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EFFECTIVENESS OF ITS ON UTAH ROADWAYS

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This report presents the findings of a comprehensive research study conducted for the Utah Department of Transportation (UDOT) to evaluate the effectiveness of commonly deployed Intelligent Transportation System (ITS) treatments in Utah, with a focus on Variable Message Signs (VMS), traffic cameras, and Road Weather Information System(s) (RWIS) sites. The study aimed to determine the impact of these ITS treatments on mobility and safety for Utah's unique road conditions and configurations. Three primary analyses were performed: a diversion rates analysis to assess the effectiveness of VMS on Utah freeways during incidents; a weather analysis to evaluate the effectiveness of VMS messages on driver speeds in Utah canyons during winter weather; and an ITS attitudes survey to gauge the usage of, attitudes toward, and potential improvements to UDOT's current ITS deployment. The findings of the diversion rates analysis indicate that the activation of VMS messages increases diversion rates by 18 percent and from the weather analysis, a negligible increase of speeds by 0.2 mph was observed. Survey results were largely positive with a high level of ITS usage and benefits reported by UDOT employees. Concerns of general device wear and maintenance were documented. The report provides detailed methodologies, results, conclusions, and recommendations derived from this research, offering valuable insights to guide UDOT's ITS deployment strategies.</td></tr>
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AASHTO	American Association of State Highway and Transportation Officials
AADT	Annual Average Daily Traffic
DOT	Department of Transportation
ETT	Excess Travel Time
IPR	Incident Progress Report
IMT	Incident Management Team
ITS	Intelligent Transportation System
NWS	National Weather Service
PeMS	Performance Measurement System
PHF	Peak Hour Flow
PSA	Public Service Announcement
RWIS	Road Weather Information System
SP	Stated Preference
TAC	Technical Advisory Committee
TOC	Traffic Operations Center
UDOT	Utah Department of Transportation
USDOT	United States Department of Transportation
VMS	Variable Message Sign
VSL	Variable Speed Limit
VTrans	Vermont Department of Transportation

EXECUTIVE SUMMARY

Intelligent Transportation System (ITS) treatments play a critical role in enhancing mobility and safety on roadways, and their effectiveness has been widely acknowledged. However, the applicability of existing research findings to Utah's unique road conditions and driver behaviors remains a challenge. The research team conducted this research for the Utah Department of Transportation (UDOT) to assess the effectiveness of commonly deployed ITS treatments, specifically Variable Message Signs (VMS), traffic cameras, and Road Weather Information System(s) within the state. The study sought to provide best practices for safety and mobility to guide UDOT's future deployment of ITS infrastructure.

Three primary analyses were conducted in this research: a diversion rates analysis, a weather analysis, and an ITS attitudes survey. The diversion rates analysis revealed that VMS messages effectively increased freeway diversion rates by 18 percent during incidents, indicating their potential to guide drivers away from congested areas. In the weather analysis, VMS messages in Utah canyons during winter weather showed a negligible increase in speeds of 0.2 mph, suggesting limited practical significance. The ITS attitudes survey reflected generally favorable sentiments among UDOT employees but highlighted concerns about maintenance and utilization.

Several limitations and challenges were encountered during the research, including the inability to account for various confounding variables in the diversion rates and weather analysis. It is also impossible to know if drivers were aware of VMS messages, even if the message was visible at the time of passing. Finally, the survey's lack of random sampling limits the generalizability of its findings to UDOT overall.

Based on the research results, it is recommended that UDOT share the findings with relevant Traffic Operations Center members to improve the quality and intent of VMS messages and optimize their usage. Additionally, UDOT should ensure that messaging and deployment strategies are consistent with the purpose of VMS to enhance the effectiveness of VMS in Utah. The implementation plan includes reviewing survey results for specific ITS improvements, enhancing data availability, and considering greater public access to ITS data. The research

findings and recommendations can serve as valuable guidance for UDOT's future ITS deployment and operations.

1.0 INTRODUCTION

1.1 Problem Statement

Intelligent Transportation System (ITS) treatments are generally known and accepted as effective strategies to improve mobility and safety; however, specific research to show these benefits is limited. The research that does exist may also not be fully applicable to Utah as road conditions, configurations, as well as driver behaviors and tendencies may not be the same in areas where such research has been performed. Having Utah-based research conducted on this topic is very beneficial to guiding ITS deployment strategies across the state.

The purpose of this research was to evaluate commonly deployed ITS treatments across the state of Utah to determine their effectiveness in terms of mobility and/or safety. The ITS treatments considered in this analysis included Variable Message Signs (VMS), traffic cameras, and Road Weather Information System(s) (RWIS) sites. The results of this research will help guide the Utah Department of Transportation (UDOT) ITS deployment plan by identifying best practices for safety and mobility.

1.2 Objectives

The primary objective of this research was to evaluate the effectiveness of commonly deployed ITS treatments in terms of mobility and/or safety on roadways in Utah. This was done through three analyses. First, the effectiveness of VMS on Utah freeways in diverting drivers off the freeway during incidents was measured. Second, the effectiveness of VMS in Utah canyons in encouraging drivers to reduce their speeds during winter weather was evaluated. Third, a survey was conducted to measure the usage of, attitudes toward, and potential improvements to UDOT's current ITS deployment of VMS, traffic cameras, and RWIS devices.

1.3 Scope

To meet the objectives of this research, a scope of work was developed that included tasks evaluated and approved by the Technical Advisory Committee (TAC). Task 1 involved holding a kick-off meeting with the TAC and solidifying the goals for the research project. Task 2 was to conduct a literature review to review findings and methodologies related to ITS effectiveness. The literature review provided an overview of current research on the effectiveness of ITS devices and previous research methods to evaluate ITS effectiveness. After the literature review was completed, Task 3 commenced to develop a unique road segment classification system that could be used for the research tasks. Task 4 was then conducted to create a current ITS device inventory. Task 5 was to complete the safety and mobility analyses of ITS treatments. The intended evaluation method was to use the road segment classifications from Task 3 to group similar roadway segments from across Utah that could then be used in a before-and-after or with-and-without ITS treatments analysis to determine effectiveness. In the process of attempting to match roadway segments for the analysis, it was determined that it was not feasible to find enough similar segments from across the state for the analysis. As a result, Task 5 was rescoped to include two separate analyses of VMS and a survey that would measure the usage of, attitudes toward, and potential improvements to UDOT's current ITS device deployment. The two analyses of VMS included one on Utah freeways to measure the change in diversion rates during an incident when upstream VMS informed drivers of a crash. The second analysis was on Utah canyons during winter weather conditions to measure if drivers slowed their speeds when a VMS message informed them of dangerous conditions. Finally, a survey was developed to provide insight into the use of VMS, traffic cameras, and RWIS, but specifically the latter two because a data-based analysis was considered to be much more difficult for traffic cameras and RWIS. Task 6 was to develop recommendations, conclusions, and implementation for the TAC based on the research observations and analysis results completed.

1.4 Outline of Report

The report is organized in the following chapters:

1. Introduction
2. Literature Review
3. Methodology
4. Results

5. Conclusions
6. Recommendations and Implementation

Chapter 2 is a literature review that provides an overview of the findings and methodologies related to ITS device effectiveness. Chapter 3 describes the methodology to collect data and prepare analyses for the ITS device inventory, the road segment classification, the diversion rates analysis, and the weather analysis. Chapter 4 presents the results for the analyses performed in Chapter 3. Chapter 5 outlines the conclusions and limitations from the results. Chapter 6 provides recommendations and implementations for the results of the research.

2.0 LITERATURE REVIEW

2.1 Overview

ITS have become a critical component of transportation infrastructure around the globe. The use of ITS is broad and multifaceted but is generally used to reduce crash rates, lower congestion severity, and improve the roadway user experience. This chapter presents a literature review to review findings and methodologies related to ITS effectiveness. First, an overview of ITS devices is provided. Second, the effects of ITS device installation are summarized. Last, previous research methods to evaluate ITS effectiveness are summarized.

2.2 Intelligent Transportation Systems Device Overview

The United States Department of Transportation (USDOT) defines ITS as, "…the union of advanced communication technology, transportation infrastructure, and vehicles to advance safety and mobility" (Pina, 2010). Although many types of ITS devices are available and in use across Utah, this report focuses specifically on the effectiveness of VMS, traffic camera networks, and RWIS devices on the UDOT network.

The following subsections will discuss the various impacts of ITS devices from conducted research studies to illustrate the role that VMS, RWIS, and traffic cameras have on roadway networks.

2.2.1 Variable Message Signs

VMS are a powerful information distribution tool that have changed in design and capabilities throughout the years. The role of this section will be to briefly describe the history of VMS and to discuss the specific impacts of VMS on congestion and weather-related safety.

The first usage of VMS dates to neon signs installed in 1950 on the New Jersey Turnpike, as shown in Figure 2.1. These signs consisted of multiple neon messages that could be turned on or off, depending on hazardous situations. The New Jersey Turnpike signs functioned for 70 years before they were replaced with modern VMS (Transportation Management, 2011).

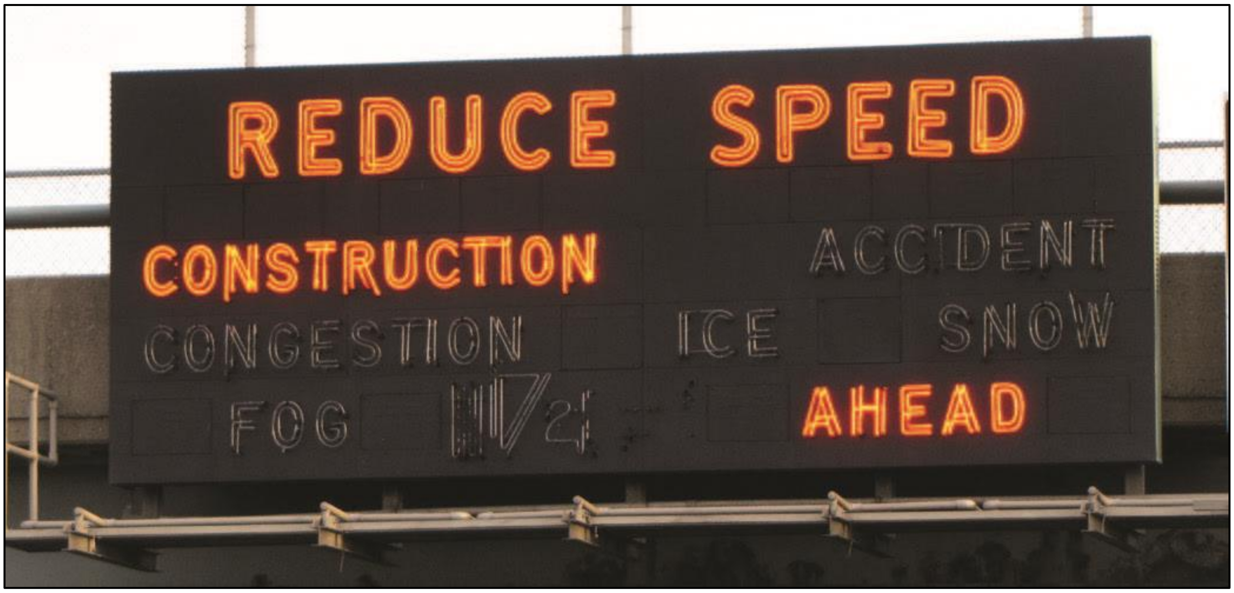


Figure 2.1: Early VMS Sign in New Jersey (Lyles School of Civil Engineering, 2015).

VMS are used to inform the traveling public of information that is not readily apparent. These messages generally include warnings about dangerous weather conditions, snowfall or rockfall on the roadway ahead, work sites, and/or crash-related congestion. VMS are a unique type of device in that they actively interact with the public (Haghani et al., 2013). RWIS and traffic camera data can be accessed through public domains, but doing so often requires specific knowledge of where the data are contained and how they are accessed.

VMS messages provide critical information in the hopes of informing route choices for drivers. A public perception survey was used to gather public responses to VMS in New York City, NY. Through the survey, Perez et al. (1993) found that 45 percent of drivers reported that they would change routes in response to the messages, and it was estimated that VMS messages save drivers about 300,000 vehicle hours of delay annually. However, drivers needed to receive accurate information that they could verify with their observations, otherwise, future interactions with VMS were less likely to be fruitful (Perez et al., 1993).

While VMS provide important information to drivers, the language that is used to convey the message can affect if and how drivers respond. Using a stated preference survey, Tay and de Barros (2006) found that many drivers do read VMS messaging and consider how useful the information may be. However, message efficacy was dependent on the emotion and directness of the message. For example, warnings such as “Two People Died Without Seatbelts Today,” which inform drivers about the direct consequences of speeding, have much stronger impacts than more vague messaging such as “Drive Safely.” Additionally, it was found that drivers preferred that agencies post messages 24/7. It was considered that a blank sign could mean that the sign was broken, or that the agency was misusing taxpayer dollars by failing to consistently utilize an expensive piece of equipment (Tay and De Barros, 2006).

Analyzing traffic conditions as a direct effect of the VMS is challenging due to consequences relating to freeway geometry. To achieve high flow rates and safe-but-steady speeds, freeway designers work to optimize freeways to maximize vehicle sight distance. In situations comparable to recognizing congestion, the American Association of State Highway and Transportation Officials (AASHTO) *A Policy on Geometric Design of Highways and Streets* recommends that drivers should have a line of sight anywhere between 765 ft. and 1,260 ft. (AASHTO, 2011, Table 3-3, pp. 3-7, and Table 9-6, pp. 9-38). However, VMS may not be legible in optimal conditions until about 630 ft. away (Upchurch et al., 1992) or 900 feet away (Norouzi, 2012). It should be recognized that these distances are only for optimal weather conditions and level road grades. Every roadway will have different sight distances depending on geometric characteristics and weather conditions. These distances are relevant because visible congestion has been shown to motivate drivers to find alternate routes and there is a possibility that diversions during incidents from the roadway may not be attributed to VMS (Xuan and Kanafani, 2014).

VMS messages are also used to warn drivers of unseen weather-related conditions. In the Netherlands, Hogema and Horst (1997) studied the installation of a series of VMS and flashing indicator signs to advise drivers of the recommended speed to drive in fog, as shown in Figure 2.2. Before the installation of these signs, a serious crash occurred with eight fatalities because drivers failed to adjust their speeds to account for reduced visibility. Visibility sensors were installed in coordination with these signs, and depending on the visibility levels, specific speeds were automatically recommended to the drivers. Similar technology is found with some Variable Speed Limit (VSL) signs.

Figure 2.2: Fog Indicators in the Netherlands (Hogema and Horst, 1997).

Using loop detectors to determine the speeds of vehicles before and after the sign, Hogema and Horst (1997) determined that as a direct result of the messaging, a speed of 8.0 to 10.0 kph (5.0 to 6.2 mph) slower than the speed limit was achieved. The standard deviation of the speeds also decreased, resulting in more uniform speeds. By reducing the average speed on the roadway, the system improved the safety of the roadway by reducing both the likelihood of a crash and the potential damage of the crash. More specifically, by using a mathematical and theoretical correlation from a previous study, it was estimated that crash rates would decrease by 15 percent.

Overall, VMS are a powerful method to convey information to the traveling public and in optimal conditions, their interactions are simple to recognize. However, in conditions that are less than optimal due to factors such as inclement weather or increased traffic, benefits to VMS can be hidden behind these factors.

2.2.2 Road Weather Information Systems

RWIS are a valuable tool in giving a Department of Transportation (DOT) the information and data they need to correctly inform the public and concerned parties of weather developments. By placing sensor stations near roadways of interest, DOTs are enabled to understand unique roadway conditions and tailor responses to the conditions. This also allows for greater prediction of weather events, accurate warnings for road users, and less expensive weather condition verification. This section will explore the abilities and limitations of these devices, and the interactions of these devices with VMS devices.

A crucial component of an RWIS network are the stations and the data they collect. Although there are a wide variety of sensors that could be installed at each station, most stations are enabled to detect air temperature, road temperature, solar radiation, humidity, and salinity on roadways (Utah Department of Transportation, 2011). This wide range of data enables the collection agency to provide appropriate responses to roadway conditions.

RWIS stations gather precise information, some of which may only be relevant to the immediate area. For ideal conditions, with flat ground and little variation and weather, RWIS stations can predict weather within 25 miles of the station. However, depending on geography, the effective radius should be reduced to better model weather conditions (Ewan and Al-Kaisy, 2017). Accordingly, many DOTs attempt to densify their network of stations on or near critical and high-importance roadways.

Specific weather-related information can be provided to the DOT through the RWIS network to assist in weather prediction and storm management. A survey was conducted in 2007 on the effectiveness of UDOT RWIS. Through interviewing UDOT winter maintenance personnel, the researchers found that UDOT's forecasts via RWIS were considered more reliable and more usable than other available weather information services. The implementation of the RWIS network weather forecasts in anti-icing strategies was estimated to have saved UDOT between $5.9 and $13.3 million a year (Shi et al., 2007).

RWIS proves especially significant when dealing with weather situations in rural areas. In a survey of multiple DOTs, it was found that most departments favored more stations with fewer sensors as compared to fewer stations with more sensors. Having more stations installed enables the department to have a comprehensive view of weather conditions across a region; however, adding more stations means higher upfront and maintenance costs for the department. Overall, it was found that the benefit-cost ratio for RWIS stations can be upwards of 40:1 (Ewan and Al-Kaisy, 2017).

