.79, depending on the water depth on the roadway.
Table 1  Typical Roadway Conditions and Corresponding Roadway Grip Values

<table>
<thead>
<tr>
<th>Roadway Condition</th>
<th>Roadway Grip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry/Trace Moisture</td>
<td>0.80-0.82</td>
</tr>
<tr>
<td>Wet*</td>
<td>0.60-0.79</td>
</tr>
<tr>
<td>Ice/Snow Warning</td>
<td>0.1-0.59</td>
</tr>
</tbody>
</table>

*An ice watch may be present while roadway grip is within this range depending on air/surface temperature

3.3 VARIABLE MESSAGE SIGN (VMS) SYSTEM ARCHITECTURE

The NH DOT has invested in and installed six VSLs throughout the entire state-owned roadway network as part of their ITS initiative. The vast majority of the speed limit signs along these roadways are standard static signs, as the seven VSLs have been installed in non-connected clusters across the state roadway network. Therefore as a safety measure, speed limits posted to these signs are not adjusted, and remain between 55 and 65 miles per hour at nearly all times to match the surrounding static speed limits.

Instead, in an effort to reduce the number of speed-related crashes and fatalities during adverse weather conditions throughout the major highway system, NH DOT has been using VMS to warn drivers about events, including roadway conditions and crashes downstream. NH DOT currently maintains a total of 55 VMS throughout the entire state, four of which are permanently located along I-93 between Manchester and Salem (Figures 5-6). NH DOT has been using the VMS to post advisory speed limits during winter storms, offering guidance to drivers to be cautious and reduce speeds for safety purposes.

Dynamic signs advising drivers to travel at a maximum speed of 45 miles per hour ("Maximum Speed 45 MPH Slow Down") were posted beginning during the 2012/2013 winter season and continued for the 2013/2014 winter season. Lower speeds have been posted along I-93 north of Concord, New Hampshire through the White Mountains region (Figure 8). Additional advisory messages that do not specify a recommended speed limit are also posted to the VMS by the TMC personnel per request of DOT or State Police including:

- Snow Covered Roadways Watch Speed;
- Winter Storm Watch Your Speed;
- Winter Storm Clean Up Watch for Plows;
- Freezing Rain Possible Slow Down;
- Black Ice Possible Slow Down; and
- Watch for Ice on Ramps Stay Alert.
The signs located within the study area are permanently mounted amber overhead signs measuring 7'11"Hx25'10"Wx4'0"D with a 12-inch border around the sign face (Figure 9). These signs are capable of displaying up to three lines of text with eighteen characters per line with a text height of eighteen inches. They can also display two lines of text with a maximum of thirteen characters per line at a height of 29-inches.
Winter advisory messages are posted to the VMS per the discretion of the NHDOT State Maintenance crews and the TMC personnel. Only TMC personnel and State engineers may down post speeds on any roadway at any given time. Speeds are typically reduced via advisory messages posted to the VMS when RWIS data shows the roadways are or will soon become icy, or visibility becomes significantly reduced due to precipitation or fog. Other winter advisory messages are typically posted based both on the available RWIS information and engineering judgment.
4. DATA SYNTHESIS

This section outlines the methodology used for analyses. The means by which data were stratified and synthesized for this study are explained within this section.

4.1 MESSAGE TYPES

A total of seven different messages were posted to the VMS during the study period in the 2013/2014 winter. Messages posted to the VMS were categorized as either being prescriptive messages or descriptive messages. Prescriptive messages are those that directly alert drivers to reduce their speeds to a certain threshold (i.e. "Max Speed 45 mph"). Descriptive messages are those that warn drivers of potential roadway hazards (i.e. "Watch for Ice on Ramps"). Messages were separated into these categories to evaluate the potential effectiveness of one message type over another for achieving a reduction in mean travel speeds.

The following advisory messages posted to VMS during the 2013/2014 winter season were posted beginning in December 2013 and continuing into March 2014:

- Prescriptive Messages:
  - Maximum Speed 45 MPH Slow Down.
- Descriptive Messages:
  - Snow Covered Roadways Watch Speed;
  - Winter Storm Watch Your Speed;
  - Freezing Rain Possible Slow Down;
  - Black Ice Possible Slow Down;
  - Winter Storm Clean Up Watch for Plows; and
  - Watch for Ice on Ramps Stay Alert.
4.2 STORM DATES AND ADVISORY MESSAGES

Out of all weather conditioning messages posted to the VMS during winter storm events, only one message is categorized as prescriptive, displaying a specific advisory speed limit ("Maximum Speed 45 MPH Slow Down"). The other six messages are purely cautionary, warning drivers to pay attention to or reduce their speeds, or to be aware of the potential for the presence of snow plows in the roadway. The purpose of this research is to determine the degree of impact these varying messages have on driver behavior, if there is any impact at all.

Advisory messages were not posted during all winter storms during this time period. Detailed reports were created by TMC staff that outline, for each storm of the season, when and if a message was requested to be posted and when messages were removed from the signs. These reports were used as the basis for determining the dates on which storms occurred. In cases where information was missing from the reports, estimations were made based on RWIS data as to when the signs would have been taken down from the signs for analysis purposes.

A total of fifteen storms were recorded for the 2013/2014 winter season ranging between December 9, 2013 and March 12, 2014. A total of seven messages were posted at various times throughout the season to the VMS during twelve of the storms, and no messages were posted during three of the storms (Tables 2-4). These various messages enable one to evaluate the effectiveness of one type of message over another, and the storm events where no messages were posted allow for a baseline of traffic patterns during storm events to be evaluated. Additionally, during many of the storms, multiple messages were posted consecutively as the weather conditions changed, which enables the impact of multiple messages during the same weather conditions to be evaluated.
Table 2  Baseline Conditions Speed and Roadway Grip Summary for 2013/2014 Winter Storm Events in NH

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
<th>Day of Week</th>
<th>NB Speed** (mph)</th>
<th>SB Speed** (mph)</th>
<th>Grip*</th>
<th>Message</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Storm Baseline</td>
<td>12/09/13</td>
<td>Mon</td>
<td>63.6</td>
<td>64.0</td>
<td>0.82</td>
<td>None</td>
</tr>
<tr>
<td>None</td>
<td>12/14/13</td>
<td>Sat</td>
<td>70.3</td>
<td>70.2</td>
<td>0.82</td>
<td>None</td>
</tr>
<tr>
<td>None</td>
<td>12/22/13</td>
<td>Sun</td>
<td>71.2</td>
<td>70.5</td>
<td>0.82</td>
<td>None</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>68.1</td>
<td>68.0</td>
<td>0.82</td>
<td></td>
</tr>
<tr>
<td>Storm Baseline</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Snow 0-5 in</td>
<td>1/25/14</td>
<td>Sat</td>
<td>69.9</td>
<td>69.1</td>
<td>0.81</td>
<td>None</td>
</tr>
<tr>
<td>Snow/Rain 2-9 in</td>
<td>1/18/14</td>
<td>Sat</td>
<td>61.7</td>
<td>59.7</td>
<td>0.73</td>
<td>None</td>
</tr>
<tr>
<td>Snow/Rain/Sleet 0-1 in</td>
<td>2/19/14</td>
<td>Wed</td>
<td>61.4</td>
<td>59.9</td>
<td>0.80</td>
<td>None</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>64.3</td>
<td>62.9</td>
<td>0.78</td>
<td></td>
</tr>
<tr>
<td>Overall Average</td>
<td></td>
<td></td>
<td>66.1</td>
<td>65.3</td>
<td>0.80</td>
<td></td>
</tr>
</tbody>
</table>

*Average Roadway Grip Value; **Average Speed

Table 3  Prescriptive Messages Speed and Roadway Grip Summary for 2013/2014 Winter Storm Events in NH

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
<th>Day of Week</th>
<th>NB Speed** (mph)</th>
<th>SB Speed** (mph)</th>
<th>Grip*</th>
<th>Message</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snow 0-5 in</td>
<td>2/15/14</td>
<td>Sat</td>
<td>46.8</td>
<td>49.6</td>
<td>0.65</td>
<td>Maximum Speed 45 mph Slow Down</td>
</tr>
<tr>
<td>5-15 in</td>
<td>12/15/13</td>
<td>Sun</td>
<td>64.8</td>
<td>44.8</td>
<td>0.15</td>
<td>Maximum Speed 45 mph Slow Down</td>
</tr>
<tr>
<td></td>
<td>02/05/14</td>
<td>Wed</td>
<td>47.7</td>
<td>50.4</td>
<td>0.50</td>
<td>Maximum Speed 45 mph Slow Down</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>56.3</td>
<td>47.6</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>Snow Average</td>
<td></td>
<td></td>
<td>53.1</td>
<td>48.2</td>
<td>0.43</td>
<td></td>
</tr>
<tr>
<td>Snow/Rain 2-9 in</td>
<td>12/29/13</td>
<td>Sun</td>
<td>64.4</td>
<td>63.9</td>
<td>0.69</td>
<td>Maximum Speed 45 mph Slow Down</td>
</tr>
<tr>
<td>9-14 in</td>
<td>01/02/14</td>
<td>Thu</td>
<td>50.7</td>
<td>50.1</td>
<td>0.36</td>
<td>Maximum Speed 45 mph Slow Down</td>
</tr>
<tr>
<td></td>
<td>02/13/14</td>
<td>Thu</td>
<td>48.9</td>
<td>48.9</td>
<td>0.58</td>
<td>Maximum Speed 45 mph Slow Down</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>49.8</td>
<td>49.5</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>Snow/Rain Average</td>
<td></td>
<td></td>
<td>56.7</td>
<td>56.4</td>
<td>0.64</td>
<td></td>
</tr>
<tr>
<td>Overall Average</td>
<td></td>
<td></td>
<td>53.9</td>
<td>51.3</td>
<td>0.49</td>
<td></td>
</tr>
</tbody>
</table>