A common unseen hazard on roadways is icy roads. When the air temperature drops below 37°F, and roadway surface temperatures drop below 32°F, moisture can adhere to the roadway surface, greatly reducing the coefficient of friction between tires and the surface of the road (Mass and Steed, 2022). Unfortunately, many drivers cannot recognize this danger for themselves and drive in an inappropriate manner relative to the danger, posing a serious threat to themselves and others (Rama, 2000).

A Vermont Department of Transportation (VTrans) report was conducted on a system that automatically connected RWIS stations to nearby VMS devices. When adverse weather conditions were detected, the RWIS was given message preemption to display a related safety message on nearby VMS to warn drivers of icy roadway conditions. By automating the connection between RWIS and VMS, a before-and-after installation study found that crashes were reduced, and the burden on VTrans staff and budget was reduced. Additionally, White (2011) mentions that warning drivers of adverse weather makes it so that drivers cannot make excuses for failing to recognize poor road conditions, increasing the severity of tickets for motorists involved in crashes.

In Finland, research was conducted on segments of freeways where drivers were warned of icy roads by VMS based on information from RWIS stations. The RWIS data were used to determine icy road conditions which the DOT then communicated through the VMS with a warning message. Because of this warning, the mean speed on the road decreased by 3.4 kph (2.1 mph) from previously recorded speeds in similar situations. The standard deviation in speeds was not substantially affected by the posted messages (Rama, 2000). This study illustrates that when dangerous situations are being communicated through VMS, drivers respond to the warning, even if only slightly.

Overall, for RWIS to be effective, the driver must choose to believe the given warning and act accordingly. However, it is difficult to prove any level of statistical significance of VMS messaging or RWIS data in assisting the driver, as variability arises from visible weather conditions, time of day, visible traffic conditions, and roadway geometry.

2.2.3 Traffic Cameras

One of the simplest yet most versatile ITS devices are traffic cameras due to their generally low maintenance cost, high functionality, and useful data stream. Traffic cameras are utilized by transportation managers and DOT staff in a variety of fashions. Although the public can have limited access to the traffic camera feed, such research illustrating related effects was limited and will not be addressed here. This section will explore DOT uses of traffic cameras for congestion, incident, and winter weather recognition and response.

When working properly, cameras are an asset for real-time road condition analysis. These cameras are often used by a DOT to determine plow conditions or incident management progression. As reinforced by a USDOT 2009 report, traffic cameras provide much-needed information to DOTs when monitoring crash progression, and real-time traffic (Center for Transportation Analysis, 2009). Sui and Young (2014) also added that the Wyoming DOT uses traffic cameras to inform traffic operations personnel when weather events occur so relevant messages can be posted on VMS.

In addition to DOT personnel utilizing raw camera feeds for information, traffic cameras can be paired with machine learning technology to increase their effectiveness for automated congestion and incident response. One such example uses incident detection software integrated with camera feeds to detect crashes and congestion. In a study where this method was applied, it was found that the cameras could reliably recognize congestion, and then by indicating these crashes to DOT staff, prompt actions could be taken where secondary crashes at the end of a queue were reduced by up to 40 percent by posting appropriate messages on VMS (Versavel, 1999).

In recent years, traffic camera data streams have been integrated with various machine learning technologies to automate data collection and enforcement. Machine learning can be used to identify risky driving behaviors (wrong-way drivers, disabled vehicles, dropped cargo), or measure traffic speeds to determine when conditions change. Cameras have also been used to automate the recognition of roadway conditions where it may become necessary to open a temporary hard shoulder, or to identify when parking spaces are occupied (Bommes et al., 2016).

Fries et al. (2007) used traffic simulation models to compare the benefits of using traffic cameras to identify crashes. On average they found that the use of traffic cameras reduces the time to recognize and verify an incident from 14 to 25 minutes to 2.5 to 5.5 minutes, and in turn, led to a benefit-cost ratio of 12:1 for the traffic cameras (Fries et al., 2007). Using traffic cameras to detect crashes and congestion, crash rates and travel time delays can be reduced.

Traffic cameras also play a vital role in winter weather recognition and driver awareness efforts. A study was conducted by Saito and Yamagata (2014) on the use of traffic cameras during winter weather road maintenance within UDOT. As part of the study, several UDOT Maintenance Station supervisors were interviewed about how they used traffic cameras during the winter months. Due to technical problems and limitations, the supervisors pointed out that at times it was difficult to see current weather conditions because the traffic camera lens was covered, or the system became unreliable. It was determined that a statistically significant effect on snow removal-related costs was not found. However, significant benefits were present to the station personnel by reducing expedition trips that cost time and money and have the potential to be dangerous.

Often, the locations of RWIS and traffic camera networks are highly correlated because most RWIS stations have an attached camera. Through a multi-departmental survey, it was found that cameras are favored compared to RWIS stations for quick assessments of roadway conditions during winter months. Additionally, it was reported that the majority of DOTs also desire to install more cameras in their roadway networks and that the RWIS sensors are less urgently needed (Ewan and Al-Kaisy, 2017).

Overall, traffic cameras are a powerful tool for assessing current roadway conditions. When traffic cameras are used in coordination with VMS and RWIS, benefits to the DOT significantly increase.

2.3 Effects of ITS Devices

ITS devices have a wide range of impacts. However, determining the impacts of one device as a single entity is challenging due to the interactions that ITS devices have with each other. But by making conclusions on the impacts of a few devices, generalizations can be made about the system.

It is difficult to evaluate the public impact of RWIS, traffic cameras, and other ITS devices that the public does not interface directly with. These devices are mainly used by DOT officials and while having many potential benefits, the usage by the public is often hard to quantify. Within Utah, UDOT-provided still images from traffic cameras are widely accessed by the public, but other technologies, such as RWIS, are often less visible to the public eye. As such, many of the following studies analyze the role of VMS, a more visible type of ITS device, in affecting driver behavior. However, many of the results in this chapter can be connected to RWIS and traffic cameras. The following sections will review the safety, diversion, and DOT-related benefits of ITS.

2.3.1 Safety

Safety on the roadway is a large consideration when it comes to roadway design and management. ITS devices generally assist in decreasing crash rates, but in rare instances, the data indicate that their use may have slightly increased crash rates. This section will focus on how ITS devices have been found to improve safe driving behaviors during incidents. This section will also address how VMS can distract drivers, potentially leading to slower reaction times and increased crash rates.

In general, ITS devices can increase safety on roadways by providing information to assist drivers in making good decisions. These impacts can be measured by looking at changes in speed, headways, and travel times as these changes directly impact safety factors (Khorasani et al., 2013).

Rama (2000) used vehicle speeds and headways to determine how effectively VMS messaging can reduce crashes related to icy roadways when posting weather-related messages informed by RWIS and traffic cameras. It was hypothesized that with the utilization of this system, drivers would be more aware of icy roads, and in turn, slow down and give more space to other vehicles. It was also cautioned that by using these systems, if messages are not shown during critical periods, drivers can become less attentive to roadway conditions, leading to less safe behaviors. By comparing speeds before and after the VMS, it was found that on average, drivers slowed up to 2.0 kph (1.2 mph), which was statistically significant. The percentage of headways less than 1.5 seconds, or what was considered "short" or unsafe headways, between vehicles decreased significantly from a range of 16 to 28 percent to a constant 13 percent during slippery conditions.

Sui and Young (2014) also used speed data to determine the effect of VMS during weather events when informed by RWIS. Vehicle speeds were recorded and connected to various weather attributes and proximity to VMS. By creating a linear regression model and removing insignificant variables, it was concluded that although weather conditions were attributed to significant speed changes, VMS messaging also had significant impacts. When high-severity messaging was posted (e.g., Road Closed, No Unnecessary Travel), it was estimated that speeds decreased by 32.0 kph (20.0 mph) (Sui and Young 2014). For more moderate-severity messaging (e.g., Slow Down/Reduce Speeds), it was estimated that speeds decreased by 11.2 kph (7.0 mph).

It should be noted that many messages related to safety come in the form of public service announcements (PSA) or creative safety messages. These messages are popular among DOTs in the United States (CTC & Associates LLC, 2019). The effects of these messages are primarily determined by conducting public surveys to gauge response. Tay and De Barros (2010) conducted a two-part study, using a public survey to evaluate the potential benefits of safety messaging. The survey was followed up with an analysis of roadway data to understand actual impacts.

The survey showed that messages that warn of bodily harm tend to be effective in influencing driver behavior, but that overall driver reactions were neutral. Vehicle speeds were not expected to be largely affected, but when roadway data were analyzed, it was determined that higher percentile speeds and standard deviation of speeds were decreased. However, mean speeds tended to increase slightly and the 85^{th} percentile speed was unchanged (Tay and De Barros, 2010). In an earlier study by the same authors, it was indicated that although speed-related messages may not be impactful, messages about driver mentality and courteousness are generally better received (Tay and De Barros, 2006).

On occasion, VMS messages can be complex enough to lead to driver inattention to roadway conditions that may be hazardous. Research in Oslo, Norway recognized that although 20 percent of drivers diverted to a different route in response to VMS messaging, there was also an increase in sudden braking in response to VMS messaging. By watching video from traffic cameras, this trend in sudden braking was confirmed as the result of drivers being distracted from the roadway by the VMS. It was found that 7 to 23 percent of vehicles braked suddenly in response to the VMS messaging (Erke et al., 2007). If messages are not designed appropriately, VMS messaging has the potential to influence drivers to engage in more risky driving behaviors, distracting drivers from the roadway, and possibly increasing crash rates.

Research in British Columbia, Canada looked at the impacts of the interaction of RWIS and VMS in warning drivers about the advent of adverse weather events. By using an empirical Bayes methodology using average daily traffic volumes and collision data, the researchers concluded that the combination of using RWIS and VMS to warn drivers of serious weather led to significant (p-value = 0.005) reductions in serious crashes during winter weather conditions. A benefit-cost ratio of 4.8 was derived, but it was recognized that a divided highway and a speed limit increase in two of the site locations led to some inaccuracy in the results. It is unclear what effect these changes to the roadway would have had if they were not present, but it is suggested that at worst, the divided highway and speed limit change would have led to an underestimation of results (El Esawey et al., 2019).

In compiling this literature review, only one study was found that attempted to correlate VMS messaging to crash rates. In a thesis by Norouzi (2012), crash data were collected and compared between various freeway segments. When segments with and without VMS messaging during the same period were compared, it was found that impacts to crash rates by VMS messaging were not significantly correlated (p-value = 0.525) However, when a specific roadway segment with a VMS was identified and situations with and without a message displayed were analyzed, a significant impact on crash rate reductions was concluded with a p-value of 0.0005. It was concluded that in general, active VMS messaging encourages safer driver behavior, while the signs in general have a neutral effect on road safety. There were no data to suggest that VMS messaging increased crash rates.

VMS and ITS improve safety primarily by warning drivers of adverse road conditions during weather events. VMS can also affect driver mentality by displaying creative safety messages, although the direct effect of those messages can be difficult to quantify. It has also been noted that the use of these messages may increase crash rates, but there has not been any consensus in the research community to conclude one way or the other.

2.3.2 Diversions

A commonly addressed outcome of VMS messaging is the impact on traffic flow, primarily by route diversion. This section will explore how VMS devices have an impact on diversion and driver behavior through the posting of crash and congestion warning messages.

When the diversion-related impacts of VMS are examined longitudinally, systematic influences can be determined. In Beijing, hourly traffic flow rates were used to determine the overall ability of a VMS to reduce the impact of recurrent congestion. It was determined that the traffic flow rate generally increased, while the frequency and duration of recurrent congestion decreased within a year after the VMS was installed. Through a two-sample t-test, the role of the VMS was deemed significant in reducing recurrent congestion (Chen et al., 2010).

By using a stated preference survey, researchers attempt to determine how VMS affects drivers, though these results usually overrepresent driver willingness to divert. A stated preference survey distributed in eight different cities found that between 33 and 89 percent of all drivers in a particular city recognized VMS messages. Of those that noticed the VMS information, 32 percent said it was useful and 45 percent said it was useful but of limited value. By using a secondary questionnaire and road-based studies in these cities, it was found that between 0 and 31 percent of the drivers who noticed the VMS information utilized a diversion route. A follow-up traffic model determined that there was a much higher probability of diversion based on actual traffic data. Although the actual impacts on traffic patterns were generally minimal, the surveys showed that user perception of the benefits related to VMS messages are not insignificant (Chatterjee and Mcdonald, 2007).

In a study conducted in Little Canada, MN, a selected study site had a variety of diversion routes available to drivers with minimal impact to travel times. The authors collected loop detector data to compare flows and travel times of vehicles during incident conditions with and without VMS messaging. It was found that although travel times on the roadway were not significantly affected, there was a significant difference in the total delay. This finding showed that fewer drivers were stuck in traffic and that a greater number of drivers took alternate routes because of the information presented on the VMS (Levinson and Huo, 2006).

One methodology to determine diversion rates is to use Bluetooth gate sensors. As a vehicle passes one detector, it is given a unique identifying code that is correlated with other Bluetooth sensors to determine the route of that vehicle. Haghani et al. (2013) used this technique to determine that when VMS displayed diversion messages, there was a 5 to 20 percent increase in traffic diversion rates. Basso et al. (2021) tracked license plates instead of Bluetooth identifiers to compare the effect of lane change messages on driver behavior, namely vehicle speeds and lane changes. The authors found that VMS messaging did not encourage drivers to make suggested modifications, with motorcycle users being the relatively least compliant, and heavy vehicle users being the relatively most compliant. These two studies (Haghani et al. (2013) and Basso et al. (2021)) were in areas with available detour routes where using them added a significant amount of travel time.

As mentioned previously in section 2.2.1, visible congestion plays a critical role in driver diversion. In a study conducted by Xuan and Kanafani (2014), flows on freeway mainline and offramps were compared during incidents. By analyzing when offramp flows increased in comparison to the placement of VMS and the location of the crash, it was determined that VMS messaging did not have a critical role in driver diversion (p-value = 0.27). However, it was found that visible congestion played a highly significant role in driver diversion (p-value = 0.00014).

VMS messaging can influence route modification. These results can be connected to the presence of available routes and visible congestion. Therefore, it can be difficult to determine the role that VMS and other ITS technologies can play in vehicle diversion.

2.3.3 Benefits to Departments of Transportation

In general, ITS networks can be used to lower safety and diversion-related concerns among roadway users. There are also benefits directly related to the primary users of these devices, mainly the DOT employees in the Traffic Operations Center (TOC), Road Management Sheds, and Response Management Teams. This section will discuss how DOTs reduce unnecessary road maintenance and operation-related costs and increase the productivity of employees by utilizing ITS networks.

In a study for the Minnesota Department of Transportation, 22 state DOTs were surveyed about their VMS usage, covering both weather-related messaging and creative safety messages. Among the 22 DOTs surveyed, 21 indicated that they use VMS regularly to warn drivers of dangerous weather conditions. Of these, most were developing an automated system between the VMS and weather information so that VMS automatically informed drivers of hazardous conditions (CTC & Associates LLC, 2019).

VTrans uses RWIS to control and display messages on VMS. By automatically displaying these messages, VTrans personnel can be more efficient in their road treatment. This also reduces the load on the staff monitoring weather on roadways. Since a substantial portion of the weather response is managed automatically, the 24/7 crews can spend more time on other tasks, when they would have been watching the camera feeds. Additionally, the use of this automated system enables a faster response to crashes and dangerous roadways (White, 2011).

In 2010, transportation agencies spent $2 billion on the removal of ice and snow from roadways (Ewan and Al-Kaisy, 2017). By utilizing ITS networks, DOTs can reduce unnecessary travel expenditures, and target areas of concern. Ewan and Al-Kaisy (2017) evaluated the benefit-cost ratio for the use of these devices for the Montana Department of Transportation. By analyzing different ITS deployment scenarios, it was found that the benefit-cost ratio can be as high as 17.9 to the DOT, and upwards of 33.3 to the state.

Specifically, cameras are a major benefit to DOTs, as explained briefly in section 2.2.3 in reference to the study by Saito and Yamagata (2014). The authors primarily discussed the role that RWIS and camera stations have for winter weather responses, but the general results from the survey are informative of the general impacts that an extensive camera network can have on DOTs. In some of the results from the survey, participants noted that the camera network saves time and is extremely efficient in providing real-time information. It was also noted that it is helpful to let the public have some, even if limited, access to roadway cameras. This is primarily because limited camera access to the public can provide answers to questions that they may ask the DOT, such as information on roadway conditions, which then reduces the draw on DOT time and resources.

Creative safety messages on VMS can also have a positive effect on the DOT. Generally, these messages are posted on a daily to weekly schedule and the messages can vary. Some examples of these messages are general advice, reminders of the number of fatalities within the state, or messages using wordplay to convey a message. It was found through a stated preference survey that the public generally responds positively to these messages, with 59 percent of respondents saying that these messages changed their driving behavior. In the comments for the survey, it was indicated the public appreciated the DOT directly communicating with them, although some participants were worried that the messages were distracting to roadway users (Ewan and Al-Kaisy, 2017).

ITS devices help improve the capabilities of DOTs by reducing extra costs and helping DOT employees use their time more effectively. By making it easier for DOT employees to accomplish their tasks, the roadway system improves and becomes safer for roadway users.

2.4 Previous Research Methods

The purpose of this section is to review previously utilized methodologies that have been used to understand the impacts of ITS, and where previous research succeeded and/or struggled. Specifically, this section will review studies conducted through surveys and road data evaluations.