*Average Roadway Grip Value; **Average Speed
### Table 4  Descriptive Messages Speed and Roadway Grip Summary for 2013/2014

Winter Storm Events in NH

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
<th>Day of Week</th>
<th>NB Speed** (mph)</th>
<th>SB Speed** (mph)</th>
<th>Grip*</th>
<th>Message</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snow</td>
<td>01/21/14</td>
<td>Tue</td>
<td>64.2</td>
<td>67.2</td>
<td>0.82</td>
<td>Watch for Ice on Ramps Stay Alert</td>
</tr>
<tr>
<td></td>
<td>02/09/14</td>
<td>Sun</td>
<td>56.6</td>
<td>54.6</td>
<td>0.82</td>
<td>Winter Storm Watch Your Speed</td>
</tr>
<tr>
<td></td>
<td>01/21/14</td>
<td>Tue</td>
<td>62.8</td>
<td>63.4</td>
<td>0.63</td>
<td>Winter Storm Watch Your Speed</td>
</tr>
<tr>
<td></td>
<td>02/15/14</td>
<td>Sat</td>
<td>61.0</td>
<td>66.2</td>
<td>0.70</td>
<td>Winter Storm Watch Your Speed</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td></td>
<td><strong>61.1</strong></td>
<td><strong>62.8</strong></td>
<td><strong>0.74</strong></td>
<td></td>
</tr>
<tr>
<td>5-15 in</td>
<td>12/15/13</td>
<td>Sun</td>
<td>49.8</td>
<td>49.7</td>
<td>0.30</td>
<td>Winter Storm Clean Up Watch for Plows</td>
</tr>
<tr>
<td></td>
<td>02/18/14</td>
<td>Tue</td>
<td>62.1</td>
<td>63.0</td>
<td>0.52</td>
<td>Winter Storm Clean Up Watch for Plows</td>
</tr>
<tr>
<td></td>
<td>12/14/13</td>
<td>Sat</td>
<td>72.2</td>
<td>58.6</td>
<td>0.24</td>
<td>Winter Storm Watch Your Speed</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td></td>
<td><strong>61.4</strong></td>
<td><strong>57.1</strong></td>
<td><strong>0.35</strong></td>
<td></td>
</tr>
<tr>
<td>Snow Average</td>
<td></td>
<td></td>
<td>61.2</td>
<td>60.4</td>
<td>0.60</td>
<td></td>
</tr>
<tr>
<td>Snow/Rain</td>
<td>03/12/14</td>
<td>Wed</td>
<td>51.9</td>
<td>65.5</td>
<td>0.73</td>
<td>Winter Storm Watch Your Speed</td>
</tr>
<tr>
<td>2-9 in</td>
<td>01/02/14</td>
<td>Thu</td>
<td>47.1</td>
<td>52.1</td>
<td>0.30</td>
<td>Snow Covered Roadways Watch Speed</td>
</tr>
<tr>
<td></td>
<td>02/14/14</td>
<td>Fri</td>
<td>68.4</td>
<td>70.7</td>
<td>0.80</td>
<td>Winter Storm Clean Up Watch for Plows</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td></td>
<td><strong>57.7</strong></td>
<td><strong>61.4</strong></td>
<td><strong>0.55</strong></td>
<td></td>
</tr>
<tr>
<td>Snow/Rain Average</td>
<td></td>
<td></td>
<td>55.8</td>
<td>62.8</td>
<td>0.60</td>
<td></td>
</tr>
<tr>
<td>Snow/Sleet</td>
<td>12/09/13</td>
<td>Mon</td>
<td>61.6</td>
<td>50.2</td>
<td>0.70</td>
<td>Snow Covered Roadways Watch Speed</td>
</tr>
<tr>
<td>Snow/Sleet Average</td>
<td></td>
<td></td>
<td><strong>61.6</strong></td>
<td><strong>50.2</strong></td>
<td><strong>0.70</strong></td>
<td></td>
</tr>
<tr>
<td>Snow/Rain/Sleet</td>
<td>12/22/13</td>
<td>Sun</td>
<td>70.2</td>
<td>66.4</td>
<td>0.81</td>
<td>Black Ice Possible Slow Down</td>
</tr>
<tr>
<td></td>
<td>12/22/13</td>
<td>Sun</td>
<td>69.1</td>
<td>66.2</td>
<td>0.78</td>
<td>Freezing Rain Possible Slow Down</td>
</tr>
<tr>
<td>Snow/Rain Sleet Average</td>
<td></td>
<td></td>
<td><strong>69.7</strong></td>
<td><strong>66.3</strong></td>
<td><strong>0.80</strong></td>
<td></td>
</tr>
<tr>
<td>Overall Average</td>
<td></td>
<td></td>
<td><strong>61.1</strong></td>
<td><strong>60.9</strong></td>
<td><strong>0.62</strong></td>
<td></td>
</tr>
</tbody>
</table>

*Average Roadway Grip Value; **Average Speed
4.2 Traffic and RWIS Data

Data collected via the roadway sensors are collected continuously. For the purpose of this research, data were gathered for a full 48-hour period for each recorded storm event during the 2013/2014 winter season, beginning at midnight the day before the storm and ending at midnight the day after the storm. Data recorded by the RWIS were also collected for the same dates and time periods.

A baseline for typical traffic patterns in both directions of travel was established using speed and roadway grip data before and after each storm when the RWIS reported dry roadway conditions (Appendix A). A total of four figures were created for each storm, two for the northbound direction and two for the Southbound direction, based on the distance the queue sensor is located downstream from the nearest VMS. Sensors were divided as follow for the speed profile figures based on the locations of VMS throughout the study area as a means of making the data more legible in the figures:

- Northbound: q02-q07 (0.3-7.1 miles downstream);
- Northbound: q08-q13 (1.9-10.3 miles downstream);
- Southbound: q14-q17 (1.4-6.0 miles downstream); and
- Southbound: q18-q25 (4.9-16.0 miles downstream).

Data were further grouped into five categories based on the distance the sensor recording the data is located downstream from the nearest VMS to simplify analysis (Table 3). Sensors are not installed in a uniform interval throughout the study area, thus the number of sensors in each group vary. These sensor groupings will hopefully lend insight into the distance over which an advisory message impacts the speed at which a driver travels. Northbound and southbound traffic was also evaluated separately to determine if any difference in adherence to the signage is present by direction of travel.
Table 5  Queue Sensor Groupings for Summary Analysis

<table>
<thead>
<tr>
<th>Distance Downstream from Nearest VMS</th>
<th>Sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0 - 3.0 Miles</td>
<td>NB: q02, q03, q04</td>
</tr>
<tr>
<td></td>
<td>SB: q08, q17</td>
</tr>
<tr>
<td>3.1 - 6.0 Miles</td>
<td>NB: q05, q06, q09, q10</td>
</tr>
<tr>
<td></td>
<td>SB: q14, q29, q15, q16, q24, q25</td>
</tr>
<tr>
<td>6.1 - 9.0 Miles</td>
<td>NB: q30, q07, q11, q12</td>
</tr>
<tr>
<td></td>
<td>SB: q23</td>
</tr>
<tr>
<td>9.1 - 12.0 Miles</td>
<td>NB: q13</td>
</tr>
<tr>
<td></td>
<td>SB: q21, q22</td>
</tr>
<tr>
<td>12.1+ Miles</td>
<td>SB: q18, q19, q20</td>
</tr>
</tbody>
</table>

For the analysis, driver speed was compared to both the baseline conditions: dry pavement and no advisory message posted; and storm event recorded with no advisory message posted. These comparisons were used to determine whether or not the driver speed was reduced while each message was posted. The roadway grip value was used to evaluate if the roadway conditions were such that the drivers were forced to slow down, or if they elected to reduce their speed based on other factors such as the posted messages.

4.2.1 AVERAGE DAILY TRAFFIC VARIATIONS

Traffic volume data collected by the roadway sensors were used to establish average daily traffic variations throughout the study area (Figures 10-11). From these data, it was determined that the weekday morning peak occurs between 7:00-8:00 a.m. in the northbound direction and 5:00-6:00 a.m. in the southbound direction. The weekday evening peak hour was found to occur between 4:00-5:00 p.m. in the northbound direction and 5:00-6:00 p.m. in the southbound direction. Heavy traffic congestion typically occurs in the southbound direction during the morning commute period (5:00-8:00 a.m.) and during the evening commute period (4:00-7:00 p.m.) in the northbound direction due to workers commuting to and from Boston during the week. It was noted that many of the storms recorded during the 2013/2014 winter season occurred during weekday peak hours, which may have affected measured speeds.
Figure 10  Average Daily Traffic Variations – I-93 NB New Hampshire MM 0.6-17.8 - Weekday
Figure 11  Average Daily Traffic Variations - I-93 SB New Hampshire MM 1.2-20.2 - Weekday
5. FINDINGS

5.1 QUALITATIVE ANALYSIS

Speed profiles were plotted along with the roadway grip profiles for both northbound and southbound traffic, presented in chronological order (Appendix A). Solid vertical lines were plotted to represent the time at which various messages were posted to and cleared from the signs. A total of four figures were created for each storm, two for the northbound direction and two for the southbound direction, based on the distance the queue sensor is located downstream from the nearest VMS. Sensors were divided as follow for the speed profile figures based on the locations of VMS throughout the study area as a means of making the data more legible in the figures:

- Northbound: q02-q07 (0.3-7.1 miles downstream);
- Northbound: q08-q13 (1.9-10.3 miles downstream);
- Southbound: q14-q17 (1.4-6.0 miles downstream); and
- Southbound: q18-q25 (4.9-16.0 miles downstream).

A qualitative analysis was performed using these figures to determine the presence of general relationships between the available data, specifically between roadway grip and traffic speed while advisory messages were posted.

5.1.1 QUALITATIVE FINDINGS

It was found that for the most part, the speed profiles closely correlated with the roadway grip. As the roadway grip decreased (the roadway became more slippery), the speeds at which drivers were traveling simultaneously decreased. As the roadway grip returned to the normal level (approximately 0.82), speeds returned to their typical level as well, which is approximately 68 mph. This relationship between roadway grip and speed was noted for both directions of travel, regardless of the type of message posted as well as when no message was posted.

For cases where a message was posted, but no significant decrease in roadway grip was observed, as was the case during the December 22-23, 2013 storm event, the observed traffic speed also did not noticeably decrease (Figures 25-28). Typically though, observations indicated that mean driver speeds tended to fluctuate similarly to the roadway grip fluctuations.
It was observed that during events where a descriptive message was posted and superseded by a prescriptive message shortly thereafter, as was the case for the December 14-15, 2013, January 1-2, 2014, and February 13-15, 2014 storms, overall speeds appeared to be lower while the prescriptive message was posted than they were while the descriptive message was posted (Figures 21-24, 33-36, and 49-52). Speeds also appeared to reduce noticeably during storm events, such as February 5-6, 2014, where the only type of message posted to the VMS was prescriptive while that message was posted (Figures 41-44).

Speeds measured during storm events where only descriptive messages were posted to the VMS did not appear to be noticeably reduced beyond that which they otherwise would based on the roadway grip profile (Figures 17-20, 25-28, 37-40, 45-48, and 57-60). The exception to this observation about the effect of descriptive messages was that during two storm events where the message "Winter Storm Clean Up Watch for Plows" was posted, speeds were observed to be reduced beyond what they otherwise would be based on the roadway grip profile (Figures 53-56 and 21-24). This observation is potentially the result of snow plows physically forcing traffic to slow down behind them as they slowly move along treating the roadway.

5.1.2 Qualitative Conclusions

During storm events while descriptive messages were posted, the messages appear to have had little or no effect on speed. The prescriptive messages, conversely, appear to have had an effect on speeds based on the observations made during the storm events where these messages were posted. Messages and grip are undoubtedly correlated, as messages are not posted to the VMS unless a reduction in roadway grip is noticed, or at the very least, anticipated. It is therefore not possible without further analysis to determine whether the messages do have an effect on speed above and beyond the typical response drivers have to a decrease in roadway grip.
5.2 MULTIVARIATE REGRESSION

A multivariate regression was performed to isolate the impacts of two independent variables, roadway grip and message type, on mean speed. The form of the linear equation derived from the analysis is:

\[ \text{Speed} = a_{\text{grip}}x_{\text{grip}} + a_{\text{pres}}x_{\text{pres}} + a_{\text{desc}}x_{\text{desc}} + b \]

where:

\[ \text{Speed} = \text{Mean speed measured over a 5 - minute interval} \]
\[ a_{\text{grip}} = \text{roadway grip coefficient} \]
\[ x_{\text{grip}} = \text{roadway grip} \]
\[ a_{\text{pres}} = \text{prescriptive message coefficient} \]
\[ x_{\text{pres}} = \text{prescriptive message (binary variable)} \]
\[ a_{\text{desc}} = \text{descriptive message coefficient} \]
\[ x_{\text{desc}} = \text{descriptive message (binary variable)} \]
\[ b = y - \text{intercept} \]

The prescriptive and descriptive message variables were entered as a binary variable with a value of 1 if they were present during the event and 0 if they were not. Values for mean speed and roadway grip during all possible storm events were included in the analysis.

Data from all storm events and also three days where no storm event was observed were used in this analysis. The data from the roadway sensors were grouped into five categories based on the distance the sensor recording the data is located downstream from the nearest VMS (Table 3). The average of the northbound and southbound speeds measured over the entire duration of time that the advisory message was posted was used for each observation; therefore, observation intervals vary by storm event. A total of 94 observations were used for the analysis.

5.2.1 MULTIVARIATE REGRESSION FINDINGS

Results of the statistical analysis are shown in Table 6. Both roadway grip and prescriptive message presence were highly significant, indicated both by high t-values (3.5 for grip and -4.9 for prescriptive message) and resulting p-values that are nearly equal to 0.00. These p-values indicate that a strong relationship exists between the mean speed and roadway grip, and between the mean speed and the presence of prescriptive messaging, with a confidence level of nearly
100%. While the analysis indicates strong relationships between these three variables, evaluation of the resulting coefficients indicates the relative impact these variables have on speed. The roadway grip coefficient of 11.6 indicates that a change in grip from the typical value of 0.82 to a value of 0.5 during a storm event would be associated with a reduction in mean speed of 3.7 mph \((11.6*(-0.32)=3.7\text{mph})\), whereas the presence of a prescriptive message alone would decrease the mean speed by 9.5 mph based on its coefficient.

The coefficient derived for descriptive messages indicates that the presence of a descriptive message would decrease the mean speed by 2.5 mph, indicating this type of message has less of an impact on reducing speeds than both roadway grip and prescriptive messages do. With a t-statistic of 1.7 and resulting p-value value of 0.08942, the relationship between the presence of descriptive messages and mean speed, though not statistically significant at the 95% confidence level, is statistically significant at the 90% confidence level. Given the available data, it appears that the descriptive messages do lower speeds; however, more data is required to establish whether a relationship between this type of message and speed does exist, or if these results are a product of chance when in fact no relationship exists.

5.2.2 Multivariate Regression Conclusions

The multivariate statistical analysis that was performed indicates that the presence of prescriptive messages has a highly significant influence on driver speed during winter storm events, with statistical significance well above the 95% level. After controlling for roadway grip, it was determined that the presence of prescriptive messages reduces mean speeds by an additional 9.5 mph. It was also tentatively determined that the presence of descriptive messages has a significant impact on reducing driver speeds by 2.5 mph at the 90% level after controlling for roadway grip. This analysis indicates that prescriptive messages have a larger impact (nearly 300% greater) on driver speeds than descriptive messages do; however, more data is required to confirm the effect of descriptive messages on driver speeds.

Regression analysis is used to determine whether or not a significant relationship exists between two or more variables, but this type of analysis cannot prove causation. From the regression analysis, it is clear that speed is related to the presence of both prescriptive and descriptive messages in addition to the value of roadway grip. What is not examined in this analysis is if the messages caused the drivers to reduce their speeds or if the relationship found between the two was forced, or the result of external factors. Data were therefore further stratified on various levels in an effort to prove causation between posted messages and speed.
Table 6  Multivariate Regression Analysis–2013/2014 NH Winter Storm Data

<table>
<thead>
<tr>
<th>Regression Statistics</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiple R</td>
<td>0.68324</td>
<td>R Square</td>
<td>0.46682</td>
<td>Adjusted R Square</td>
<td>0.44905</td>
<td>Standard Error</td>
</tr>
<tr>
<td>Observations</td>
<td>94</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>df</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>2518.48189</td>
<td>839.49396</td>
<td>26.26602</td>
<td>2.70334E-12</td>
</tr>
<tr>
<td>90</td>
<td>2876.50931</td>
<td>31.96121</td>
<td></td>
<td></td>
</tr>
<tr>
<td>93</td>
<td>5394.99120</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>Standard Error</th>
<th>t Stat</th>
<th>P-value</th>
<th>Lower 95%</th>
<th>Upper 95%</th>
<th>Lower 95.0%</th>
<th>Upper 95.0%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>56.39784</td>
<td>2.91223</td>
<td>19.36586</td>
<td>0.00000</td>
<td>50.61219</td>
<td>62.18350</td>
<td>50.61219</td>
</tr>
<tr>
<td>Roadway Grip</td>
<td>11.67571</td>
<td>3.33235</td>
<td>3.50375</td>
<td>0.00072</td>
<td>5.05542</td>
<td>18.29601</td>
<td>5.05542</td>
</tr>
<tr>
<td>Descriptive</td>
<td>-2.66872</td>
<td>1.55431</td>
<td>-1.71698</td>
<td>0.08942</td>
<td>-5.75663</td>
<td>0.41918</td>
<td>-5.75663</td>
</tr>
</tbody>
</table>
5.3 Statistical Significance of Reduction in Speed by Message Posted

From the average values of speed calculated for each message type and direction of travel, a statistical analysis was performed to determine the significance of the reduction in speed against the baseline conditions while each message type was displayed. This analysis was performed to determine which specific messages correlated to statistically significant reductions in driver speed. Average speeds recorded during the 2013/2014 winter season storms were compared against two baselines. The first baseline evaluated was for the condition of dry pavement and no storm event or message posted to the VMS. The second baseline evaluated against was for the condition where a storm event took place but no message was posted to the VMS for the duration of the storm event.