2.4.1 Surveys

For many types of research studies, conducting a survey is a simple and popular method to evaluate the general impacts of a treatment. Additionally, large percentages of the collected literature regarding ITS have been conducted through surveys. Although surveys typically collect and present generalized findings and opinions, they play a vital role in modern research. Table 2.1 summarizes the location, method, and findings of eight survey-based studies that evaluated VMS messaging. The following section will summarize general results, and specific studies will be discussed to explore the role of surveys in evaluating VMS messaging.

Table 2.1: Survey Evaluation-Based Studies

Author(s)	*Site Location*	*Type of Study*	*Abbreviated Outcome*
Wardman et al. (1997)	Leeds, England	SP* Survey	VMS compliance is significantly correlated with driver demographics and driver diversion; however, visible congestion also has a significant effect on driver diversion
Chatterjee et al. (2002)	London, England	SP Survey w/ model and road data	VMS is slightly effective in diverting drivers, with 1.09 percent of drivers diverting due to messaging in a survey, but with only 0.33 percent actually diverting in the road data
Chatterjee and Mcdonald (2007)	Europe	SP Survey w/ road data	VMS is generally perceived to have a stronger impact (47 percent believed VMS diverts drivers) than is shown with road data (only 1 percent divert)
Kusakabe et al. (2012)	Osaka, Japan	Long-term repeated SP Survey	VMS travel time messages are shown to be effective when drivers can accurately confirm traffic speeds, and consequently, travel times with those messages
Zhong et al. (2012)	Beijing, China	SP Survey w/ model	VMS compliance is significantly correlated with driver demographics, however, most of the study was concerning the effectiveness of various modeling methods
Kim et al. (2013)	South Korea	SP Survey w/ model	VMS are effective when drivers are aware of travel time delay, but driver diversion is also largely dependent on the placement of the VMS relative to the opportunity for an alternate route
Shen and Wang (2018)	Yangzhou, China	SP Survey w/ model	VMS is effective in reducing driver speeds within a short radius of the VMS, but drivers return to previous speeds quickly after passing the VMS
Ma et al. (2020)	Xi’an, China	SP Survey	VMS compliance is significantly correlated with driver demographics, and generally, the more frequently a driver uses the roadway, the more likely they are to follow VMS messaging

**SP = Stated Preference*

Most stated preference surveys consist of short one-time questionnaires (Zhao et al., 2020), but Kusakabe et al. (2012) utilized a long-term survey to provide more personalized questions to respondents. The researchers asked the respondents to fill out a web diary for several weeks to capture their daily routes and trips. Based on the results of the web diary, situations with VMS messages were presented to each respondent in freeway segments that they frequently traveled on to present more life-like situations for the respondents. The researchers concluded that drivers can accurately assume the travel time of alternate routes based on the congestion level or crash travel time information provided by VMS signs.

It is interesting to note that some surveys are followed up by simulated models to verify results (Zhong et al., 2012). Research conducted in South Korea used an initial set of surveys to understand the relationship between demographics and VMS-influenced detours. A binary logit model was then created, which was thereafter verified by another revealed preference survey. It was concluded that more than 70 percent of drivers recognize nearby national roads as detours and that estimated travel time delay is the most influential factor in whether or not a driver makes a detour (Kim et al., 2013).

In England, a stated-preference survey concluded that visible queues had a stronger effect than VMS in affecting driver diversion (Wardman et al., 1997). However, this study is isolated as few consider the role of visible congestion. In a stated preference survey not included in Table 2.1, it was found that although many other factors cloud the effectiveness of VMS messaging, VMS information in general can be found to play a critical role in impacting route change-categorized delays as caused by normal congestion or by crashes (Gan et al., 2012). It was also found that crashes rerouted drivers onto local streets more than normal congestion. In some locations, drivers may be less sensitive to congestion and react more strongly when a crash or something unexpected happens. The same study also found that various demographics have significant effects on VMS obedience and that a high number of traffic lights disincentivize drivers from taking local roadways. Similar results were found by Ma et al. (2020).

In conclusion, it is important to note that surveys can be a powerful tool to analyze the general impacts of ITS devices. However, results can be difficult to validate, due to the potential for human error in the responses.

2.4.2 Road Data Evaluations

One vital study method used in measuring effectiveness is road data evaluations where collected road data is used to conduct analyses based on specific criteria such as safety, traffic flow, and driver awareness. Table 2.2 summarizes the characteristics and findings of six road data-based evaluation studies, which are described in more detail in this section. While surveys are beneficial in gathering data from individuals on how they may act in prescribed situations, they are often very expensive to conduct and measure human opinion rather than actual driver behavior. Road data evaluations provide the opportunity to study historical behavior, and, in many cases, these studies end up being cheaper due to readily available types of data. This section will explore how empirical-based studies have been conducted in the past and the various results that have been concluded.

Table 2.2: Road Data Evaluation Studies

Author(s)	*Site Location*	*Type of Study*	*Abbreviated Outcome*
Lam and Chan (2001)	Hong Kong	With-and-Without	Reduced travel time delay during crash or work zone congestion
Levinson and Huo (2006)	MN, USA	With-and-Without	No clear reduction in travel times, but significant increases in diversion rates were observed
Erke et al. (2007)	Oslo, Norway	With-and-Without	Increased diversions by 20 percent
Xuan and Kanafani (2014)	CA, USA	Before-and-After	No significant effect on diversions
Ghosh et al. (2018)	Singapore	Before-and-After	Increased diversions by 14 percent
Basso et al. (2021)	Chile	Before-and-After	No influence on driver behavior (speed, lane change, traffic volume)

Empirically based road data studies gather and analyze information on how drivers reacted or behaved historically on roadways, providing insight into the true behavior of drivers instead of individual statements of behavior. Most of the literature on the effectiveness of VMS has been conducted using driving simulators and surveys, so there is a limited number of empirically based studies, but they provide valuable insight into varying methodological approaches and findings on the effectiveness of VMS.

Like additional analysis that often accompanies surveys, some researchers have developed statistical models to measure the effectiveness of VMS. Lam and Chan (2001) utilized a time-dependent traffic assignment model to evaluate the effect of providing travel times by VMS. The researchers defined a ratio between the total network time with and without VMS at different locations in the roadway network to determine that VMS had more of an effect in reducing travel time during non-recurrent congestion but used statistical distributions for their input data rather than actual road data conditions. While Lam and Chan (2001) had a strong statistical model, there is a risk of not representing real-world conditions and outcomes by not using empirical data as the basis for a model. On the contrary, Levinson and Huo (2006) used flow rate data collected from loop detectors in Little Canada, MN to base their discrete diversion choice model. In addition, a t-test was performed using this same data and the researchers found that VMS can significantly influence driver diversion rates within 10 minutes of activation. Statistical models are useful tools for simulating real-world outcomes and can yield very accurate results, especially when utilizing empirical road data.

Other researchers have directly analyzed empirical road data without using models. Erke et al. (2007) measured the proportion of vehicles that diverted onto a specific route recommended by a designated VMS sign. While 20 percent of vehicles did divert according to the recommended route, the study period was from 10:30 p.m. to midnight over two nights, for a total of three hours of observation, which is a noticeably short study period. However, Levinson and Huo (2006) did find that diversion rates are significantly affected by the presence of a VMS message within 10 minutes of activation, meaning that the Erke et al. (2007) findings may not be as limited as they seem.

Ghosh et al. (2018) used flow rate data from loop detectors to calculate a flow change rate, which is a moving percent difference from the median value. Data were used from days without crashes to determine the median flow rate value and data from days with crashes were used to determine how the flow rate change was affected once a VMS message was activated due to the crash. While the researchers found that VMS messages have a significant effect on the outgoing flow rate of an off-ramp, they also acknowledged that crash information can be obtained through many channels (e.g., television, radio, internet) and that it is difficult to fully determine the individual effect of VMS on diversions (Ghosh et al., 2018).

Basso et al. (2021) utilized anonymous vehicle data collected by automatic vehicle identification gates stationed before and after a VMS sign to determine how speed and lane change behavior were affected by a VMS message activation. Six months of data were analyzed, and the researchers found that 88 percent of the time, VMS messages displayed did not reduce driver speeds, and 72 percent of the time, messages failed to initiate driver lane changes. As is seen in the literature, there are many different methodologies for empirically based road data evaluations that have been developed to determine the effects of VMS.

Xuan and Kanafani (2014) developed a two-part methodology involving a with-and-without analysis as well as a before-and-after analysis conducted on the same flow rate dataset from freeway loop detectors in Southern California. Both analyses controlled for visible congestion while also considering the situation where visible congestion was not controlled for. The with-and-without analysis compared data from the same off-ramp location during periods with and without VMS message activation, while the before-and-after analysis compared the period just before and just after a VMS message was activated to measure the difference in diversion rate because of the message activation. The combination of these two analyses as well as the consideration of the effect of visible congestion creates a robust analysis to measure the effect of VMS message activation on diversion rates. However, because of the lack of with-and-without locations, an exact replication of this study by the research team was not feasible, but elements of it were considered in the development of the proposed methodology.

2.5 Conclusion

The literature on ITS devices is as broad and diverse as it is inconclusive on its own. While some methodologies appear to have proven the benefits of ITS, other methodologies argue that there are little to no benefits. Some studies have even shown a negative impact of ITS, which should not be ignored.

This research hopes to develop a general understanding of the critical role ITS plays within UDOT and to develop both general and specific recommendations for further implementations. It has been shown that a survey is efficient in gathering broad data while being inconclusive regarding actual behavior, while road studies can give an in-depth analysis of a specific site, but struggle to show the effects outside of the study area. By combining these two approaches, the goal of this research is to better understand the ideal impacts of ITS within UDOT, while also developing specific recommendations.

3.0 METHODOLOGY

3.1 Overview

The methodology for this research is explained in this chapter. First, the compilation process to create the ITS device inventory/road segment classification datasets will be discussed. Second, the diversion rates analysis data collection, crash selection process, and building of a mixed effects model for the analysis will be summarized. Third, the weather analysis data selection and collection processes will be explained as well as the building of a mixed effects model for this analysis. Last, the purpose behind the creation and distribution of the UDOT ITS attitudes survey will be discussed.

3.2 ITS Device Inventory/Road Segment Classification

The purpose of the ITS device inventory was to create an up-to-date map of current VMS, RWIS, and traffic camera treatments for UDOT. Currently, UDOT databases and websites contain geographic and descriptive data on many ITS devices, but these sources of data are spread across the organization and are not contained in one centralized location. This map provides a snapshot of the current device locations that can be used to determine gaps in coverage and plan the placement of future devices. This section describes the creation and utilization of this map. First, the compilation of data for the ITS device inventory will be detailed. Second, the need and process for creation of a road segment classification dataset to pair with the ITS device inventory will be explained. Third, the way in which these datasets helped in choosing a type of analysis for the research will be summarized.

3.2.1 ITS Device Inventory

To build the ITS device inventory, geographic and metadata about each device were collected from UDOT's TransSuite database. For all three types of devices, the latitude, longitude, and device ID were collected as well as information useful for the potential VMS analyses such as installation date, model, milepost, and route name. Each of these datasets were imported into ArcGIS Pro software and displayed graphically. After the data were inputted into the map, the research team meticulously compared the VMS device information to the information on udottraffic.utah.gov to ensure accuracy.

The data pulled from UDOT's TransSuite database contained the most comprehensive dataset, but not all the data were relevant or up to date. For example, the research team only wanted information on permanent VMS and were not interested in movable VMS or VSL signs, both of which are included in the TransSuite database. In addition, individual devices that were not shown to be in service via udottraffic.utah.gov were filtered out of the map as they were not of interest. Overall, the TransSuite database enabled a cross-referencing of each VMS device that UDOT had in their system to investigate which devices were currently being used to create an up-to-date map inventory of UDOT ITS devices. Camera and RWIS data points were not compared to the TransSuite database due to the large number of devices in the dataset. The final map, shown in Figure 3.1, displays a macroscopic view of the state with each individual device denoted with a symbol for RWIS, traffic camera, or VMS. This map was created using an interactive ArcGIS database, which can be used for microscopic investigation into current devices in the state.

3.2.2 Road Segment Classification

In addition to the ITS device inventory, UDOT requested a road segment classification dataset to pair with the ITS device inventory. The purpose of the road segment classification was to compile road characteristic data for all major freeways across the state and create separate road segments whenever a change in road characteristic occurred. Comparable to the ITS device inventory, the road characteristic data existed across UDOT websites and data sources, but no central dataset with all the information existed in one place. This dataset was then paired with the VMS locations from the ITS device inventory to help determine the possible effects of VMS signs on comparable road segments across the state of Utah.

To create a road segment classification dataset, many types of road characteristic data from existing UDOT databases were needed. Most of the datasets were found through UDOT's Open Data Portal. These datasets included number of lanes, annual average daily traffic (AADT), speed limit, percent trucks, urban code, access category, and functional class. Each of these datasets were available as shapefiles, which allowed them to be represented graphically or

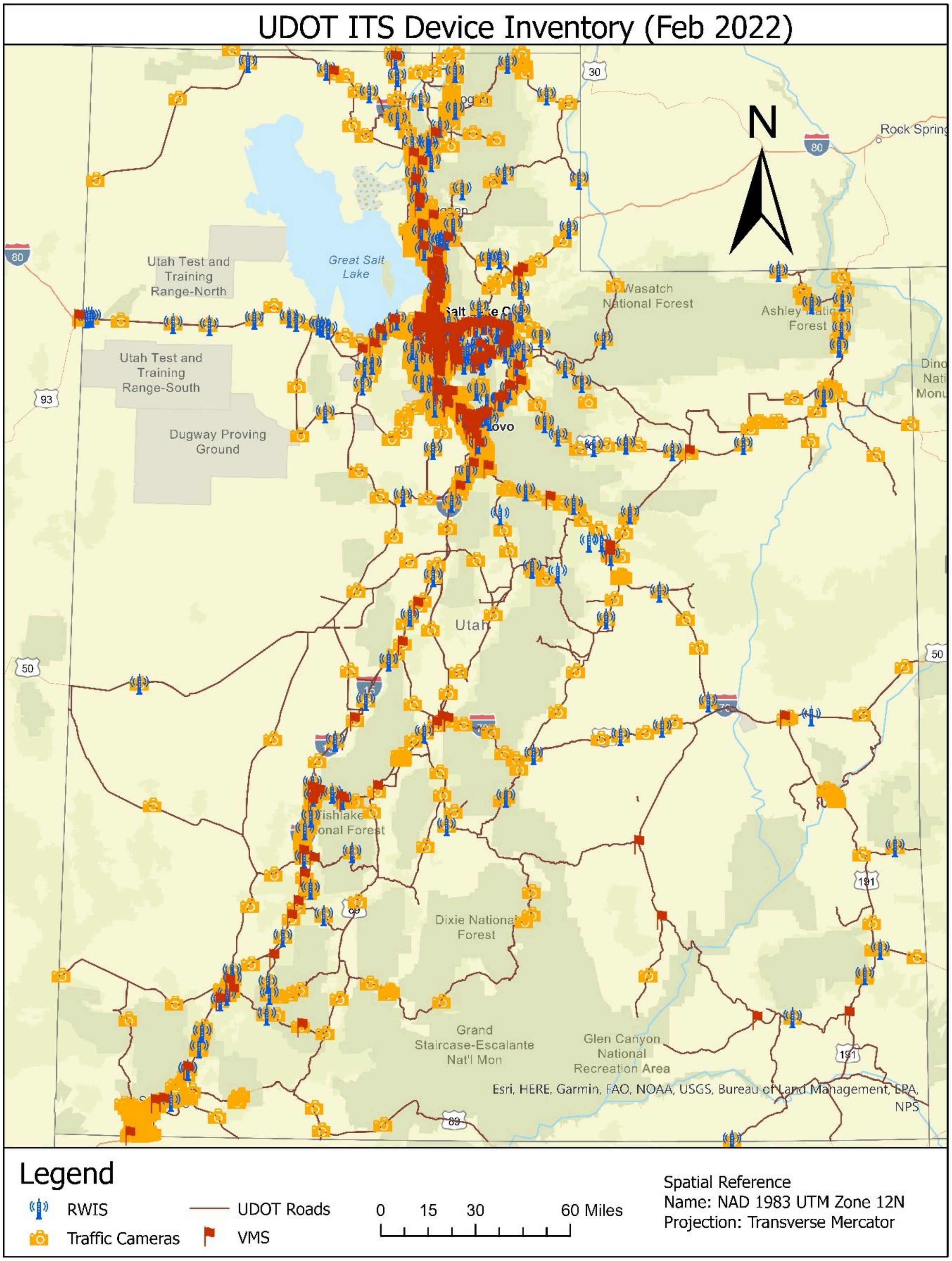


Figure 3.1: ITS device inventory map.

tabular. Two pieces of data that were not readily available on the Open Data Portal were access category and urban code. Both datasets required coordination with UDOT employees, but eventually, the access category map was made available via the Open Data Portal and a line type shapefile of the urban code boundaries was provided to the research team.

Once the datasets were gathered by the research team, they were combined using R, a statistical computing and graphics tool, to create a dataset of road segments when individual road characteristics changed. The R code used to combine the datasets came from work done in UDOT Report UT-23.15 (Schultz et al., 2023a). Based on route name and mileposts of VMS devices, each VMS was assigned corresponding road attributes. It was not feasible to do the same with RWIS and traffic cameras due to the high level of variation in location descriptions for those devices.