Hypothesis testing was conducted as follows:

\[ H_0 = \bar{x} \geq \bar{X} \]

\[ H_1 = \bar{x} < \bar{X} \]

where:

\( H_0 = \text{null hypothesis} \)

\( H_1 = \text{alternative hypothesis} \)

\( \bar{x} = \text{sample average speed} \)

\( \bar{X} = \text{baseline average speed} \)
### Table 7  Average Speed Reduction vs. Baseline No Storm Event, No Message  
#### Test for Statistical Significance

<table>
<thead>
<tr>
<th>Message</th>
<th>Statistical Significance</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>NB p-value</td>
<td>SB p-value</td>
<td>Average p-value</td>
</tr>
<tr>
<td>MAXIMUM SPEED 45 MPH SLOW DOWN</td>
<td></td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>BLACK ICE POSSIBLE SLOW DOWN</td>
<td></td>
<td>0.7870</td>
<td>0.2047</td>
<td>0.4959</td>
</tr>
<tr>
<td>FREEZING RAIN POSSIBLE SLOW DOWN</td>
<td></td>
<td>0.6698</td>
<td>0.3040</td>
<td>0.4869</td>
</tr>
<tr>
<td>SNOW COVERED ROADWAYS WATCH SPEED</td>
<td></td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>WATCH FOR ICE ON RAMPS STAY ALERT</td>
<td></td>
<td>0.1373</td>
<td>0.0972</td>
<td>0.1172</td>
</tr>
<tr>
<td>WINTER STORM CLEAN UP WATCH FOR PLOWS</td>
<td></td>
<td>0.0197</td>
<td>0.0000</td>
<td>0.0098</td>
</tr>
<tr>
<td>WINTER STORM WATCH YOUR SPEED</td>
<td></td>
<td>0.0126</td>
<td>0.0001</td>
<td>0.0063</td>
</tr>
<tr>
<td>No Message Posted – Storm</td>
<td></td>
<td>0.2718</td>
<td>0.0128</td>
<td>0.1423</td>
</tr>
</tbody>
</table>

Shading indicates statistically significant at $\alpha=0.05$

Shading indicates statistically significant at $\alpha=0.10$

### Table 8  Average Speed Reduction vs. Baseline Storm Event, No Message  
#### Test for Statistical Significance

<table>
<thead>
<tr>
<th>Message</th>
<th>Statistical Significance</th>
<th></th>
<th></th>
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<tr>
<td></td>
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<td>NB p-value</td>
<td>SB p-value</td>
<td>Average p-value</td>
</tr>
<tr>
<td>MAXIMUM SPEED 45 MPH SLOW DOWN</td>
<td></td>
<td>0.0006</td>
<td>0.0000</td>
<td>0.0003</td>
</tr>
<tr>
<td>BLACK ICE POSSIBLE SLOW DOWN</td>
<td></td>
<td>0.8869</td>
<td>0.9918</td>
<td>0.9394</td>
</tr>
<tr>
<td>FREEZING RAIN POSSIBLE SLOW DOWN</td>
<td></td>
<td>0.8167</td>
<td>0.9983</td>
<td>0.9075</td>
</tr>
<tr>
<td>SNOW COVERED ROADWAYS WATCH SPEED</td>
<td></td>
<td>0.0010</td>
<td>0.0000</td>
<td>0.0005</td>
</tr>
<tr>
<td>WATCH FOR ICE ON RAMPS STAY ALERT</td>
<td></td>
<td>0.3378</td>
<td>0.9446</td>
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<td>0.1050</td>
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<tr>
<td>WINTER STORM WATCH YOUR SPEED</td>
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<td>0.0055</td>
<td>0.0426</td>
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<tr>
<td>Normal Operation – No Storm</td>
<td></td>
<td>0.6998</td>
<td>0.9999</td>
<td>0.8499</td>
</tr>
</tbody>
</table>

Shading indicates statistically significant at $\alpha=0.05$

Shading indicates statistically significant at $\alpha=0.10$
5.3.1 Statistical Findings

With a one-sided confidence interval of 95%, it was found that measured average speeds were significantly lower than both baseline conditions in both directions of travel during the times when two of the messages were posted: "Maximum Speed 45 MPH Slow Down", and "Snow Covered Roadways Watch Speed" (Tables 7-8). Statistically significant reductions in speed at the 95% confidence level were also confirmed for both directions of travel during the storm events where the message "Winter Storm Clean Up Watch for Plows" and "Winter Storm Watch Your Speed" were posted against the baseline condition of no storm and no message posted.

Average speeds measured in the southbound direction while "Winter Storm Clean Up Watch for Plows" and "Winter Storm Watch Your Speed" were posted were found to be statistically significant at the 95% confidence level when compared to the baseline condition where a storm event occurred and no message was posted. It was additionally determined that average speeds for the baseline condition of storm events where no message was posted were significantly lower than they otherwise would be given dry pavement conditions with no storm and no message posted at the 95% confidence level in the southbound direction only.

With a wider confidence interval of 90%, average speeds measured in the southbound direction become statistically significant while the message "Watch for Ice on Ramps Stay Alert" was posted when compared to the baseline condition of no storm event and no message posted to the VMS. At this confidence level, the reduction in average speed for the northbound direction of travel while the message "Winter Storm Watch Your Speed" was posted becomes statistically significant for the baseline condition being a storm event where no message was posted to the VMS.

Even with a confidence interval of 90%, reductions in speed for both directions of travel compared to both baselines are not statistically significant for the storms during which the messages "Black Ice Possible Slow Down" and "Freezing Rain Possible Slow Down" were posted to the VMS. Additionally, when compared to the baseline of no storm event with no message posted to the VMS, the measured speeds in the northbound direction were not found to be statistically lower than the baseline average while the message "Watch for Ice on Ramps Stay Alert" was posted. Compared to the baseline condition of a storm event occurring where no message was posted to the VMS, measured speeds in both directions were not found to be statistically significant while this message was posted to the VMS.
5.3.2 Statistical Conclusions

The findings from this statistical analysis further support the conclusion from the multivariate regression analysis. The prescriptive messages correlate more significantly with reductions in speed than the presence of many descriptive messages do. This analysis highlighted the fact that descriptive messages informing the driver that they should reduce their speed using terms such as "Watch (Your) Speed" correlate most significantly with reductions in driver speeds when compared against both baselines. The message indicating that snow plows may be present in the roadway also correlated to significant reductions in speed, but this may be the result of the snow plow itself forcing traffic to slow behind it. Overall, cautionary messages using terms such as "Slow Down" or "Stay Alert" do not appear to correlate to significant reductions in driver speeds.

5.4 Correlation of Message Type to Average Speed and Roadway Grip

Further analysis was performed to examine the correlation of roadway grip on mean observed speeds to evaluate whether reductions in speed are influenced more by physical roadway characteristics, or other factors such as posted messages. Mean speed and roadway grip values measured during the 2013/2014 winter season storms were stratified based on the message type that was posted to the VMS (Figure 12). The available data that were summarized in 5-minute intervals were averaged over the entire time interval during each storm event while the message was posted. For the storm events where no messages were posted, the roadway grip profiles were used as a means to estimate the time interval during which the storm took place. Values of speed and roadway grip were averaged over these entire time intervals. This section details the analysis performed to determine average speeds and roadway grip values measured for each message type.

5.4.1 Baseline: Normal Operations, No Storm Event

One of the baseline conditions was taken to be dry pavement with no storm event and no advisory messages posted to the VMS. Average speeds were calculated for weekday off-peak hours based on the average daily traffic variations determined using data from the roadway sensors (Figures 10-11). The average speeds were calculated based on data collected the day before and the day after each recorded storm. The average speed for the northbound direction was determined to be approximately 68 mph. In the southbound direction, the average speed was determined to be approximately 69 mph. The average roadway grip value for the baseline condition was taken as 0.82.
5.4.2 BASELINE: NO MESSAGE POSTED, WITH STORM EVENT

The second baseline condition used for analysis was taken as storm events where no advisory message was posted to the VMS. The average roadway grip value for these storms was measured as 0.77. This value for the mean roadway grip shows approximately a 6% reduction from that recorded for the other baseline condition of dry pavement with no advisory message posted (Figures 10-11). The mean speeds in the northbound and southbound directions during these events were 65.8 mph and 64.3 mph, respectfully. The mean speeds observed in the northbound and southbound directions show approximately a 5% reduction in speed from that recorded for the other baseline condition. These reductions in speed were found to be statistically significant for the southbound direction, with a p-value calculated as 0.0128. The reduction in speed was not found as statistically significant for the northbound direction, however, with a p-value calculated as 0.2718, well outside the acceptable confidence level of $\alpha=0.05$ (Table 6).

5.4.3 MAXIMUM SPEED 45 MPH SLOW DOWN

During the six winter storms while the "Maximum Speed 45 MPH, Slow Down" message was posted, the overall average speed reduced from the normal 68 mph to 53.9 mph in the northbound direction and 50.5 mph in the southbound direction. The mean roadway grip value for all storms while this message was displayed was 0.49, which is a 39% reduction from the normal value of 0.82 on dry pavement and indicates the roadway was icy and/or snow covered (Table 1, Figures 13-14). Mean reductions in speed measured in the northbound and southbound represent an approximate 20% and 26% decrease from typical operating speeds on dry pavement, respectfully, and were found to be statistically significant reductions in speed when evaluated against both baseline conditions (Tables 7-8). While the recorded speeds were higher on average than the posted advisory speed, they were well below the typical speeds traveled along this portion of roadway, and were also considerably lower than the average speed traveled during storms where no advisory message was posted.

5.4.4 BLACK ICE POSSIBLE SLOW DOWN

Mean speeds measured while the message "Black Ice Possible, Slow Down" was posted were slightly faster than those measured for the baseline conditions, most notably in the northbound direction where mean speeds were measured to be 70 mph (Figure 13). Obviously, no statistically significant reduction in mean speed was observed while this message was displayed, as supported by the calculated p-values of 0.8869 for the northbound direction and 0.9918 for the
southbound direction (Table 7). The mean roadway grip measured while this message was posted was 0.81, which is nearly equal to that measured on dry pavement during normal operations.

During the study period, this message was only displayed one time for a short duration between 9:01 p.m. and 12:00 a.m. on December 22, 2013 (Table 4). Average daily traffic during this time period is well below roadway capacity. With roadway grip values nearly equal to those recorded for the baseline condition of dry pavement with no message posted coupled with low traffic volumes, it is reasonable for speeds to be slightly higher than the overall daily average speed would be (Figures 13-14). Due to so little data being available for this message, however, no significant conclusions can be made pertaining to its impact on driver behavior.

5.4.5 Freezing Rain Possible Slow Down

The message "Freezing Rain Possible, Slow Down" was posted during the study period on Sunday December 22, 2013 between 12:25 a.m. and 8:23 p.m. (Table 4). The average speeds measured during the time that this message was posted were 69 mph in the northbound direction and 68 mph in the southbound direction (Figures 13-14). These measured speeds were found to insignificantly differ from the baseline conditions. The roadway grip measured during this time was found to be 0.78, an approximate 5% decrease from the baseline condition of dry pavement with no message posted, indicating the roadway condition was wet (Table 1).

This information leads one to draw the conclusion that this message does not have an impact on reducing mean driver speeds, but the data are limited to only one date when this message was displayed. Further research should be done to better draw conclusions pertaining to this message.

5.4.6 Snow Covered Roadways Watch Speed

On the two storm days while the message "Snow Covered Roadways, Watch Speed" was posted, the mean speed in the northbound direction was 54.4 mph and was 50.8 mph in the southbound direction (Figures 13-14). Mean reductions in speed measured in the northbound and southbound accounted for an approximate 20% and 26% decrease from normal operating speeds with dry pavement conditions, respectfully, and were found to be statistically significant reductions in speed. The reduction in speed was determined statistically significant, with a p-value of 0.0000 for both the northbound and southbound direction when compared against the baseline condition of dry pavement with no advisory message posted (Table 6). Compared against the baseline condition of a storm event where no advisory message was posted, the p-values calculated were 0.0010 for the northbound direction and 0.0000 for the southbound direction (Table 7).
Additionally, the mean roadway grip value was 0.50, a 39% reduction from dry pavement conditions, while this message was posted. This roadway grip value indicates the roadways were icy and/or snow covered (Table 1).

5.4.7 Watch for Ice on Ramps Stay Alert

While the message "Watch for Ice on Ramps, Stay Alert" was posted, mean speeds were measured to be 64 mph in the northbound direction and 66 mph in the southbound direction (Figures 13-14). Although the measured speeds were approximately 5% lower than those measured for the baseline condition of dry pavement conditions with no advisory message posted, these reductions in speed were not found to be statistically significant compared against either baseline condition at the confidence level of $\alpha=0.05$ (Tables 7-8). If the confidence level is expanded to $\alpha=0.10$, the reduction in speed for the southbound direction becomes significant (p-value=0.0972) when compared against the baseline condition of dry pavement with no advisory message posted (Table 6).

The average roadway grip value measured while this message was displayed was found to be 0.82, which is equal to the value present in the baseline condition. The lack of significant reduction in speed is most likely due to the roadway grip value being the same as under dry pavement conditions and drivers feeling comfortable traveling at their normal speed through the study area.

5.4.8 Winter Storm Clean Up Watch for Plows

During the time periods in which the message "Winter Storm Clean Up, Watch for Plows" was posted, the mean roadway grip was measured as 0.63, an approximate 24% reduction in roadway grip from dry pavement conditions, indicating the roadway was wet (Table 1). While this message was displayed, mean speeds were 61.2 and 60.5 mph in the northbound and southbound directions respectfully. These reductions in speed were found to be statistically significant at the $\alpha=0.05$ confidence level, with p-values of 0.0197 for the northbound direction and 0.0000 for the southbound direction when compared to the baseline condition of dry pavement with no advisory message posted (Table 6).
The reduction in speed in the southbound direction was statistically significant in the southbound direction with a p-value of 0.0005 when compared to the baseline condition of a storm event during which no advisory message was posted to the VMS (Table 7). This finding indicates that, while drivers were observed to travel slower on average than they otherwise would have under dry conditions with no message posted, they were not traveling slower than that would with stormy conditions with no message posted.

It should be noted that snow plows travel at speeds well below the posted speed limit, slowing traffic in at least one lane of traffic, if not two. This influence on slowing traffic is concentrated to the location of the snow plow in the roadway network, but may be significant depending on the length of the queue extending behind the snow plow and the number of travel lanes blocked by the plow. Given the available data, it cannot be stated without uncertainty whether or not the slowly traveling snow plows had an effect on the measured significant reduction in mean speed while this message was posted to the VMS.

5.4.9 WINTER STORM WATCH YOUR SPEED

During the time periods in which the message "Winter Storm, Watch Your Speed" was posted, the mean roadway grip was measured as 0.62, an approximate 24% reduction in roadway grip from dry pavement conditions, indicating the roadway was wet (Table 1). An advisory speed for the roadway was not displayed while this message was posted on the VMS. During the storm events in which the message was displayed, mean speeds in the northbound and southbound direction were approximately 60.6 and 61.3 mph, respectfully.

These mean speeds for both directions of travel were found to be statistically significant at the \( \alpha=0.05 \) confidence level when compared to the baseline condition of dry pavement conditions with no advisory message posted. P-values calculated for the speed reductions were 0.0126 in the northbound direction and 0.0001 in the southbound direction (Table 6). When compared against the baseline condition of a storm event during which no advisory message was posted, the measured reductions in speed were found to be significant at the confidence interval of \( \alpha=0.05 \) for the southbound direction with a p-value of .0055, and with a confidence interval of \( \alpha=0.10 \) for the northbound direction with a p-value of 0.0798 (Table 7).
5.4.10 Conclusions

The analyses indicate that no significant reductions in mean speed occurred during the winter storms during which the messages "Black Ice Possible Slow Down" and "Freezing Rain Possible Slow Down" were posted to the VMS. Additionally, no significant reductions in speed were observed during the winter storms when "Watch for Ice on Ramps Stay Alert" was posted to the VMS when compared against the baseline of a storm event where no message was displayed. The roadway grip values measured while these messages were posted also did not differ greatly from the baseline condition of no storm event and no message posted. These findings indicate that either these messages are ineffective at encouraging drivers to reduce their rate of speed, or the roadway grip did not warrant a significant reduction in speed, or a combination of both.

Alternatively, the reductions in speed observed while the messages "Maximum Speed 45 MPH Slow Down," "Snow Covered Roadways Watch Speed," and "Winter Storm Watch Your Speed" were determined to be statistically significant compared against both baselines. The average roadway grip values measured while these messages were posted greatly reduced from what they otherwise would be given dry pavement conditions with no storm event taking place. These findings indicate that the messages posted may have been effective at encouraging drivers to reduce their mean rates of speed, but the value of roadway grip likely played a role in causing the observed reductions in speed to occur.