3.2.3 Analysis Selection

While the main purpose of compiling the ITS device inventory was to create a centralized database, a secondary purpose was to use the data to perform VMS effectiveness analyses in conjunction with road segment data. A with-and-without analysis could be performed on road segments with similar characteristics from urban and rural parts of Utah where one segment contained a VMS sign and the other did not. Safety metrics like severity and number of crashes on the nearby segment could be measured and compared to see if the presence of a VMS sign decreases crashes. In addition, a before-and-after analysis could be completed on segments where VMS signs were recently installed and a comparison of safety metrics before and after the installation of the VMS sign could be done to measure if the sign increased safety near the segment.

While both analyses were originally planned to be completed, the research team and TAC members jointly decided against this approach shortly after the completion of the road segment classification task. The team determined that due to the sheer number of road characteristics to match, the short distance of segments created, and the difference in AADT between urban and rural segments, the process to find matches for longer road segments where the majority of road characteristics were the same would not be feasible. There were also issues with the VMS data where the installation dates were inconsistent and oftentimes conflicting when compared to devices in the field. Additionally, it was nearly impossible to find installation dates for RWIS or traffic cameras due to the sheer volume of these devices. For these reasons, the team decided to pursue a series of different analyses to measure the effectiveness of VMS in Utah.

In reviewing the literature and the UDOT VMS message history, instead of conducting a with-and-without or before-and-after installation analysis, a message-type specific approach was selected. Once cleaned and sorted, a general overview of message intents was conducted. Key message categories included public interaction messages, travel time awareness postings, congestion-based warnings, and safety-based driver warnings. Example messages are included in Table 3.1.

Table 3.1: Message Classification Scheme

Public Interactions	Travel time Awareness
SOLAR ECLIPSE SAT OCT 14 PLAN TRAVEL	I-15 10600 S TO LEHI MAIN 20 MIN
Congestion Warnings	Driver Safety Warnings
CRASH AHEAD USE CAUTION	TRUCKS/SEMIS SHARP CURVES AHEAD

3.3 Diversion Rates Methodology

The research team decided to perform a before-and-after study to measure the effect of VMS on Utah freeway diversion rates during incidents. This section describes the methodology behind this analysis. First, the data collection process and decision on what types of data were needed is listed. Second, the determination of four crash selection criteria is discussed. Third, the implementation of the crash selection criteria on the crash data collected is shown. Last, the building of a mixed effects model to analyze the effect of VMS and to control for confounding variables is outlined.

3.3.1 Data Collection

For this analysis, many types of data were reviewed to control for as many confounding variables as possible. VMS message data were collected from UDOT's TransSuite server to identify when messages were visible and what kind of messages were shown to drivers. While the message data contained many types of messages such as travel time information, PSAs, amber and silver alerts, etc., only messages pertaining to crashes were of interest for this analysis. The research team noticed that messages pertaining to incidents were much more likely to have been written by an individual or denoted under the "Source Type" column as "USER." This was expected as most messages written to inform drivers of crashes are individualized based on the circumstances and sent out from individuals at the UDOT TOC. Due to this finding, only VMS messages with a "Source Type" of "USER" were selected for consideration.

The freeway selected to focus on in this study was I-15, which runs north to south across Utah and serves as the state's main interstate freeway. This decision was made because the majority of VMS signs and freeway crashes are both located on I-15. A belt route, I-215, was also included as it intersects with I-15 at key bottleneck points and also contains a high density of VMS. Utah and Salt Lake counties were specifically chosen as the study area due to the high number of crashes, high density of VMS on I-15 and I-215, and the availability of alternative routes.

Crash data were also collected to supply incidents to analyze if the presence of VMS messages encouraged drivers to exit the freeway. The research team evaluated two sources of data, UDOT's Incident Progress Report (IPR) and Excess Travel Time (ETT) data from UDOT Report UT-23.05 (Schultz et al., 2023b), to obtain useful crash data. UDOT's IPR is an internal website that contains details on major crash events in short reports. Basic information on the crashes such as Incident Management Team (IMT) level, impact, start and end times, fatalities, and location are recorded as well as optional supplementary information such as traffic camera still images, VMS messages displayed, and select updates by TOC operators on response actions, queuing updates, delays, and more detailed information on the crash and who responded. This source seemed to provide many useful pieces of data on incidents all on one page, which could reduce the data collection time for the research team. Unfortunately, the lack of filtering options on the website interface prevented its use in this project. The website allowed a user to enter a start and end date for a search window, but this was the only filter capability for the entire website. Information such as impact on drivers and delay are contained in the report but are not shown on the search page as filterable characteristics. If a crash was labeled in the report as a "High" impact crash, its row was marked green, but a user needed to scroll through pages limited to 50 results to identify all applicable "High" impact crashes. Due to these difficulties, a new source of crash data was needed that identified high-impact crashes easily, even if it did not include the additional VMS and cameras data.

The new source of data was found through UDOT Report UT-23.05 (Schultz et al., 2023b), which focused on measuring the benefits of expanding IMTs on Utah freeways. The authors evaluated a metric called ETT that calculated the aggregate delay time of drivers caught in a queue due to a crash. They then gathered data for individual crashes on Utah freeways and their effect from March to August of 2018 and 2022, which provided data on traffic not explicitly affected by the COVID-19 pandemic. The ETT metric was calculated in hours, so it was possible to sort crashes based on total delay. This dataset provided the time, milepost location, and impact of all Utah freeway crashes during the study time, so due to its ability to be sorted and its focused scope of applicable crashes, the dataset became the core source for selecting crashes in the research.

3.3.2 Crash Selection Criteria

Once the crash dataset was secured, a set of criteria were determined to guide what types of crashes were ideal for the diversion rates analysis. These criteria also helped minimize the effects of confounding variables by defining specific conditions under which the crashes needed to take place. The four criteria developed by the research team were high impact crash, alternate routes available, posting of a VMS message, and no confounding crashes or congestion.

First, the crash needed to have a high impact because high impact crashes meant more drivers were impacted, leading to more potential diversions and a higher chance at observing an effect. A higher impact also meant that the queues covered more space, meaning that more offramps were available for analysis.

Second, alternate routes needed to be available so that vehicles had an incentive to exit the roadway. If no alternate routes were available, the probability of drivers exiting the freeway to circumvent the crash would be much lower. Examples of alternate routes could be parallel roadways or detours around crashes. It was important that at least one alternate route was available to drivers to bypass the crash.

Third, the posting of a VMS message was inherently important to the analysis. The activation of a VMS message was the dividing point between the before-and-after analysis; hence, the presence of one or more VMS messages upstream of a crash were integral to the inclusion of a crash.

Fourth, independence of the crash queues from other congestion or crashes on the freeway was important to reduce the effect of confounding variables and increase the probability that any increase in vehicles exiting the freeway were due to the incident being studied. If a crash queue interacted with an additional crash queue or congestion, the independence of the crash and ability to measure the before-and-after effect of the VMS sign activation was reduced. These four crash selection criteria were chosen specifically to control, to the best of the research team's ability, the situations under which these crashes occurred and to provide the best circumstances under which to study the effect of VMS messages.

3.3.3 Implementation of Crash Selection Criteria

To implement the crash selection criteria, a workflow of vetting and selecting crashes was established. This workflow enabled a consistent and efficient method to vet crashes for their compatibility with the requirements of the diversion rates analysis.

First, the compiled crash dataset was sorted by crash from highest impact to lowest impact by ETT. Crashes with the highest impact were chosen first because they had the highest vehicle-hours of delay and had the potential for a higher observable diversion rates impact. Figure 3.2 shows the first rows of the crash dataset sorted by ETT.

C.crash.id	C.location	C.affected.volume	C.ETT	C.start.time
77	272499 I15 SB	11789	7192.00	2018-05-17 10:54:18
136	12300 S I15 NB	8463	6355.07	2018-07-18 14:35:29
158	284049 I15 SB; MM 284 I15 SB	23581	6139.31	2022-06-27 14:08:57
88	600 S I15 NB	19376	5958.45	2018-05-30 15:25:45
123	15572 S I15 SB; MM 287 I15 SB	22346	5665.10	2022-05-27 14:33:01
43	7800 S I15 NB	14081	4641.95	2018-04-10 16:15:43
86	14538 S I15 NB; MM 288.5 I15 NB	23238	4510.88	2022-04-29 15:24:37
102	14600 S I15 NB	14542	4471.19	2022-05-15 14:47:42
47	12300 S I15 NB	20653	4407.22	2018-04-13 05:37:50
179	16423 S I15 SB	7957	4189.47	2018-09-07 16:37:41
107	2100 S I15 NB	18748	4174.59	2018-06-21 15:41:53
58	8000 S I15 NB	12529	4098.08	2018-04-26 18:41:54
43	12300 S I15 SB	21716	4053.53	2022-03-25 14:12:18
143	11400 S I15 SB	10869	3673.17	2018-07-30 18:18:19

Figure 3.2: Crash dataset rows sorted by ETT.

Once a crash was selected, the date and time of the crash were entered into ClearGuide (www.udot.iteris-clearguide.com), a GPS-based speed visualization tool. ClearGuide provides an aerial map view of freeways and arterials with colors denoting the speed as a percentage of free-flow speed of the vehicles. Figure 3.3 shows an example of the ClearGuide interface. This tool enabled the research team to verify that a crash occurred at the time and place indicated, observe the impact of the queues caused by the crash, and ensure that there were no confounding crashes or congestion that would interfere with the queues caused by the crash. This was done by observing the speeds in the area at the time of the crash. If additional congestion from up or downstream merged with the congestion due to the crash in question, the crash was discarded from the crash selection process. This ensured that the effects measured in the final analysis were only due to the crash and no other crash or peak hour congestion.

If the congestion from the crash was deemed independent of other effects, the time and milepost location were cross-referenced in the filtered VMS dataset, shown in Figure 3.4. All VMS messages posted around the time of the crash were identified and each message was checked for message relevance to the crash and proximity to the crash. The milepost and route information aided in verifying that messages that seemed to refer to a crash were located upstream from and close enough to the crash to be relevant. A list of relevant VMS messages was compiled for each crash based on message relevance and location proximity.

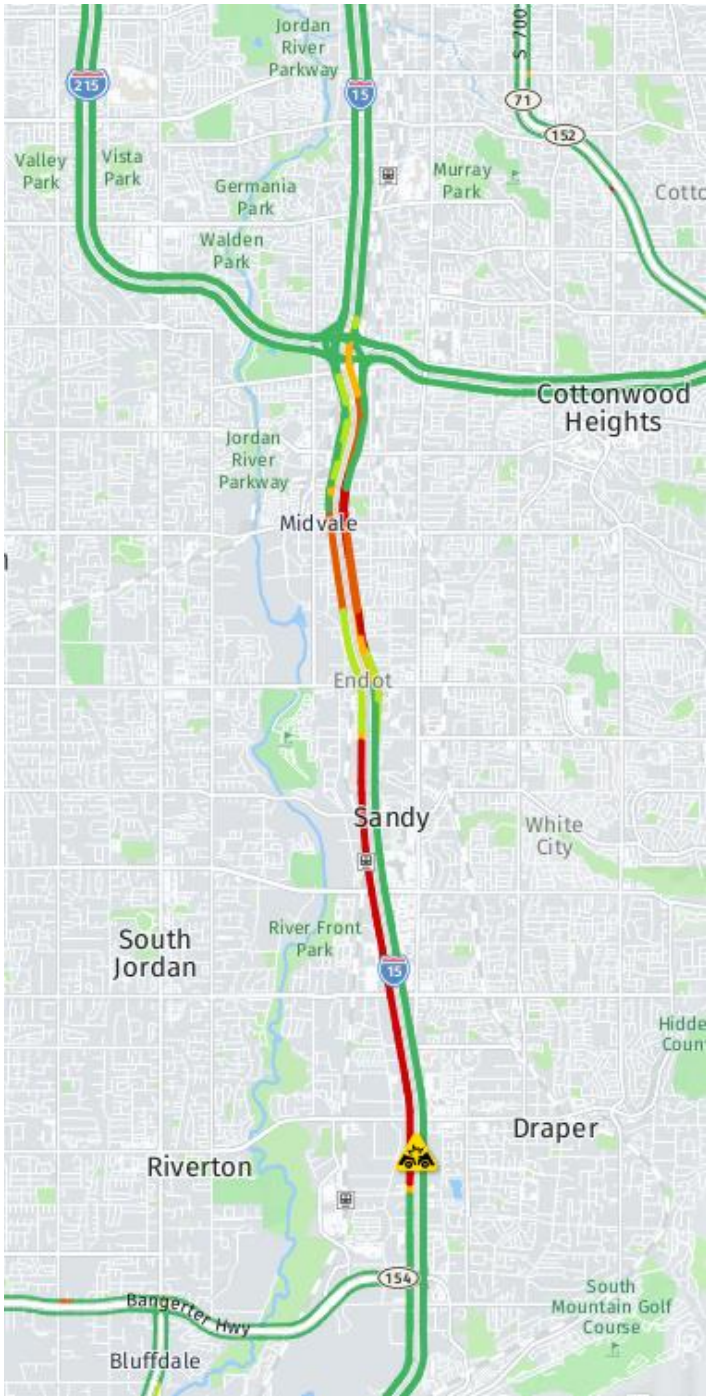


Figure 3.3: View of the ClearGuide interface.

V.device.id	V.start.time	V.month	V.year	V.day	V.location	V.route	V.milepost	V.message
1	2018-03-04 00:53:00	3	2018	4	I-15 SB @ 350 N / MP 308.92, SLC	I-15	308.92	WET ROADS USE CAUTION WET ROADS REDUCE SPEED
1	2018-03-04 02:04:00	3	2018	4	I-15 SB @ 350 N / MP 308.92, SLC	I-15	308.92	SNOWY/ICY ROADS USE CAUTION SNOWY/ICY ROADS RED...
1	2018-03-04 09:42:00	3	2018	4	I-15 SB @ 350 N / MP 308.92, SLC	I-15	308.92	RIGHT LANE BLKD AHEAD USE CAUTION
1	2018-03-04 11:46:00	3	2018	4	I-15 SB @ 350 N / MP 308.92, SLC	I-15	308.92	STOPPED TRAFFIC AHEAD PREPARE TO STOP
1	2018-03-04 11:46:00	3	2018	4	I-15 SB @ 350 N / MP 308.92, SLC	I-15	308.92	TRAFFIC SLOWS AHEAD USE CAUTION
1	2018-03-05 08:38:00	3	2018	5	I-15 SB @ 350 N / MP 308.92, SLC	I-15	308.92	RIGHT LANE BLKD AHEAD
1	2018-03-05 21:19:00	3	2018	5	I-15 SB @ 350 N / MP 308.92, SLC	I-15	308.92	CRASH I-80 AT 2400 E USE I-215
1	2018-03-05 21:39:00	3	2018	5	I-15 SB @ 350 N / MP 308.92, SLC	I-15	308.92	CRASH I-80 AT 2400 E EXPECT DELAYS
1	2018-03-05 21:49:00	3	2018	5	I-15 SB @ 350 N / MP 308.92, SLC	I-15	308.92	CRASH I-80 AT 2400 E USE I-215 E
1	2018-03-05 21:50:00	3	2018	5	I-15 SB @ 350 N / MP 308.92, SLC	I-15	308.92	CRASH I-80 AT 2400 E USE SB I-215 E
1	2018-03-05 22:38:00	3	2018	5	I-15 SB @ 350 N / MP 308.92, SLC	I-15	308.92	CRASH I-80 AT 2400 E USE I-215E 3300 S
1	2018-03-08 16:38:00	3	2018	8	I-15 SB @ 350 N / MP 308.92, SLC	I-15	308.92	STOPPED TRAFFIC AHEAD REDUCE SPEED
1	2018-03-08 16:49:00	3	2018	8	I-15 SB @ 350 N / MP 308.92, SLC	I-15	308.92	STOPPED TRAFFIC AHEAD PREPARE TO STOP
1	2018-03-08 22:14:00	3	2018	8	I-15 SB @ 350 N / MP 308.92, SLC	I-15	308.92	LEFT LN CLOSED AT 2700 S USE CAUTION

Figure 3.4: Example of VMS message dataset.

Next, the udottraffic.utah.gov website was used to identify the geographic location for each VMS sign. Each sign was located on the website's interactive map of ITS devices and a screenshot was taken of the area containing all the VMS signs. On the screenshot, circles were added to show the location of VMS, lines for available offramps between the crash and the last applicable VMS, and an "X" for the crash location. This map was then used to identify all applicable offramps to be analyzed and to keep track of the geography of the crash study area, as illustrated in Figure 3.5. Maps for each crash can be found in Appendix A.

Last, the volume detectors for the offramps identified from the map were entered into UDOT's Performance Measurement System (PeMS) database (https://udot.iteris-pems.com/) to collect mainline and offramp volumes for analysis. Figure 3.6 shows an example of the PeMS interface. Based on results of the literature review, it is likely that once a VMS message is activated, a difference in behavior will be observed within 10 minutes (Levinson and Huo, 2006). To accommodate for this, volumes for 20 minutes before and 40 minutes after the activation of the sign were collected. This allowed for a control period before the VMS activation time as well as accounting for the time the vehicles would take to travel to the offramp from the VMS during the after time. An in-between period to accommodate the time it took for a vehicle to travel from the VMS sign to the exit was considered, but due to the dynamic nature of congestion buildups and limited speed observation points, this method was deemed too complex for this analysis and the after period of 40 minutes was assumed to contain this travel time period. The before-and-after time frames were also chosen to eliminate the potential for confounding traffic interactions. The crash data used from UDOT Report UT-23.05 (Schultz et al., 2023b) ensured that no secondary crashes caused by the crash in question would occur, but in some incidents, an additional crash upstream or downstream a few miles from the crash site did occur. In these situations, the congestion from the additional crash often merged with the congestion from the crash in question, creating intermingled congestion that could not be attributed to one crash or the other. Because of this issue, the research team chose a smaller time window to prevent the potential for these interactions to occur. Lastly, in addition to the volumes for the mainline and offramps, speeds for the mainline segment were also collected in an effort to control for visible queues that could form.