The results from this analysis generally indicate that observed reductions in mean speeds traveled are significant when the message itself includes either a specific recommended speed limit or the terms "Slow Down" or "Watch (Your) Speed" during a winter storm event. It was also determined that the average roadway grip values during the storm events while these messages were posted were much lower than they otherwise would be given dry pavement conditions. Descriptive messages warning of potential future hazards using terms such as "Freezing Rain Possible" did not appear to correlate to a significant reduction in mean speeds traveled, and average roadway grip values tended to be closer to the value they would be given dry pavement conditions while these messages were posted. These findings indicate that roadway grip and certain advisory messages posted to VMS potentially have an influence on the observed reductions in mean speeds, but the only definitive conclusion that can be drawn from this analysis is that mean speeds did significantly reduce given the aforementioned conditions.
5.5 CORRELATION OF DISTANCE FROM NEAREST VMS AND DIRECTION OF TRAVEL TO AVERAGE SPEED AND ROADWAY GRIP

A quantitative analysis was performed on the data to determine the effect of the advisory messages on traffic behavior based on driver distance from the nearest VMS (Figures 13-14). Analysis was performed for each direction of travel for each storm event recorded by the NHDOT TMC for the 2013/2014 winter season. Results of the analysis were broken down by the seven messages posted. These results were compared against the two baseline conditions of dry pavement with no storm or advisory message posted, and during the recorded storm events where no advisory message was posted.

5.5.1 FINDINGS

It was found that, in general, traffic in the southbound direction travels at a slightly slower speed than that in the northbound direction (Figure 12). Average speeds in the southbound direction were found to be slightly higher than they were in the northbound direction for the baseline condition of no storm and no message displayed though. Also, while the descriptive messages, "Watch for Ice on Ramps Stay Alert" and "Winter Storm Watch Your Speed" were posted, the average speeds recorded in the southbound direction were respectively 3.0 and 1.2 mph higher than in the northbound direction.

It was also found that, regardless of which message (if any) was posted in addition to the roadway condition, the northbound direction mean driver speeds typically decrease the further away from a VMS the vehicle is (Figure 13). Conversely, it was found that mean driver speeds in the southbound direction typically increase as the vehicle travels further away from a VMS, but driver speeds tend to drop off again once the vehicle travels 12.0 or more miles away from the nearest VMS (Figure 14).

5.5.2 CONCLUSIONS

It is not clear why average speeds increase the further away from a VMS the measurement was taken in the southbound direction and they decrease in the northbound direction. These observed patterns could be due to differences in roadway geometry. The differences could also be due to factors such as perceived dissimilarities in the presence of law enforcement along the roadway. Given the available data, the precise cause of this discrepancy cannot be determined.
5.6 Correlation of Day of Week to Average Speed and Roadway Grip

Each of the events that took place during the 2013/2014 winter season took place during a wide variety of days of the week. Whether or not day of the week had an impact on the rate at which drivers traveled was therefore possible to be investigated. The baseline condition for this analysis was taken to be the average of the values for both baseline conditions stratified by day of week. The speeds measured during storm events were averaged for each day of the week and stratified by message type posted to the VMS: descriptive or prescriptive.

5.6.1 Findings

It was observed that the average baseline speeds were slightly higher during the weekends than they were during the weekdays (Figure 15). Average speeds on Saturday and Sunday were measured as 67 and 71 mph, respectively, and average speeds were measured on Monday and Wednesday as 61 and 64 mph, respectively. The slight reductions in speed during the weekdays may be due to congestion resulting from commuter traffic.

It was also determined that the average speeds measured while descriptive messages were posted to the VMS were generally higher than they were when prescriptive messages were posted. For the storm events that occurred on Thursday while a prescriptive message was posted to the VMS, the average roadway grip value was 0.47 and the mean speed was 50 mph. During the storm events that occurred on Saturday while a descriptive message was posted, the roadway grip was also 0.47, but the average speed measured was 64 mph. For the storm events that occurred on Thursday while a prescriptive message was posted to the VMS, the average roadway grip value was 0.47 and the mean speed was 50 mph. During the storm events that occurred on Saturday while a descriptive message was posted, the roadway grip was also 0.47, but the average speed measured was 64 mph. These data indicate that factors aside from roadway grip affect the rate of speed at which drivers elect to travel.

Further evidence that roadway grip and descriptive advisory messages posted to the VMS may not be the primary factors at play in affecting driver behavior presents in the data available for Thursday and Saturday storm events. For the Thursday baseline condition, the average measured speed was 50 mph, and the roadway grip was 0.47. For the Thursday storms during which a descriptive message was posted, the average measured speed was also 50 mph, but the roadway grip was only 0.30. The fact that the roadway grip values measured for both of these conditions differed so greatly from one another, and yet the measured average speeds were precisely the same indicates that some other factor(s) impacted the driver behavior.
5.6.2 CONCLUSIONS

These data indicate that factors aside from roadway grip affect the rate of speed at which drivers elect to travel. They also indicate that descriptive messages are not entirely effective at causing drivers to reduce their rate of speed. An observation occurred where the measured average speed for the baseline condition was equal to that for the descriptive message case even though the roadway grip values greatly differed from one another, indicating that that the descriptive messages posted to the VMS may not be effective at causing drivers to slow down during storm events. This coupled with the observation that average speeds were typically higher while a descriptive messages were posted than they were when prescriptive messages were posted to the VMS further indicates that the descriptive messages may not be as effective at causing drivers to reduce their average rate of speed as prescriptive messages. Additionally, the measured mean speed during the events where a descriptive message was posted was higher than would be expected given the roadway grip value, which further indicates that both the descriptive messages and roadway grip may not be entirely effective at causing drivers to slow their mean rate of speed.

5.7 CORRELATION BETWEEN EVENT TYPE/MAGNITUDE AND AVERAGE SPEED/ROADWAY GRIP

Data were available for the 2013/2014 winter season for four different storm event types:

- Snow (0-5” and 5-15”);
- Snow/Rain (2-9” and 9-14”);
- Snow/Sleet; and
- Snow/Sleet/Rain (0-1”).

These data were evaluated to determine whether or not messages posted during different storm events with different precipitation magnitudes would have a varying effect on average speeds traveled. Storm event magnitudes used for this analysis were grouped based on the precipitation range reported in the NHDOT storm logs. No precipitation magnitude was provided for the event that had Snow/Sleet.

Average speeds measured during each of these storm events were evaluated for three conditions. The baseline condition was for storms where no advisory message was posted to the VMS. Average speeds were also evaluated for times when descriptive messages were posted to the VMS for each storm event type, as well as for times when prescriptive messages were posted to
he VMS for each storm event type. No correlation was found between speed and roadway grip when stratified based on both event and message type.

5.7.1 Snow

Lower average speeds were measured under snow conditions while prescriptive messages were posted than when descriptive messages or no message at all were posted (Figure 16). For the storms that received 0-5 inches of snow, the average speed was the lowest while prescriptive messages were posted at 48 mph on average. During these storms, the average speed while descriptive messages were posted was 62 mph, and with no message posted, the average speed was 69 mph.

5.7.2 Snow/Rain

Data measured during this storm event condition differed from what may be expected (Figure 16). For the storms that received 2-9 inches of snow/rain, the average speed measured while prescriptive messages were posted to VMS (64 mph) was higher than both that measured while descriptive messages were posted (59 mph) and no message was posted (61 mph). Conversely, for the storms that received 9-14 inches of snow/rain, the average speeds measured while descriptive messages were posted to the VMS (60 mph) were higher than those measured while prescriptive messages were posted (50 mph). These data may indicate that the prescriptive messages are more effective at causing drivers to reduce their rate of speed during storms that receive larger amounts of precipitation.

5.7.3 Snow/Sleet

Insufficient data were available for this storm event type (Figure 16). Only one storm was recorded during the study period with this event condition. No conclusions can therefore be drawn from this data point.

5.7.4 Snow/Rain/Sleet

The average speed measured for this storm event condition was lower while no message was posted to the VMS (61 mph) than it was while descriptive messages were posted to the VMS (68 mph) (Figure 16). These data indicate that for this weather type with very little accumulating precipitation of 0-1 inch, the descriptive messages posted to the VMS likely are not effective at causing drivers to reduce their rate of speed.
5.7.5 CONCLUSIONS

Based on the available data for each storm event condition, it appears as though prescriptive advisory messages are most effective at causing drivers to reduce their rate of speed during storms with a large amount of accumulating precipitation. This can be clearly seen for storm events where both messaging types were employed and the baseline was also recorded, as was the case for the 0-9 inches of snow condition. A trend can be seen from the snow conditions data that average speeds tend to be largest when no advisory message is displayed on the VMS, with a reduced mean speed measured when descriptive messages are posted, and a further reduced mean speed when prescriptive messages are posted. This trend only holds true for the snow conditions and the snow/rain condition with 9-14 inches accumulation, however. For the storm events with lesser amounts of accumulation, mean speeds tended to be higher while advisory messages were posted than they were without any messages posted. This leads to the conclusion that, perhaps, advisory messaging overall is most effective during storms with heavy precipitation accumulation; however, further research is necessary to fully make that claim.