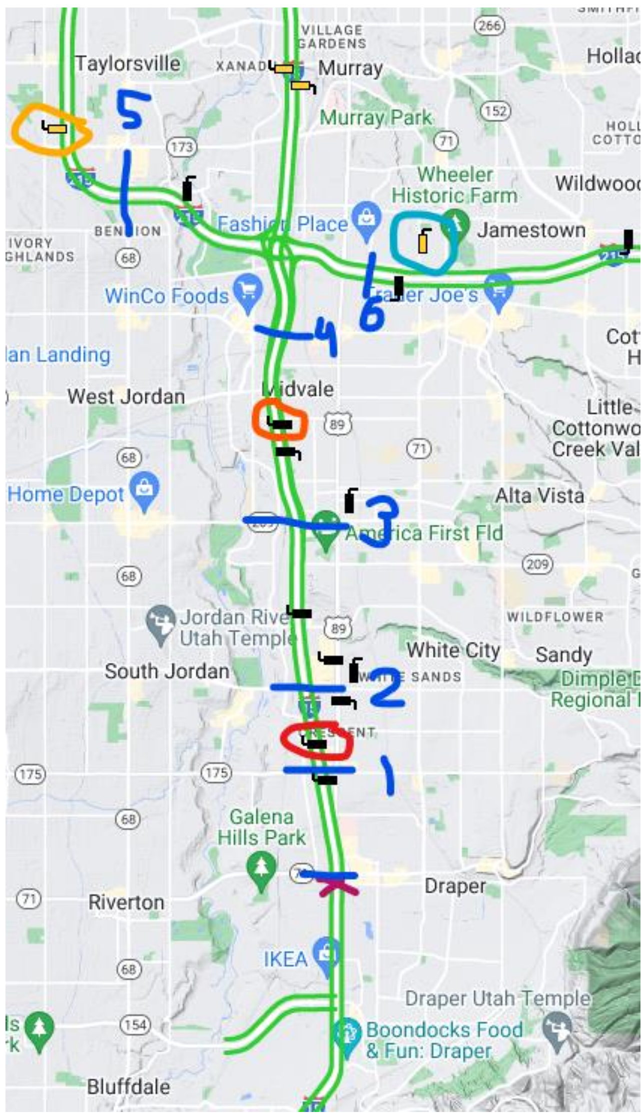
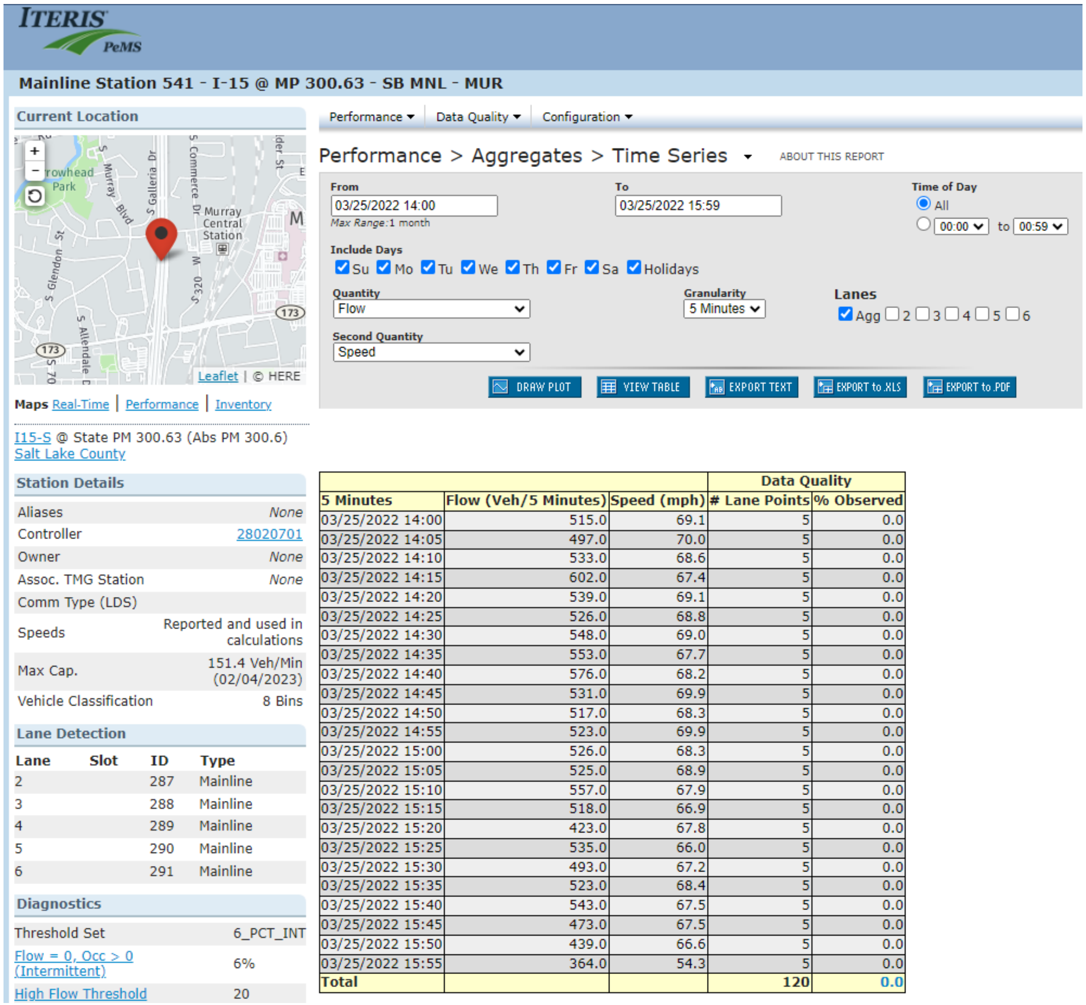


Figure 3.5: Screenshot from udottraffic.utah.gov with VMS, offramp, and crash markups.



			Data Quality	
5 Minutes	Flow (Veh/5 Minutes)	Speed (mph)	# Lane Points	% Observed
03/25/2022 14:00	515.0	69.1	5	0.0
03/25/2022 14:05	497.0	70.0	5	0.0
03/25/2022 14:10	533.0	68.6	5	0.0
03/25/2022 14:15	602.0	67.4	5	0.0
03/25/2022 14:20	539.0	69.1	5	0.0
03/25/2022 14:25	526.0	68.8	5	0.0
03/25/2022 14:30	548.0	69.0	5	0.0
03/25/2022 14:35	553.0	67.7	5	0.0
03/25/2022 14:40	576.0	68.2	5	0.0
03/25/2022 14:45	531.0	69.9	5	0.0
03/25/2022 14:50	517.0	68.3	5	0.0
03/25/2022 14:55	523.0	69.9	5	0.0
03/25/2022 15:00	526.0	68.3	5	0.0
03/25/2022 15:05	525.0	68.9	5	0.0
03/25/2022 15:10	557.0	67.9	5	0.0
03/25/2022 15:15	518.0	66.9	5	0.0
03/25/2022 15:20	423.0	67.8	5	0.0
03/25/2022 15:25	535.0	66.0	5	0.0
03/25/2022 15:30	493.0	67.2	5	0.0
03/25/2022 15:35	523.0	68.4	5	0.0
03/25/2022 15:40	543.0	67.5	5	0.0
03/25/2022 15:45	473.0	67.5	5	0.0
03/25/2022 15:50	439.0	66.6	5	0.0
03/25/2022 15:55	364.0	54.3	5	0.0
Total			120	0.0

Figure 3.6: Iteris PeMS database interface.

Overall, 8 crashes were selected for the diversion rates analysis. Three crashes were from 2018 and five crashes were from 2022. A total of 650 flow and speed observations were compiled over 32 offramp locations across Salt Lake and Utah counties for the analysis. These crashes were compiled into a single dataset and prepared for data analysis.

3.3.4 Diversion Rates Mixed Effects Model

Once crashes were selected and the volume and speed data were retrieved, the analysis of diversion rates was conducted. The research team was primarily interested in determining how the diversion rates at ramps immediately before an incident were affected by an upstream VMS message indicating a crash had taken place or providing information about the congestion caused by the crash. To measure the effect of VMS messaging, a mixed effects model was developed.

The diversion rate on the crash day was selected as the variable of interest for the model but needed to be evaluated in a way to compare it against the diversion rate on the control day. It was determined that the best way to do so would be to choose the dependent variable as the ratio of the diversion rate on the crash day compared to that of the control day. This would allow a comparison on how the diversion rate differed from a crash-free day.

There was concern regarding a phenomenon in statistics that when ratios are included in a regression, spurious correlation can be created. Kronmal (1993) warns against this practice and includes many examples of false inferences that can occur by the inclusion of ratios. As a precautionary measure, the reciprocal of the control day diversion rate was included as a predictor variable to measure the stability of the model. This helped to preserve the interpretation of the intercept in the model and act as a measure of the stability of the model. If the estimate for this predictor was small, it would indicate a stable model and that the ratio of diversion rates can be modeled without the chance of spurious correlations.

Confounding variables also needed to be included in the model to control external factors. The most meaningful factor that could influence diversion rates was congestion. The best measure of congestion that was available to the research team was speed. Because the analysis would be comparing data on the day of the crash to a similar crash-free day either a week before or after the crash, speed was controlled for as a ratio of the speed on the mainline of the freeway on the crash day compared to the control day.

Even after accounting for speed, because each crash is unique, it stands to reason that there would be substantial variability between each crash and between each offramp for each crash. To more accurately measure those effects, the random effects for each crash and for each offramp for each crash were included. This allowed for each offramp's diversion rate to have its own mean, which could then be affected in a consistent way by the factors being controlled for in the model. It also allowed for a more accurate estimate of the error associated with the model, which led to a more accurate inference on the effects of the variables shown by the model.

The research team was concerned that if not controlled for, an interaction between the "VMS" and "SR" variables would cause the results to inaccurately describe the true effect of VMS. Due to this, an interaction term of "VMS*SR" was included in the mixed effects model. This interaction allowed for a comparison of the data to occur that accounted for changes in only one of the variables, such as if the VMS was activated but the speed ratio did not change. This then enabled the research team to properly clarify what effect the VMS activation had on diversion rates, rather than part of the effect of an increase in diversion rates due to a decrease in speeds being attributed to VMS activation.

An additional variable called, "VUpstream" was created, which was not included in the mixed effects model but was important in verifying the results of the model. The research team wanted to keep track of the position of the offramps in relation to each other, so for each VMS message, the offramps were given a number relative to their position upstream of the crash. For example, the first offramp upstream of the crash was numbered "1," the second offramp upstream of the crash numbered "2," and so on. This allowed the research team to perform a more in-depth analysis once the mixed effects model was run.

With all relevant variables accounted for, the research team proposed to model the diversion rate ratios as a function of the speed ratio, whether or not a VMS message was activated, the reciprocal of the control day diversion rate, and an interaction term of VMS activation and the speed ratio. In addition, the random effects for each crash and offramp were included. Equation 3.1 displays the model that was built for this analysis.

$$DR = RCD + VMS + SR + VMS * SR + (1|Crash{:}Mramp) \tag{3.1}$$

where: *DR* = ratio of crash day diversion rate to control day diversion rate,

RCD = reciprocal of control day diversion rate,

VMS = binary variable indicating if the VMS was active or inactive,

SR = ratio of crash day mainline speed to control day mainline speed,

*VMS*SR* = interaction of *VMS* and *SR* variables,

Crash = crash identification number, and

Mramp = offramp identification number.

3.4 Weather Analysis

While the diversion rates analysis was concerned with congestion warning VMS messaging, additional research was conducted on driver safety warnings, specifically those pertaining to adverse winter weather conditions in Utah canyons. The purpose of the weather analysis was to develop an understanding of driver behavior in response to VMS messages about weather conditions that would reduce driver response time or vehicle maneuverability. One example of these messages could read, "WARNING ICY ROAD CONDITIONS, SLOW DOWN" or "BLACK ICE, REDUCE SPEED."

Unlike the diversion rates analysis, crash rates were not included for the weather analysis. Instead, vehicle speeds before and after the position of a VMS sign were measured. Through measuring changes in driver speeds, inferences to driver safety could be estimated. In addition, a variety of roadway factors needed to be controlled for to better understand the interactions between driver speeds and VMS messaging. This section outlines the methodology that the research team developed to do so. First, confounding factors and time constraints on what data were collected to control for those factors are detailed. Second, the process of selecting geographic study locations is outlined as well as the selected areas. Third, the types of VMS messages selected for this analysis are laid out. Fourth, the data collection process for RWIS and speed observation data is detailed. Fifth, important assumptions made in the data collection process are outlined. Last, the mixed effects model built for the analysis is described.

3.4.1 Base Parameters for Data Collection

To reduce the effects of confounding variables on driver speeds, several base parameters for VMS message, RWIS, and speed data collection were defined. While these parameters limited what days or what times data were able to be collected, they provided the ideal circumstances under which a thorough analysis could be conducted. This section describes three parameters set for data collection. First, time constraints placed on the data collected will be justified. Second, unusual traffic conditions that were controlled for will be explained. Last, the method chosen for controlling for days without VMS messages will be described.

To retrieve the most well-distributed speed data, time constraints were selected for VMS and speed data that ensured higher flows of vehicles. For VMS, messages that were activated between 8:00 a.m. and 5:30 p.m. were chosen for the analysis. Speed data pertaining to each message were collected for 2 hours before the message was activated, while the message was activated, and 1 hour after the sign was turned off. To also ensure higher vehicle flows for the speed data, only data for the hours between 7:00 a.m. and 6:00 p.m. were used for the final analysis.

To reduce the likelihood of unusual traffic conditions, driver interactions with crashes, construction, and snowplows were minimized by the research team. Using the AASHTOWare Numetric UDOT crash database (https://udot.aashtowaresafety.com/), the research team entered the dates and times selected for the analysis to verify that no crashes occurred near the VMS during these times. In relation to construction, UDOT does not keep a comprehensive log of current and past construction dates, so it was assumed that construction was minimal during winter months and could be ignored. The research team realized that snowplows could create an interaction with drivers, but as there was not a way to track historical snowplow paths and timing, any interactions were assumed to be randomly distributed across the speed data.

To control for days without VMS messages, a control period of speed data was needed, and the research team considered two methods to obtain this data. The first method was to collect data on similar non-incident days with varying weather conditions, but to do so, the research team would need a method to view weather longitudinally over time for many RWIS stations. This type of tool was not available at the time of the study and the creation of this tool was outside the scope of this research. The second method considered was to use the before-and-after activation periods as the control data. This method provided comparisons directly adjacent to and with the same road and weather conditions as the VMS activation period. The team decided that by comparing observations during the sign “off” periods to the sign “on” periods, reliable comparisons could be made.

3.4.2 Location Selection Process

When choosing geographic locations for analysis, the research team decided that messages should be applicable to all vehicles throughout the corridor where all drivers are likely affected by the same conditions warned against in the message. Northern and central Utah have several multi-lane canyon freeways that provide this type of study environment. Specific criteria needed for the analysis in these canyons included the presence of vehicle detection units, RWIS stations, favorable VMS placement that could affect driver behavior, and winter weather.

With this criteria, five canyons were initially selected: Ogden Canyon, Parley's Canyon, Provo Canyon, Sardine Canyon, and Weber Canyon. To be appropriate for the analysis, each canyon needed VMS sign(s) placed in a position to affect vehicles throughout the canyon, numerous vehicle detection units and RWIS stations throughout the canyon, and to be in areas that were expected to have several winter weather events each year. Upon further evaluation, Odgen Canyon was noted as having had only one weather-related message during the selected time frame and was disqualified because it did not occur between 8:00 a.m. and 5:30 p.m. Parley's Canyon was also eliminated from consideration due to the presence of VSL signs, as these devices were outside the scope of this research. However, the final three canyons each had relevant messaging that could be applied to this study. Figure 3.7 shows the geographic locations for each of these canyons with their associated VMS, PeMS, and RWIS stations.

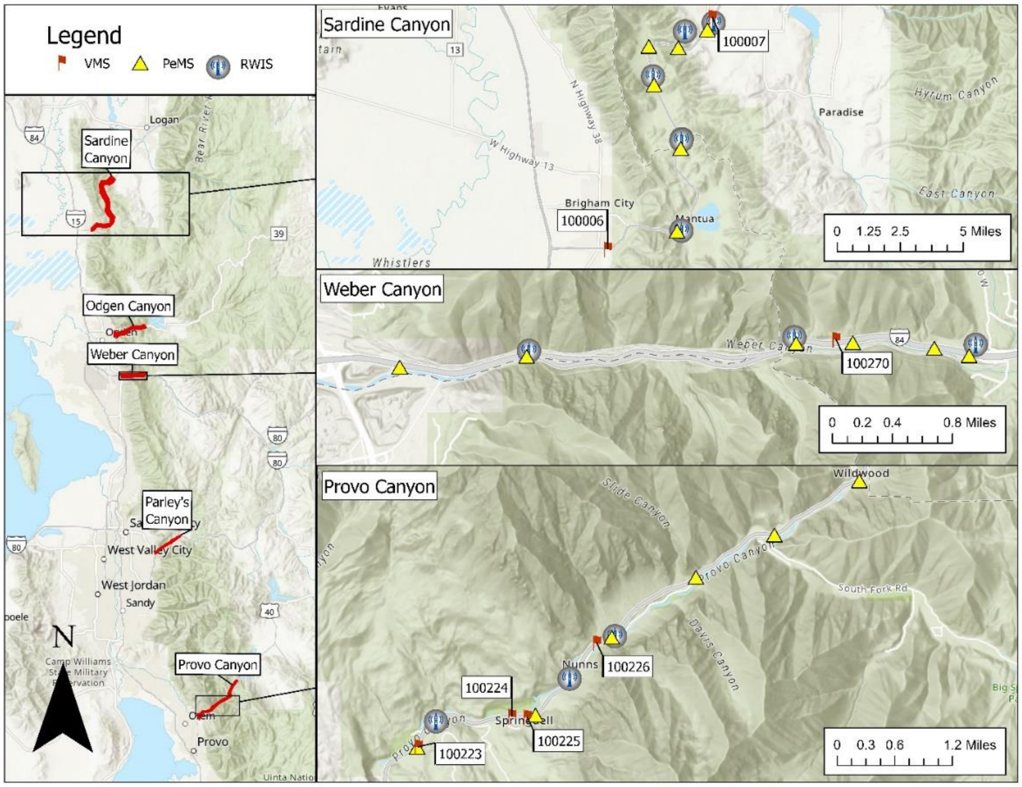


Figure 3.7: Canyon locations and data collection sites.

<u>3.4.3 VMS Message Selection Process</u>

The research team decided that only messages applicable to all vehicle types and roadway segments should be included in the analysis. Common message types that were disqualified for inclusion included messages primarily for vehicles with large amounts of surface area (e.g., "HIGH WINDS AHEAD") or messages that were applicable to only one portion of the canyon corridor (e.g., "BLACK ICE 4 MILES AHEAD"). In addition, because the analysis was focused on winter weather messages, only those messages that specifically pertained to winter weather conditions were selected. Any message selected also needed to pertain to weather conditions that could be verified by RWIS data.

Messages were selected within the last two winter seasons at the time of the study, or from October 2020 to April 2022. Messages needed to have been activated for at least 30 minutes to be considered, as a shorter activation time may not have provided a large enough number of vehicle speeds for a well-distributed sample. After each message was selected, the before, during, and after time periods of the message were checked for any missing speed data or

RWIS data. No messages were disqualified for this reason, but the procedure was performed to ensure data completeness. Overall, 47 messages were selected for the analysis. The research team considered taking a random sample of these messages to analyze the statistical significance of the findings but decided against it due to the already small sample size. Specifics about the various messages selected are presented in Appendix B, including dates of the message, location, and message phrasing.

3.4.4 RWIS and Speed Data Collection

In addition to the VMS and crash data collected, weather and speed observation data were integral to the robustness of the analysis. This section outlines where the data were collected and the attributes of these data.

RWIS data for winter weather conditions were collected through the University of Utah's MesoWest website (https://mesowest.utah.edu/). This website conglomerates information from several weather databases from across the United States, including several RWIS stations in Utah. For each message selected for analysis, all available weather data were collected including air temperature, road temperature, soil temperature, road grip, precipitation, visibility, wind speed, wind direction, wind gust, sea level pressure, dew point, relative humidity, and snow depth. Each of these data categories were collected to ensure a thorough data collection process, but not all categories were included in the final analysis. Many categories of data were not consistently available at all VMS locations and the research team determined that certain types of data, such as sea level pressure, would not be perceptible to drivers or impact their behavior. As such, only road grip, precipitation, and visibility data categories were selected for analysis, as they were considered perceptible to drivers as well as the only three categories with consistently available data at each VMS location.

Speed observation data were collected using UDOT's Freeway Performance Metrics Occurrence Data website (https://www.udottraffic.utah.gov/FPM/VehicleEvent/EventReport). Collecting occurrence data allowed for a more detailed analysis of traffic patterns and conditions. The data were not aggregated into bins, like in the diversion rates analysis, but instead, each vehicle was individually recorded. Information about each vehicle was compiled in the dataset, which included lane number, vehicle direction, vehicle class, speed, length, duration of detection and timestamp of detection. This data enabled further filtering including exclusion of vehicles traveling in a direction opposite to the message displayed and vehicles traveling outside of the study windows. Using the occurrence data allowed for a more granular analysis than aggregated data would allow.

3.4.5 Combining Datasets

To combine the VMS, RWIS, and speed observation datasets, a script in R, a statistical computing and graphics tool, was utilized. Although most of the syntax and functions of the R script are outside the scope of this report, highlighting several characteristics of it are essential to communicate the assumptions made in the combination of the datasets. These assumptions include the approximation of the time that the driver passed the VMS message and the assignment of weather data to speed observations.

When considering how to determine whether a driver had observed the VMS sign as active or inactive, the research team decided that an adjustment to the timestamp of each vehicle's speed observation was necessary. The team considered standardizing a travel time from each vehicle detector station to the VMS for each canyon, which meant that only one adjustment would need to be made, but a dynamic methodology was decided on as a more accurate option.

To compute a dynamic travel time, an adjusted timestamp was made for each speed observation individually. First, Google Maps was used to estimate the travel time between the vehicle detector station and the VMS for the chosen VMS message. The travel time, t, was then added to and subtracted from the recorded timestamp, RT_i, of each individual speed observation to create a time envelope of $[RT_i – t, RT_i + t]$. For observation, i, all speed observations within the time envelope were averaged to create an average speed observation, i. An adjusted timestamp was then made for speed observation, i, as a function of the recorded timestamp, the distance from the vehicle detector station to the VMS, and the average speed described. Once an adjusted timestamp was determined for each speed observation individually, the VMS message activation time was used to determine if the driver would have observed the sign as active or inactive. Equation 3.2 illustrates the process used to calculate an adjusted timestamp based on an estimated travel time.

$$\mathrm{AT_i} = \mathrm{RT_i} - \left(D_i / \left(\frac{1}{\mathrm{N_i}} \sum_{\mathrm{N}=1}^{\mathrm{N_i}} \mathrm{S}_t\right)\right) \quad (3.2)$$

where: AT_i = adjusted timestamp of observation *i*,

RT_i = recorded timestamp of observation *i*,

D = distance from observation *i* to VMS sign, ft,

N_i = number of speed observations, and

S_t = average speed of vehicle observations within time envelope, *t*.

After collecting the weather observation data for the analysis, the next step was to determine which weather data should be assigned to each speed observation. The complication with the weather data is that the RWIS and UDOT speed observation systems are not correlated, they are two separate systems with different priorities and purposes. While traffic cameras are often placed on RWIS stations close to the freeway, RWIS stations are not necessarily placed at regular intervals near roadways and many times are placed further in the mountains rather than closer to the roadway. This meant that for each selected message, data from multiple RWIS stations and at different times needed to be collected to help estimate the weather conditions at the VMS. The following is an example scenario that illustrates the challenge described:

"Two weather points are available. Point 1 is 0.5 miles away and was recorded 10 minutes before the speed observation. Point 2 is 2.0 miles away and was recorded 2 minutes after the speed observation. Which observation should be used?"

The research team had considered using linear interpolation methods to predict the weather at the VMS based on the combination of data from nearby RWIS stations, but the challenge of making accurate predictions with such limited data was too great and the interpolation method was abandoned. To select which point should be used, a methodology was developed based on the cumulative product of minimum-maximum normalizations for time and distance (Han et al., 2012).

Equation 3.3 illustrates the equation that was used for the selection of one weather data point over another. The equation calculates the normalization for a specific subset of data.

$$F_{ijR} = T_{iR} * \prod_{k=1}^{k}\left(\frac{obs_{ijk} - min_{obs_{ijk}}}{max_{obs_{ijk}} - min_{obs_{ijk}}}(Max_{new} - Min_{new}) + Min_{new}\right) \quad (3.3)$$

where: F_{ijR} = best fit factor for RWIS observation type, *R*, correlating to, *i*, RWIS value for, *j*, speed observation,

T_{iR} = data present factor for, *R*, data type and, *i*, RWIS observation; if the specific RWIS weather attribute for the given, *i*, is "NA" then $T_{iR} = 0$, else $T_{iR} = 1$,

obs_{ijk} = *i*, RWIS difference from, *j*, speed observation for, *k*, data type,

min_obs_{ijk} = minimum, *i*, RWIS difference from, *j*, speed observation for, *k*, data type,

max_obs_{ijk} = maximum, *i*, RWIS difference from, *j*, speed observation for, *k*, data type,

Max_{new} = new maximum value, or 1.0,

Min_{new} = new minimum value, or 0.0,

i = RWIS weather attribute data,

j = vehicle speed observation,

k = [Time difference, Distance difference], and

R = RWIS value of interest (road grip, air temperature, precipitation, etc.).

This method took two or more weather data points and based on the distance from the VMS and the time the weather observation occurred, selected the observation that was more reasonable and relevant for the speed observation at a specific time. The subset of data, *ij*, were identified by finding rows with the smallest difference between the identified vehicle speed observation, and the RWIS observation timestamp. Up to four times the number of RWIS stations of data rows were collected and a F_{ijR} factor was calculated for each, with 1.0 being optimal, and 0.0 being least optimal. Corresponding weather values, *i*, to the maximum F_k were then assigned for the speed observation, *j*. In this way, one weather observation out of potentially multiple were assigned to each vehicle speed observation.

With the data collection and data processing methodology described, 47 VMS messages with corresponding weather and speed observations were collected and prepared for analysis.

3.4.6 Weather Mixed Effects Model

Following the data collection, it was desirable to develop an understanding of how VMS messages affected speeds during various weather conditions. A mixed effects model was selected as the optimal method of analysis for the collected speed and weather data. The following section describes the model and the various random and fixed effects. Table 3.2 describes the variables used in the model.

In the data, observations were sourced from seven different VMS and 47 different messages with unique phrasing and intent across two different winter seasons. Because the messages came from varying areas and were presented on different VMS, it was decided that the mixed effects model should include random effects for each VMS and each message.

The different weather stations were considered as a random effect, but in comparing models, it was determined that adding an additional constraint did little to change the model results. Instead, a fixed effect variable using the distance between the VMS and the speed observation location was used to estimate the effect of distance traveled from the VMS on the model.

Historically, the AM, Midday, and PM time periods function in unique patterns from each other. A data category was created that put each observation into one of three bins based on when the speed was observed, or also referenced as the time interval. The exact bins were chosen loosely, providing for fluctuations in the traffic flow. To measure that flow, the Peak Hour Flow (PHF) and hourly flow were calculated for each observation. These variables were also used as fixed effects.

From the large amount of available RWIS data, ultimately two variables were selected as fixed effects: road grip and visible precipitation conditions. Although drivers may be aware of air temperature as they enter their vehicles, modern comforts may make it difficult to anticipate weather conditions outside the vehicle. Additionally, although newer vehicles are provided with technology to predict road conditions based on various sensors, they were not yet commonly available to warrant the inclusion of road or air temperature. Additional variables including dew point and wind speed/direction were also excluded due to the lack of applicability to most roadway users.

Table 3.2: Variables in Speed/Weather Mixed Effects Model

Variable	*Extended Name*	*Effect*	*Brief Description*
SD	Speed	Fixed	Observed Speed of Vehicles (mph)
SP	VMS Stage	Fixed	Binary indicating the presence of VMS information
TS	Time Interval	Fixed	AM, 7:00-10:00 a.m.; Midday, 10:00 a.m.-4:00 p.m.; PM, 4:00-7:00 p.m.
MPD	Milepost Difference	Fixed	Difference between the VMS milepost and the observation
PHF	Peak Hour Factor	Fixed	Traffic engineering factor to estimate traffic distribution during the hour
HrF	Hourly Flow	Fixed	Total of all vehicles passing within 1 hour of observation
Gr	Road Grip Factor	Fixed	Reported road grip factor
Vis	Visibility State	Fixed	Categories of reported visibility from the RWIS
VMS	VMS ID	Random	UDOT TransSuite ID#
MN	Message Number	Random	Assigned message number

For categorical variables such as the sign phase, time interval, and visible precipitation conditions, analysis was conducted using the speeds in one category as the basis for comparing against all other variables. Table 3.3 illustrates for each of these variables, what state was used as the basis for comparing against. For example, in the last row, the variable is the precipitation phase, with the “No Precipitation” state compared to the “Light,” “Moderate,” and “Heavy” precipitation states.

Table 3.3: Categorical Variables, Control vs. Compared

Variable	*Control Category*	*Other Categories*
Sign Phase	Off	On
Time Interval	Midday	AM, PM

Visible Precipitation	No Precipitation	Light Precipitation, Moderate Precipitation, Heavy Precipitation

With the necessary variables defined, the mixed effects model equation was defined as outlined in Equation 3.4.

$$SD = SP + TS + MPD + PHF + HrF + Gr + Vis + (1 \mid VMS{:}MN) \tag{3.4}$$

where, *SD* = observed vehicle speed,

SP = sign phase (on or off),

TS = time state of the observation,

MPD = milepost difference between the VMS and observed speed,

PHF = Peak Hour Factor,

HrF = hourly flow rate,

Gr = road grip,

Vis = visibility factor,

VMS = VMS ID number, and

MN = message number.

Non-linear transformations were considered for the road grip factor. Research exploring the relationship between driver speed patterns and road grip is limited, but most use a linear model to correlate the two (Boodlal et al., 2015; Sui and Young, 2014). One paper by de Vos (1992) correlates a theoretical safe speed to the square root of the ratio of the friction and following distance, but also used a linear model between actual speed and the ratio of the road friction and the amount of water on the roadway (< 2mm). Figure 3.8 illustrates various attempts to transform the data to determine a model to best fit the data. For each plot, the x-axis is vehicle speeds from 0 to 100 mph while the y-axis is the transformed road grip factor. The scales are not detailed as they are not needed to visualize the overall relationship between speed and various transformations of the road grip factor. If there was a clear linear relationship, then that transformation would be selected as the optimal relationship between road grip and vehicle speed. However, for each of the transformations, there were no clear linear relationships in the plots.

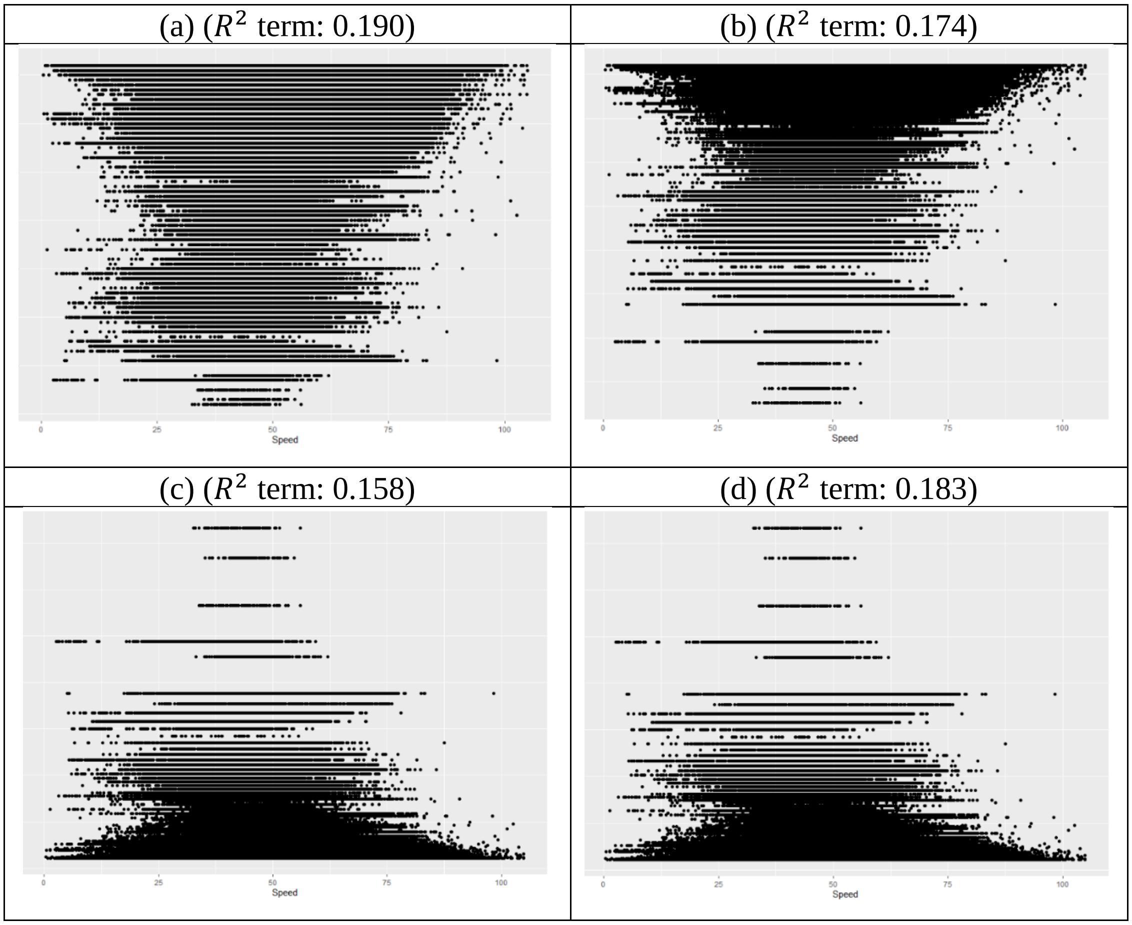


Figure 3.8: Road grip transformations for (a) existing, (b) log transform, (c) inverse transform, and (d) square-root transform.