5.8 CORRELATION BETWEEN AVERAGE SPEED AND ROADWAY GRIP

Linear regression analyses were performed to determine if a direct correlation exists between average measured speed and roadway grip. Baseline conditions were analyzed as an overall average of both conditions (with and without storm events) and as two separate conditions (with a storm event and without a storm event). Regression analyses were performed for the data recorded while descriptive messages were posted, while prescriptive messages were posted, and for the overall average for all storm events. No regression analysis could be performed on the baseline condition of dry pavement without an advisory message alone posted due to a lack in roadway grip variability for this condition.

5.8.1 ALL STORM EVENTS EVALUATED TOGETHER

The strongest linear correlation between average speed and roadway grip was found when the data from all storm events were evaluated together. The $R^2$ statistic for all storms together was found to be 0.86092 (Figure 69). This value indicates that, overall, roadway grip correlates relatively strongly to average speed, although this correlation could certainly be stronger.
5.8.2 Baseline Conditions

This correlation is not as strong once the data are categorized by message type and evaluated separately. The $R^2$ statistic for the combined baseline conditions was calculated as 0.45869 (Figure 70). When the data for the baseline conditions were separated apart, the $R^2$ statistic was found to be 0.35175 for the condition of a storm event where no advisory message was displayed (Figure 71). These statistics indicate that little correlation exists for these conditions between average speed and roadway grip; however, due to there being little data available for this condition, these analyses are not very reliable.

5.8.3 Events Where Descriptive and Prescriptive Messages Were Posted

The calculated $R^2$ statistic for the storm events where descriptive messages were posted was calculated as 0.25782 (Figure 72). Most interestingly, the $R^2$ statistic calculated for storm events where prescriptive messages were posted to the VMS was 0.01571, indicating almost no correlation exists between the average speed and roadway grip for this condition (Figure 21). These small correlation values very likely are influenced by the small number of data points available for the analysis, however, and the analysis may not be entirely reliable.

5.8.4 Conclusions

These analyses indicate that (for all events evaluated together), overall, roadway grip correlates relatively strongly to average speed. Once the data were separated and evaluated based on individual categories, however, it was found that little correlation exists between the mean observed speed and mean roadway grip; however, due to there being little data available for this condition, these analyses may not be entirely reliable. The sharp decreases in $R^2$ statistic values for the conditions where descriptive and prescriptive messages were posted to the VMS indicate that factors aside from physical roadway conditions (roadway grip) appear to affect driver behavior regarding speed traveled during winter storms. Further analysis would be required to determine the precise extent of influence roadway grip has on affecting mean driver speeds, and which other factors also have an influence.
Figure 12  Average Speed and Roadway Grip by Message Type and Direction of Travel for New Hampshire 2013/2014 Winter Storm Events Manchester-Salem
Figure 13  Average Speed by Distance from Nearest VMS—New Hampshire I-93 Northbound Manchester-Salem During 2013/2014 Winter Storm Events

<table>
<thead>
<tr>
<th>Distance from VMS</th>
<th>Average Speed</th>
<th>Roadway Grip</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0-3.0 Miles</td>
<td>57.2</td>
<td>0.00</td>
</tr>
<tr>
<td>3.1-6.0 Miles</td>
<td>54.3</td>
<td>0.00</td>
</tr>
<tr>
<td>6.1-9.0 Miles</td>
<td>51.9</td>
<td>0.00</td>
</tr>
<tr>
<td>9.1-12.0 Miles</td>
<td>52.2</td>
<td>0.00</td>
</tr>
<tr>
<td>Avg Roadway Grip</td>
<td>0.49</td>
<td>0.00</td>
</tr>
</tbody>
</table>

- **MAXIMUM SPEED 45 MPH SLOW DOWN**
- **BLACK ICE POSSIBLE SLOW DOWN**
- **FREEZING RAIN POSSIBLE SLOW DOWN**
- **WINTER STORM WATCH YOUR SPEED**
- **SNOW COVERED ROADWAYS WATCH SPEED**
- **WATCH FOR ICE ON RAMPS STAY ALERT**
- **WINTER STORM CLEAN UP WATCH FOR PLOWS**
- **No Message Posted – Storm**
- **Normal Operation – No Storm**

Legend:
- Blue bar: 0.0-3.0 Miles from VMS
- Red bar: 3.1-6.0 Miles from VMS
- Green bar: 6.1-9.0 Miles from VMS
- Purple bar: 9.1-12.0 Miles from VMS
- Black line: Avg Roadway Grip
Figure 14  Average Speed by Distance from Nearest VMS–New Hampshire I-93 Southbound Manchester-Salem During 2013/2014 Winter Storm Events
Figure 15  Average Speed and Roadway Grip by Day of Week–New Hampshire I-93 Manchester-Salem During 2013/2014 Winter Storm Events
Figure 16  Average Speed by Event Type – New Hampshire I-93 Manchester-Salem During 2013/2014 Winter Storm Events
5.9 CRASH ANALYSIS

A total of five vehicular crashes were reported during the recorded storm events between December 2013 and March 2014 within the study area. Three crashes occurred during the December 14, 2013 storm, and two occurred during the February 15, 2014 storm. No crashes were reported within the study area during any of the other recorded storms during the study period.

Two messages were posted to VMS advising drivers to reduce their speed during both storm events:

- Winter Storm Watch Your Speed; and
- Maximum Speed 45 MPH Slow Down.

These messages were both posted to VMS during both storm events at different times (i.e. only one message or the other was posted at any given time). Crash data was not available for the previous winter season. The five data points recorded for the 2013/2014 winter season all occurred during time periods when advisory messages were posted to the VMS. This information may indicate that the advisory messages posted to the VMS may not be entirely effective at preventing motor vehicle crashes, but without historical data to compare against, no specific conclusions can be drawn.

5.10 CONCLUSIONS

The available data from the 2013/2014 winter season indicate that the advisory messaging does have an impact on reducing driver speeds during winter storm events, most notably while prescriptive messages are posted to the VMS. The multivariate regression analysis indicated that, while reductions in speed were found to significantly correlate to the roadway grip, they also significantly correlate most notably to the presence of prescriptive messages and, to a lesser extent, to the presence of descriptive messages. The bivariate analysis further supported this fact, finding reductions in mean speed measured while prescriptive messages were posted to VMS statistically significant when compared against both baselines.
The bivariate analysis found reductions in mean speed measured while many of the descriptive messages were posted to VMS statistically significant compared against both baselines as well, with four exceptions. Reductions in mean speed were determined statistically insignificant while the messages "Black Ice Possible Slow Down," "Freezing Rain Possible Slow Down," and "Watch for Ice on Ramps Stay Alert" were posted to the VMS. Reductions in mean speed while the message "Winter Storm Clean Up Watch for Plows" was posted were determined statistically significant compared to the baseline of dry pavement conditions with no message posted, but were statistically insignificant compared to the baseline condition of a storm event where no advisory message was posted, indicating that the measured reductions in speed were no greater than that which would naturally occur anyway without any advisory messages posted and were likely the result of snow plows themselves forcing traffic to slow behind them. These messages therefore appear to have little effect on driver behavior.

An overall correlation was found to exist between mean speed and roadway grip; however, once the data were further stratified by messaging condition, the correlation decreased. It was determined that almost no correlation exists between mean speed and roadway grip for the storm events during which a prescriptive message was posted, indicating that perhaps the message is the cause of the significant reductions in speed measured. Very little correlation was also determined to exist between average speed and roadway grip for storm events where descriptive messages were posted to the VMS, indicating that perhaps these messages had an impact on the measured reductions in mean speed.

When the data were stratified by storm condition, it was observed that speeds were considerably lower while prescriptive messages were posted during snow and snow/rain events with accumulations greater than 9.0 inches than they were for baseline conditions and while descriptive messages were posted. Additionally, when the data were stratified by message type, it was observed that, for nearly equal roadway grip values, the mean speeds measured while the prescriptive message "Maximum Speed 45 MPH Slow Down" was displayed were notably lower than they were while the prescriptive message "Snow Covered Roadway Watch Speed" was posted. Average speeds also tended to be lower during storm events where prescriptive messages were posted to the VMS than when descriptive messages were posted to the VMS when the data were stratified by day of week. Mean speeds tend to be highest when no advisory message is displayed on the VMS, with a reduction in mean speed measured when descriptive messages are posted, and a further reduction in speed when prescriptive messages are posted.
These analyses support the initial hypothesis that the presence of advisory messages does correlate to a mean reduction in observed driver speeds, and that mean speeds, especially while prescriptive messages are displayed, do decrease beyond that which they otherwise would given the roadway conditions. The regression analysis supports the theory that speed is correlated to the presence of the advisory messages, and the supporting analysis further stratifying the data indicates that causation likely exists between speed and advisory messages. Based on these analyses, the advisory messages appear to cause drivers to reduce their rate of speed. Prescriptive messages appear to have a more significant impact on speed reductions, although descriptive messages appear to have a degree of impact as well. The analyses were performed using data from only one winter season though; therefore, available data points were limited. Further research should be conducted to determine the precise correlation between the presence of advisory messages and mean reductions in driver speed. This research indicates, however, that this type of messaging is effective at reducing mean speeds during inclement weather on highways.
Winter storm events present a significant safety hazard to the traveling public, especially when high rates of speed are present on roadways. Drivers exercise a certain level of judgment when adjusting their speeds during inclement weather, although this judgment is not necessarily always enough to significantly increase roadway safety. Methods such as advisory messaging are therefore implemented by state DOTs in an effort to increase roadway safety as much as possible. The findings from this research indicate that the presence of such advisory messages, especially prescriptive messages, appear to have a positive effect on reducing mean driver speeds.

The analysis generally indicates that the presence of either a prescriptive advisory message or a descriptive one using the terms "Watch (Your) Speed" during winter storm events correlate to a significant reduction in mean driver speeds. Descriptive messages warning of potential future hazards using terms such as "Freezing Rain Possible" did not appear to correlate to a significant reduction in mean speeds traveled, and average roadway grip values tended to be closer to the values they would be given dry pavement conditions while these messages were posted. It was also determined that advisory messages had the most significant impact during storms with a large amount of accumulating precipitation.

It is therefore recommended that prescriptive messages or descriptive ones using the term "Watch (Your) Speed" be posted during inclement weather to reduce mean driver speeds, and that the posting of those messages be reserved for storm events with significant reductions in roadway grip values. Cautionary messages warning of potential roadway hazards should be posted based on the current roadway conditions to increase driver confidence in the reliability of the messaging. Further research within the topic of VMS applications should be conducted in the future to evaluate the full extent of utility this technology can provide to DOTs regarding safety. Additionally, further research should be conducted to better evaluate the correlation of speed with the presence of descriptive messages.
Based on this research, the implementation of this type of messaging during winter storm events is recommended as an effective measure to reduce driver speeds and improve overall safety conditions. These findings support the necessity for ITS infrastructure, specifically related to VMS technology, to be expanded and thoroughly utilized by transportation departments in an effort to improve safety. This type of infrastructure is versatile, as it can be used to disseminate messages to the public ranging from advisory winter messages to travel times during periods of congestion and warning drivers about crashes or other hazards ahead, and it utilizes infrastructure that most states already have in place. For this reason, posting these messages would prove to be a useful safety measure during winter storm events with few barriers, if any, to implementation. It would be a valuable use of funding to expand the state operated VMS network to cover high speed divided highways.
7. REFERENCES


APPENDIX A: SPEED PROFILES
Figure 17  December 9-10, 2013 I-93 NB Sensors q02-q07 Speed Profile

Figure 18  December 9-10, 2013 I-93 NB Sensors q08-q13 Speed Profile
Figure 19  December 9-10, 2013 I-93 SB Sensors q14-q17 Speed Profile

Figure 20  December 9-10, 2013 I-93 SB Sensors q18-q15 Speed Profile
DECEMBER 14-15, 2013 – SNOW (9.0 INCHES)

**Figure 21** December 14-15, 2013 I-93 NB Sensors q02-q07 Speed Profile

**Figure 22** December 14-15, 2013 I-93 NB Sensors q08-q13 Speed Profile
Figure 23  December 14-15, 2013 I-93 SB Sensors q14-q17 Speed Profile

Figure 24  December 14-15, 2013 I-93 SB Sensors q18-q25 Speed Profile
DECEMBER 22-23, 2013 – SNOW/RAIN/SLEET (0.5-1.0 INCHES)

Figure 25  December 22-23, 2013 I-93 NB Sensors q02-q07 Speed Profile

Figure 26  December 22-23, 2013 I-93 NB Sensors q08-q13 Speed Profile
Figure 27  December 22-23, 2013 I-93 SB Sensors q14-q17 Speed Profile

Figure 28  December 22-23, 2013 I-93 SB Sensors q18-q25 Speed Profile
DECEMBER 29-30, 2013 – SNOW/RAIN (4.0-8.0 INCHES)

Figure 29  December 29-30, 2013 I-93 NB Sensors q02-q07 Speed Profile

Figure 30  December 29-30, 2013 I-93 NB Sensors q08-q13 Speed Profile
Figure 31  December 29-30, 2013 I-93 SB Sensors q14-q17 Speed Profile

Figure 32  December 29-30, 2013 I-93 SB Sensors q18-q25 Speed Profile
JANUARY 1-2, 2014 – SNOW/RAIN (9.0-14.0 INCHES)

Figure 33  January 1-2, 2014 I-93 NB Sensors q02-q07 Speed Profile

Figure 34  January 1-2, 2014 I-93 NB Sensors q08-q13 Speed Profile
Figure 35  January 1-2, 2014 I-93 SB Sensors q14-q17 Speed Profile

Figure 36  January 1-2, 2014 I-93 SB Sensors q18-q25 Speed Profile
January 18-19, 2014 – Snow/Rain (2.0-5.0 Inches)

Figure 37  January 18-19, 2014 I-93 NB Sensors q02-q07 Speed Profile

Figure 38  January 18-19, 2014 I-93 NB Sensors q08-q13 Speed Profile
Figure 39  January 18-19, 2014 I-93 SB Sensors q14-q17 Speed Profile

Figure 40  January 18-19, 2014 I-93 SB Sensors q18-q25 Speed Profile
JANUARY 21-22, 2014 – SNOW (1.0-4.0 INCHES)

Figure 41  January 21-22, 2014 I-93 NB Sensors q02-q07 Speed Profile

Figure 42  January 21-22, 2014 I-93 NB Sensors q08-q13 Speed Profile
Figure 43  January 21-22, 2014 I-93 SB Sensors q14-q17 Speed Profile

Figure 44  January 21-22, 2014 I-93 SB Sensors q18-q25 Speed Profile
Figure 45  January 25-26, 2014 I-93 NB Sensors q02-q07 Speed Profile

Figure 46  January 25-26, 2014 I-93 NB Sensors q08-q13 Speed Profile
Figure 47  January 25-26, 2014 I-93 SB Sensors q14-q17 Speed Profile

Figure 48  January 25-26, 2014 I-93 SB Sensors q18-q25 Speed Profile
February 5-6, 2014 – Snow (9.0-15.0 inches)

**Figure 49**  February 5-6, 2014 I-93 NB Sensors q02-q07 Speed Profile

**Figure 50**  February 5-6, 2014 I-93 NB Sensors q08-q13 Speed Profile
**Figure 51**  February 5-6, 2014 I-93 SB Sensors q14-q17 Speed Profile

**Figure 52**  February 5-6, 2014 I-93 SB Sensors q18-q25 Speed Profile
FEBRUARY 9-10, 2014 – SNOW (1.0-2.5 INCHES)

**Figure 53**  February 9-10, 2014 I-93 NB Sensors q02-q07 Speed Profile

**Figure 54**  February 9-10, 2014 I-93 NB Sensors q08-q13 Speed Profile
**Figure 55**  
February 9-10, 2014 I-93 SB Sensors q14-q17 Speed Profile

**Figure 56**  
February 9-10, 2014 I-93 SB Sensors q18-q25 Speed Profile
Figure 57  February 13-15, 2014 I-93 NB Sensors q02-q07 Speed Profile

Figure 58  February 13-15, 2014 I-93 NB Sensors q08-q13 Speed Profile
Figure 59  February 13-15, 2014 I-93 SB Sensors q14-q17 Speed Profile

Figure 60  February 13-15, 2014 I-93 SB Sensors q18-q25 Speed Profile
February 18-19, 2014 – Snow (4.0-12.0 inches)

Figure 61  February 18-19, 2014 I-93 NB Sensors q02-q07 Speed Profile

Figure 62  February 18-19, 2014 I-93 NB Sensors q08-q13 Speed Profile
Figure 63  February 18-19, 2014 I-93 SB Sensors q14-q17 Speed Profile

Figure 64  February 18-19, 2014 I-93 SB Sensors q18-q25 Speed Profile
MARCH 12-13, 2014 – SNOW/RAIN (5.0 INCHES)

Figure 65  March 12-13, 2014 I-93 NB Sensors q02-q07 Speed Profile

Figure 66  March 12-13, 2014 I-93 NB Sensors q08-q13 Speed Profile
Figure 67  March 12-13, 2014 I-93 SB Sensors q14-q17 Speed Profile

Figure 68  March 12-13, 2014 I-93 SB Sensors q18-q25 Speed Profile
APPENDIX B: LINEAR REGRESSION
FIGURES
Figure 69  Roadway Grip vs. Average Speed–All Storm Conditions

\[ y = 39.898x + 34.97 \]

\[ R^2 = 0.86092 \]
Figure 70  Roadway Grip vs. Average Speed–Baseline Conditions Overall

\[ y = 90.776x - 6.7197 \]

\[ R^2 = 0.45869 \]
Figure 71  Roadway Grip vs. Average Speed–Baseline: Storm, No Message Posted

\[ y = 69.474x + 9.4022 \]

\[ R^2 = 0.35175 \]
Figure 72  Roadway Grip vs. Average Speed–Descriptive Message Posted

\[ y = 15.844x + 51.249 \]

\[ R^2 = 0.25782 \]
Figure 73  Roadway Grip vs. Average Speed—Prescriptive Message Posted

$y = 3.798x + 50.716$

$R^2 = 0.01571$