The R^2 term reflects the overall fit of the model detailed in Equation 3.4 with the various transformations to the road grip data. As none of the transformations provided a better fit than the existing mixed effects model and none of the other transformations presented a linear relationship, the existing mixed effects model was selected for the data analysis.

3.5 UDOT ITS Attitudes Survey

In conversation with the TAC, concerns were raised that while the diversion rates and weather analyses would provide evidence on the effect of VMS, they would provide minimal actionable information for UDOT on the usage of, attitudes toward, and potential improvements to UDOT's current ITS device deployment. With this concern in mind, a survey of UDOT employees was proposed and conducted by the research team to understand this information and provide additional recommendations to UDOT. This section details the creation and distribution of the UDOT ITS attitudes survey. First, the reasoning of why and how the survey was built will be discussed. Second, the distribution details and dates for the survey will be summarized.

3.5.1 Survey Creation

The research team created a survey that measured the usage of, attitudes toward, and potential improvements to UDOT's current ITS device deployment. The survey was built to provide all UDOT employees with an opportunity to share their thoughts. To do this, an adaptable survey was constructed that accommodated individuals' differing usage of ITS devices. Qualtrics$_{XM}$ was identified as an optimal survey platform to do so because of the extensive capabilities of the platform as well as convenient access for the research team provided by Brigham Young University.

While a survey of the general population was considered, several reasons deterred the team from doing so and led to a survey for UDOT employees. Surveys of the general population are expensive, time intensive, and often have low response rates. In addition, many ITS devices, such as RWIS, are often invisible to the public eye, which makes it difficult to ascertain their opinions on the devices. A survey of drivers' responses to VMS messages was also considered but was disregarded due to possible driver response bias when asked how they responded, as well as the associated challenges of collecting a random sample. Ultimately, the TAC recommended a survey of UDOT employees. Through UDOT management, it was possible to distribute the survey to all UDOT employees, with the intent to collect a large enough sample size to justify recommendations to UDOT.

The general layout of the survey included five sections: general employee information, traffic camera use, RWIS use, VMS use, and general comments. For the device-specific sections, subsections regarding UDOT uses of the device, personal uses, and lack of use were developed. Multiple choice, rank choice, and free-response questions were all included to provide a variety of ways for respondents to express their feedback. In total, 77 questions were developed for the survey. However, because of the dynamic nature of the survey, some respondents did not view questions that were not applicable to them. All survey materials, including survey layout and raw response data, were provided to UDOT in a shared folder at the conclusion of the survey administration. Any inquiries into the survey structure or results should be directed to the UDOT ITS Division.

Routing logic was included throughout the survey to tailor the questions to the participants' experience with ITS devices. For example, if a participant indicated that they did not use VMS for personal or UDOT-related purposes, they would be rerouted to a set of questions asking them why they do not use VMS, and for what theoretical purposes VMS could be useful to them if such information was made available. If a particular respondent indicated that they used each device for both personal and work uses, they would see the maximum number of questions (65 questions), except for those questions directed toward respondents that did not use the particular device. However, if the participant indicated that they did not use any of these devices for any purposes, then they would be asked the minimum number of questions (25 questions).

To promote higher response rates, some questions were marked as optional. These included most questions with a free-response option and questions that only those who did not use a specific device would see. Examples of these questions were, "How do you use Traffic Cameras in your work at UDOT?" "Why do you not use RWIS data?" and "How could VMS be useful to you?"

3.5.2 Survey Distribution

Prior to distribution, the survey was provided to UDOT employees who served on the TAC. Their comments and thorough testing of the survey provided invaluable calibration and correction to the survey. Based on their comments, the survey was developed to be applicable to the majority of UDOT employees, but not to overload employees.

To avoid unbiased results, no incentives, besides that results would be reviewed and recommendations made to UDOT, were provided to potential survey respondents. No identifying information was collected on participants so the results would be anonymous, unless the participant wished to include their email in a free-response box for future comments. Such inclusions of data were not requested.

The survey was initially distributed via email on November 8, 2022 and closed on January 8, 2023. Two reminder emails were sent to remind employees of the survey on November 17, 2022 and December 1, 2022. The final reminder email stated that the survey would be closed on December 2, 2022, but to allow for more responses, it was left open until January 8, 2023.

3.6 Summary

The purpose of this chapter was to explain the methodology for each of the three parts of this research. An ITS device inventory and road segment classification database were created to establish an up-to-date inventory on traffic cameras, VMS, and RWIS stations in the state. Traffic flow data was collected for the diversion rates analysis, and four crash selection criteria were developed to aid in selecting appropriate crashes. A total of 8 crashes between March and August of 2018 and 2022 were selected for data analysis with a total of 650 flow and speed observations. A mixed effects model controlling for whether the VMS was active and the ratio of speeds on the crash compared to control day was constructed. For the weather analysis, criteria were set to control for confounding variables. Provo, Sardine, and Weber canyons were selected as the ideal geographic locations for the analysis. Forty-seven VMS messages from the winter months between October 2020 to April 2022 were selected for analysis and over 1.4 million speed and weather observations were compiled. A mixed effects model was also developed for the weather analysis and controlled for various weather and traffic conditions. The ITS attitudes survey was created to measure the usage of, attitudes toward, and potential improvements to UDOT's current ITS device deployment. The survey consisted of three sections pertaining to traffic cameras, VMS, and RWIS, and was built to adapt which questions a respondent would answer depending on their usage of a particular ITS device. The survey consisted of up to 77 possible questions for a respondent to see and was distributed to all UDOT employees. The results of these analyses will be discussed in the next chapter.

4.0 RESULTS

4.1 Overview

The results for this research are explained in this chapter. Mixed effects models were built for the diversion rates analysis and the weather analysis to evaluate the effect of VMS messages for both scenarios. The ITS attitudes survey was created and sent to UDOT employees to measure the usage of, attitudes toward, and potential improvements to UDOT's current ITS device deployment. This chapter will detail the results of each of these analyses. First, the results from the diversion rates analysis mixed effects model will be presented. Second, the results from the weather analysis mixed effects model will be presented. Last, general survey results from each section of the ITS attitudes survey will be reviewed.

4.2 Diversion Rates Analysis

The research team utilized R, a statistical computing and graphics tool, to conduct the diversion rates analysis. The analysis involved running a mixed effects model and visualizing the results in R to understand the effect of VMS on freeway diversions during incidents. The results of the mixed effects model as well as results that verify the validity of the model are discussed in the following subsections.

4.2.1 Mixed Effects Model Results

The results of the mixed effects model discussed in section 3.3.4 are summarized in this section. Due to the model chosen for this analysis, two key characteristics of the model are crucial to be aware of before properly understanding the findings.

The first characteristic is that the model includes an interaction between the "VMS" and the "SR_{adj}" variables. This interaction term measures how the effect of "VMS" on "DR," the ratio of diversion rates, changes as a function of "SR," the speed ratio. In addition, the inclusion of the interaction term changes how the estimates for "VMS" and "SR" are interpreted. Figure 4.1 provides a visualization of this change in interpretation for the "VMS" variable. In this figure, two lines are presented representing the predicted values of 100 sampled “SR” data points with the same “RCD” value and an indicator variable for if “VMS” was TRUE or FALSE. As a note, the “RCD” value assigned was the median value of the “RCD” of “0.0113.” As shown in the figure, when a VMS is activated, the predicted “DR” value is higher, indicating that the effect on “DR” is greater than if the VMS is not activated. This trend is accentuated as “SR” decreases, showing that as speeds on the crash day decrease in relation to speeds on the control day, the effect of the VMS being activated increases. To measure the size of the effect, the difference in the y-value of the two lines is calculated as the estimate for “VMS.” With the inclusion of the interaction term, this estimate is by default taken when “SR” is equal to “0,” but this is impractical for this analysis as that is never the case. To provide a practical estimate, a shift in the “SR” data points was implemented.

The second characteristic is a shift in the “SR” data points to create a meaningful estimate for “VMS.” As described, the default estimate for “VMS” is taken when “SR” is equal to “0,” which is not possible. The shift was done by subtracting the median “SR” value from each “SR” data point. This change ensures that the estimate for “VMS” is taken at the median “SR” value instead of when “SR” is equal to 0. While this change shifts the “SR” data points, it does not affect any of the other estimates included in the model. In Figure 4.1, a black line is included at the median point of the “SR” data, which is “0.987,” to indicate where the estimate for “VMS” is taken.

With the two key characteristics of the model acknowledged, the findings of the mixed effects model are presented in Table 4.1. The most important findings from this table are contained within the “Estimates” column for the three independent variables and the interaction term.

The first independent variable in the table is “RCD.” This variable was included as a modeling convenience to ensure that the model would not create spurious correlations from a ratio being included as the dependent variable. The estimate for “RCD” is low at 0.03, which verifies that the model is stable and thus is appropriate to model the ratio of the diversion rates directly.

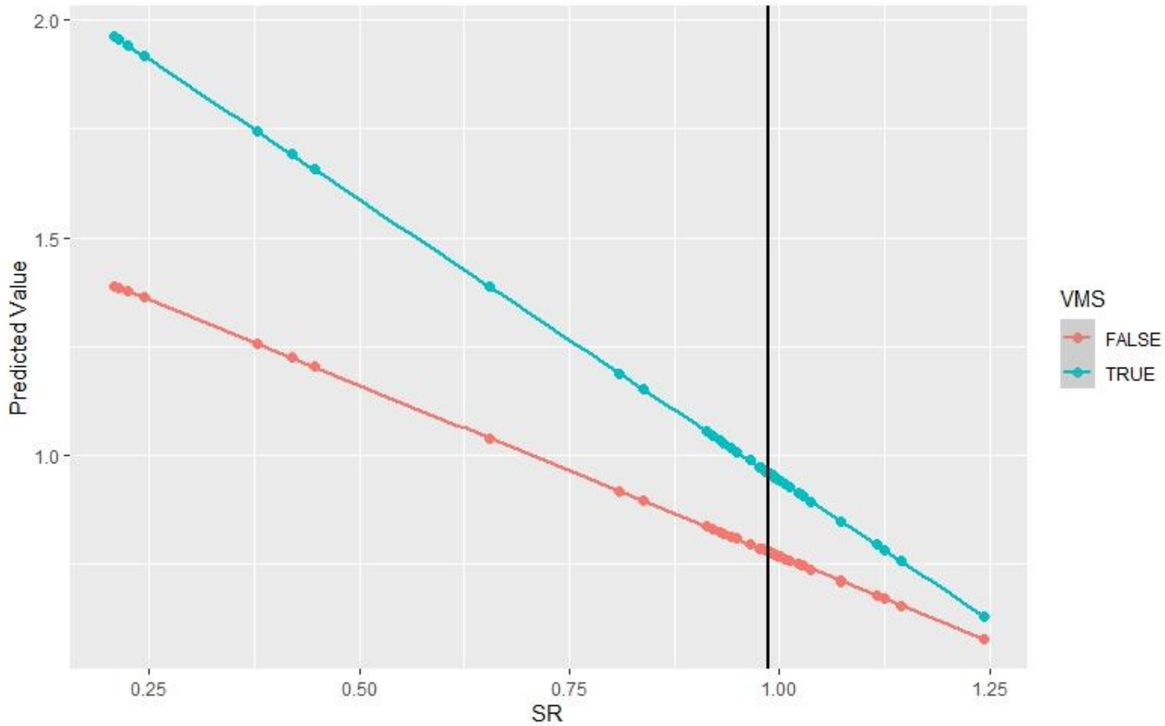


Figure 4.1: Predicted value of 100 sample data points if "VMS" equals TRUE and FALSE.

Table 4.1: Diversion Rates Mixed Effects Model Results

	Diversion Rate Model		
Predictors	*Estimates*	*CI*	*p*
(Intercept)	0.78	0.58 – 0.97	**<0.001**
RCD	0.03	0.02 – 0.04	**<0.001**
VMS	0.18	0.12 – 0.24	**<0.001**
SR_{adj}	-0.78	-0.99 – -0.58	**<0.001**
VMS*SR_{adj}	-0.50	-0.72 – -0.29	**<0.001**
Random Effects			
σ^2	0.13		
$\tau_{00\ Crash:Mramp}$	0.04		
$\tau_{00\ Crash}$	0.05		
ICC	0.42		
N_{Crash}	8		
N_{Mramp}	31		
Observations	624		
Marginal R^2/Conditional R^2	0.455/0.681		

Of particular interest to this research is the findings from the second independent variable "VMS." This variable is a binary variable indicating whether the VMS was active or inactive during the flow observation. The estimate for this variable is 0.18, indicating that the activation of a VMS was associated with an approximate increase in diversion rates by 18 percent. The 95 percent confidence interval bounds for this effect range from 12 percent to 24 percent and importantly does not include "0," meaning that the VMS effect is significant.

The third independent variable is "SR_{adj}." This variable is defined as the ratio of the crash day mainline freeway speeds to the control day mainline freeway speeds. It is denoted as an adjusted "SR" because the median of "SR" was subtracted from each "SR" data point to find the estimate at the median instead of when "SR" is equal to "0." It is of note that the estimate is negative, meaning that as speeds decrease, diversion rates increase. Important to reiterate is that this variable estimates the effect of the speed ratio on the diversion rates ratio, so a value of "-0.78" indicates that an approximate decrease in speeds by 10 percent indicates an increase in diversion rates by approximately 7.8 percent. It is important to note, however, that these findings are generalized trends across all the data analyzed and are not able to be applied to one instance of a crash that exhibits these exact trends.

The fourth estimate is that of the interaction term, "$VMS*SR_{adj}$." The estimate of the interaction term describes, as previously mentioned, how the effect of "VMS" on "DR," the ratio of diversion rates, changes as a function of "SR_{adj}," the speed ratio. The estimate for the interaction is negative and in conjunction with Figure 4.1, this estimate shows that as the speeds on the crash day decrease in relation to speeds on the control day, the effect of "VMS" on "DR" increases. With an estimate of "-0.50," this means that the effect of the activation of a VMS on the ratio of diversion rates decreases by "0.05" when "SR_{adj}" increases by "0.1." This interaction is important to note because not including it could potentially inflate the supposed influence that the activation of VMS have on diversion rates. As seen in the results of this model, the activation of VMS does influence the ratio of diversion rates, but the inclusion of the interaction term clarifies exactly how much of an effect VMS have if the speeds on the crash day were the same as the speeds on the control day.

4.2.2 Mixed Effects Model Verification

The research team wanted to know if diversion rates increased at offramps that were closer to the crash than at offramps further upstream. A variable, "Vupstream," which was listed in section 3.3.4, had been created to list the position upstream of an offramp relative to the crash. If an offramp had a "Vupstream" value of "2," that meant that it was the second offramp upstream of the crash. This variable was used to measure the random effects of each crash and offramp in relation to each other. Random effects measure the unobservable and unmeasurable variability within the data that cannot be explained using the predictor variables included in the mixed effects model. Figure 4.2 shows the random effects for each offramp within each crash and a single connected line in the figure represent the offramps associated with a particular crash. Note that the x-axis is reversed to represent the location closest to the crash on the right of the figure. If the trend of increased diversion rates at offramps closer to the crash was present in the data, there would be a clear upward trend as the offramps got closer to the crash. While that may be the case to some degree, the correlation is not strong enough to warrant this finding. A more crucial finding from this figure is that the random effects for each crash are unique. To the extent that any two crashes share a pattern, it seems that as a whole, they seem to have a relatively constant random effect across all offramps.

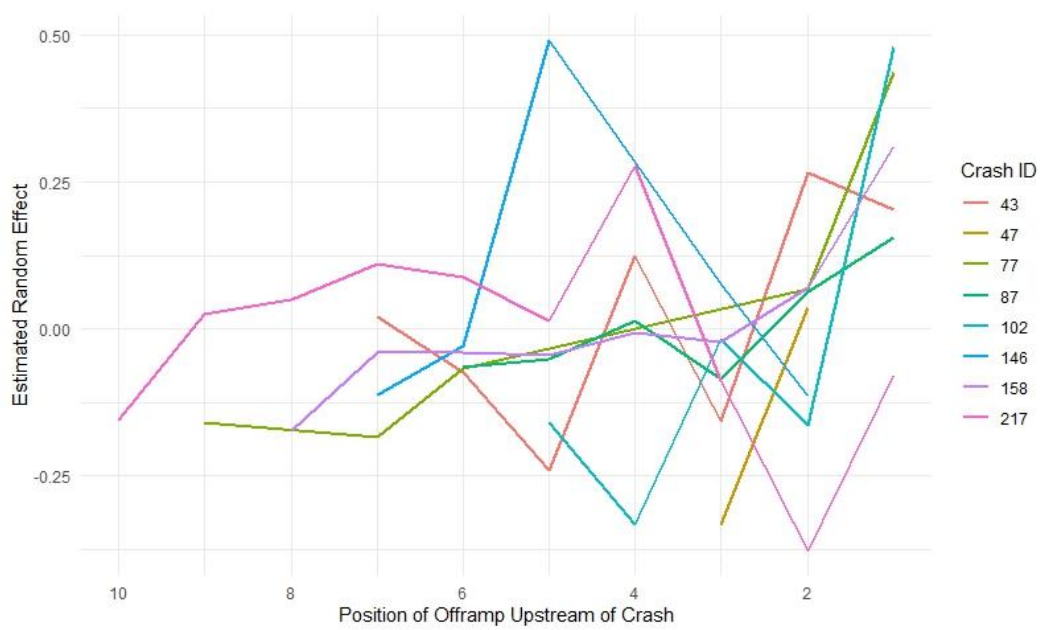


Figure 4.2: Random effects of each crash as offramps get closer to the crash.

Another finding from the model results comes from the residuals. Figure 4.3 displays a histogram of the residuals calculated in the model. A residual is the difference between the observed value and the predicted value in a linear regression. If a linear regression is a good fit for the data it is modeling, more observations will have smaller residuals and fewer observations will have larger residuals, which will provide a normally distributed histogram of residuals that is centered around 0. For the residuals histogram of the diversion rates data, the mean is centered around "0" and the distribution is approximately normal, indicating that the model selected does a good job at fitting the data.

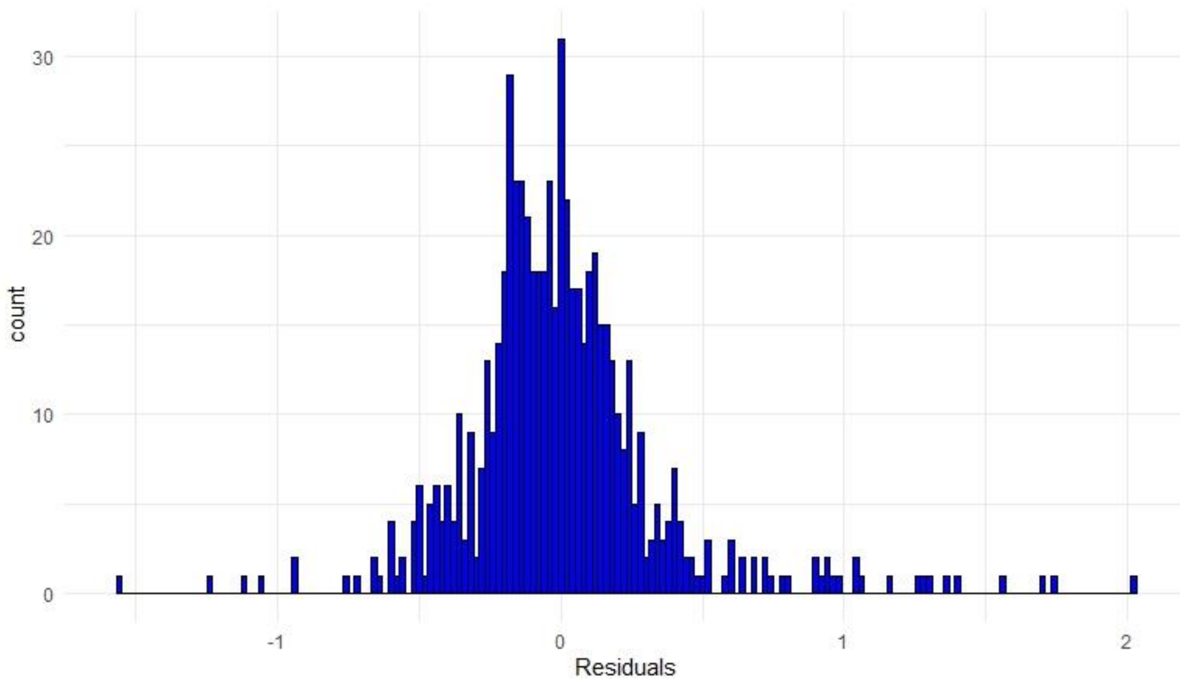


Figure 4.3: Histogram of residuals for the mixed effects model.

Before the model described in section 3.3.4 was chosen, additional models were built and compared. Table 4.2 shows model results from three additional models and the selected model to show a results comparison. Models 1 and 2 were built with the ratio of crash day offramp flow to control offramp flow as the dependent variable while Models 3, 4, and 5 had the ratio of crash day diversion rate to control day diversion rate as the dependent variable. Model 2 includes "RCD1," or the reciprocal of the control offramp flow and Models 4 and 5 include "RCD," the reciprocal of the control diversion rate as predictors to measure the stability of the model, as discussed in section 3.3.4. Overall, the results appeared to be similar for all four models. While the intercepts varied slightly, the general trends for the "VMS" and "SR" variables were consistent across all models, with none of the 95 percent confidence intervals containing "0." Ultimately, a model needed to be chosen for analysis. Because Models 1 and 2 had a different dependent variable than Models 3, 4, and 5, we could not compare metrics such as AIC, BIC, and RMSE across all models, but we could compare them across models with the same dependent variables. In general, a lower AIC, BIC, and RMSE value indicate a model with lower error, so Models 2 and 5 would be preferred based on these criteria. Of these two models, Model 5 was mainly considered, as it involved a ratio of diversion rates and not just a ratio of offramp

Table 4.2: Diversion Rates Models Comparison

	Model				
	(1)	**(2)**	**(3)**	**(4)**	**(5)**
(Intercept)	1.077	1.037	2.178	1.937	0.778
	(0.055)	(0.058)	(0.094)	(0.121)	(0.099)
VMS	0.146	0.154	0.195	0.202	0.181
	(0.023)	(0.023)	(0.031)	(0.031)	(0.031)
SR	-0.104	-0.102	-1.189	-1.175	
	(0.045)	(0.045)	(0.062)	(0.061)	
RCD1		2.035			
		(0.561)			
RCD				0.030	0.030
				(0.006)	(0.006)
SR_{adj}					-0.784
					(0.103)
VMS*SR_{adj}					-0.504
					(0.109)
SD (intercept Crash:Mramp)	0.168	0.172	0.228	0.224	0.209
SD (intercept Crash)	0.036	0.052	0.162	0.229	0.221
SD (observations)	0.272	0.269	0.372	0.365	0.360
Num.Obs.	624	624	624	624	624
R_2 Marg.	0.064	0.085	0.448	0.437	0.455
R_2 Cond.	0.331	0.367	0.648	0.683	0.681
AIC	259.0	247.5	652.3	641.5	625.2
BIC	285.6	278.5	678.9	672.6	660.7
ICC	0.3	0.3	0.4	0.4	0.4
RMSE	0.26	0.26	0.36	0.35	0.35

flows and included the “RCD” variable with a fairly low estimate. Model 5 also included the interaction of the “VMS” and “SR” variables, which was considered important to include to properly measure the effect of “VMS” on “DR.” Ultimately for these reasons, Model 5 was chosen for the analysis.

4.3 Weather Analysis

The research team utilized R, a statistical computing and graphics tool, to conduct the weather analysis. The analysis involved running a mixed effects model and visualizing the results in R to understand the effect of VMS activation on vehicle speeds during various weather scenarios. The results of the mixed effects model as well as results that verify the validity of the model are discussed in the following subsections.

4.3.1 Mixed Effects Model Results

The results of the mixed effects model discussed in section 3.4.6 are presented in Table 4.3. As with the diversion rates model, the key findings are in the estimates column of the results. Note that these values are in units of miles per hour (mph) and are not ratios. Interpretation should instead be that for every 1 unit increase of the independent variable, speeds increase or decrease by the amount estimated. For example, the “MilePost Diff,” or milepost difference, estimates of 0.015 should be interpreted as for every 1.0 mile away from the VMS that the speed observation was taken, drivers increase speeds by 0.015 mph. This differs for the PHF as it is interpreted that for every 0.2 increase in PHF, drivers increase speeds by approximately 0.5 mph. Road grip is interpreted similarly, as for every 0.1 increase in road grip, speeds increase by approximately 3.3 mph. In contrast, the hourly flow is interpreted as for every increase in 500 vehicles per hour (vph), driver speeds increase by approximately 2.9 mph.

It is important to note that as previously described in Table 3.2, some variables are categorical and are compared to each other across the denoted category. These variables are indicated in Table 4.3 with “[]” to indicate the state being compared. For example, “SignPhase [On]” indicates that driver speeds increase by approximately 0.2 mph when a VMS is turned “On” as compared to the “Off” state.

Variables for road grip, PHF, and hourly flows were adjusted to provide comparable effects. Prior to running the model, the road grip and PHF values were multiplied by 5 and 10 respectively while the hourly flow values were divided by 500. This had no other effects on the model besides changing the Estimates and confidence intervals for the specific variables. This allows for a direct comparison of effects. Without these transformations, the effect of hourly flow in increments of 1 vph was 0.007 mph. At face value this was a minor impact, but with the transformation of data, greater understanding of the model was available. Similar considerations were present with the road grip and PHF effects.

Table 4.3: Weather Mixed Effects Model Results

	Weather Speed Model		
Predictors	*Estimates*	*CI*	*p*
(Intercept)	28.942	26.07 – 31.82	**<0.001**
SignPhase [On]	0.228	0.17 – 0.29	**<0.001**
TimeState [AM]	-0.311	-0.37 – -0.26	**<0.001**
TimeState [PM]	-2.393	-2.42 – -2.36	**<0.001**
MilePost Diff	0.015	0.01 – 0.02	**<0.001**
PHF (per 0.2)	0.502	0.47 – 0.54	**<0.001**
Hourly Flow (per 500 vph)	2.894	2.85 – 2.94	**<0.001**
Road grip (per 0.1)	3.344	3.32 – 3.37	**<0.001**
Visibility [Light Precip]	-1.613	-1.65 – -1.57	**<0.001**
Visibility [Mod. Precip]	-2.669	-2.74 – -2.6	**<0.001**
Visibility [Heavy Precip]	-5.104	-5.2 – -5.01	**<0.001**
Random Effects			
σ^2	81.4		
$\tau_{00\ Crash:Mramp}$	8.97		
$\tau_{00\ Crash}$	12.84		
ICC	0.21		
N_{Crash}	47		
N_{Mramp}	7		
Observations	1426105		
Marginal R^2/Conditional R^2	0.190/0.361		

There were 1.4 million observations in the dataset, and as a natural consequence, all interactions were highly "statistically significant." In this case, practical significance and statistical significance may not be the same due to the large number of observations. For example, although the increase in speeds of approximately 0.2 mph was statistically significant, it was unlikely that such a minor increase in speeds holds practical significance. It was possible that the general trends shown in these effects may be accurate, but the confidence in these rates are reduced due to the large number of data points. A resampling model could provide greater clarity for these interactions but was forgone for the purposes of this research.

Figure 4.4 plots the fixed effects from the mixed effects model. With the use of the transformations for road grip, PHF, and hourly flow, such a plot shows the relative effects of the different independent variables. The most significant effects were the road grip and hourly flow, even with the transformations. The milepost difference had a minimal effect on driver behavior, at a speed increase of 0.015 mph per increase in 1 mile traveled from the sign. This finding seems to suggest that the influence of the VMS message does not change as the driver travels away from the VMS.

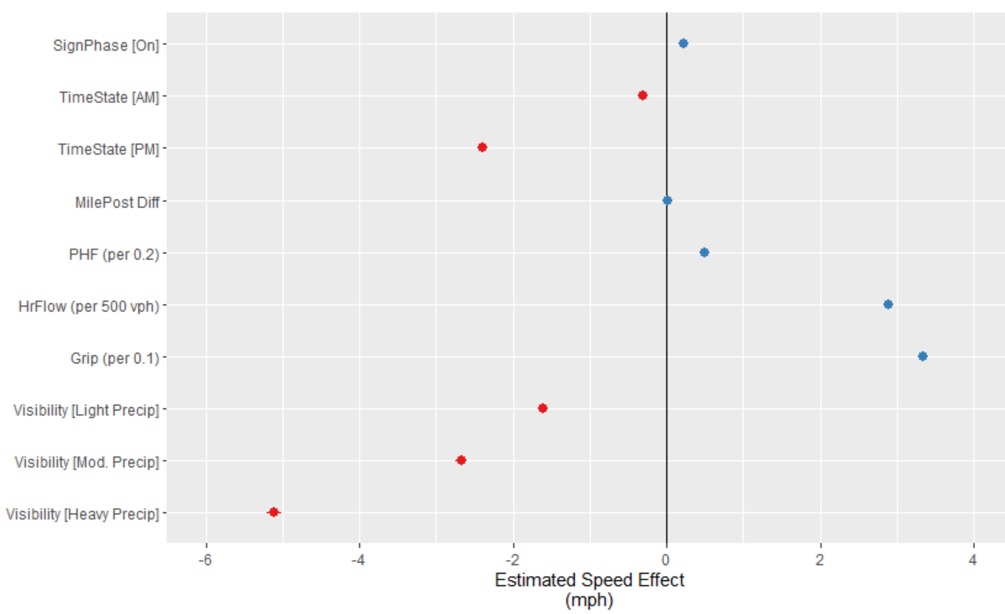


Figure 4.4: Speed fixed effects.

The effects of precipitation were consistent with conventional understanding that as precipitation increased, speeds decreased. A significant increase in speed reduction was present from heavy to moderate precipitation states. This could indicate that drivers responded consistently to a reduction in visibility, rather than the presence of precipitation. As road grip levels increased, so did speeds, which indicated that drivers responded to either how the vehicle responded to road conditions or that drivers were able to predict road grip conditions by external weather conditions, including air temperature and previous precipitation. However, it was challenging to confirm one hypothesis or another due to the limited research on this behavior.

The time state fixed effects results indicate that drivers reduced speeds during AM and PM peak periods. This suggests that traffic conditions during these peak periods differed significantly from midday traffic conditions. However, in these canyons, PHF and hourly flows also differ widely from day to day depending on weather conditions. In major canyons, including Provo and Sardine, these results likely hold true, but it is difficult to confirm this effect in Weber Canyon due to the limited data available and the lower traffic flows.

Figure 4.5 plots the random effects for each individual VMS. Corresponding VMS IDs were noted previously in Figure 3.7. Based on these random effects, the activation of VMS in Provo and Weber canyons tend to reduce speeds while the activation of VMS in Sardine Canyon tend to increase speeds. This effect also appears to be correlated with the length of the canyon, as Provo and Weber canyons are shorter than Sardine Canyon. However, causation cannot be assumed, and this correlation is observational only.

It is also interesting to note that the confidence intervals for Provo and Weber canyons do include an effect of zero mph. This indicated that it is possible for these VMS to have no effect on driver speeds. However, it is also important to note that out of the 1.4 million observations, Provo and Weber canyons consisted of roughly 30 percent of the observations while Sardine Canyon consisted of roughly 70 percent. The size of the confidence intervals may have been in direct response to the differences in population sizes for the varying VMS. Figure 4.6 further details this data in pairings of VMS and their associated messages. For example, “47:100270” is interpreted as the random effect for VMS message ID 47 and VMS ID 100270 (Weber Canyon).

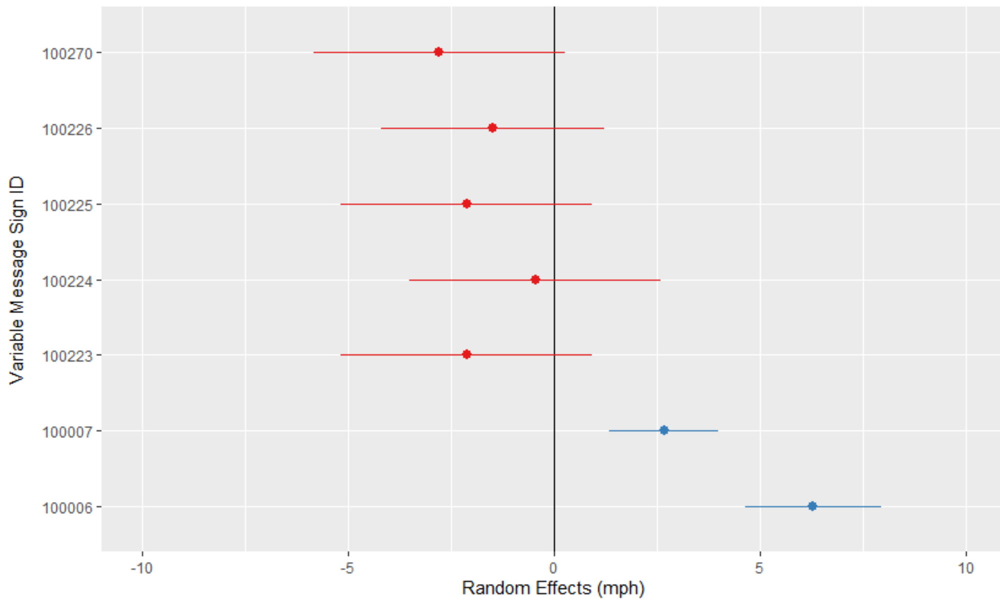


Figure 4.5: Random effects of VMS signs.

Each of the observations for messages in Provo and Weber canyons had about 25,000 observations while each of the observations in Sardine Canyon had on average 32,000 observations with a wide range of situational variability (i.e., time of day, weather characteristics, message phrasing). The results show that there is little consistency between the various messages presented by the same VMS. For example, messages at Weber Canyon (ID 100270) have a message with a strong negative impact, strong positive impact, and almost negligible impact. Similar trends can be found for VMS messages presented in Sardine Canyon. Messages presented in Provo Canyon tended to be more negative in impact, but with such a small sample size, it was difficult to make any meaningful comparisons between canyons.

Tay and De Barros (2010) showed that VMS signs tended to lower extreme speeds and the standard deviation of speeds, while the average speeds were not affected. Summary results for when the VMS was “Off” or “On” are presented in Table 4.4. It was found that a reduction in standard deviations is present in the data, while the median also decreased when the VMS was “On.” However, the mean and almost all other summary statistics increased when the VMS was “On.” Much of the changes to the summary statistics should be treated lightly as it was shown that other included variables had a strong influence on speeds.

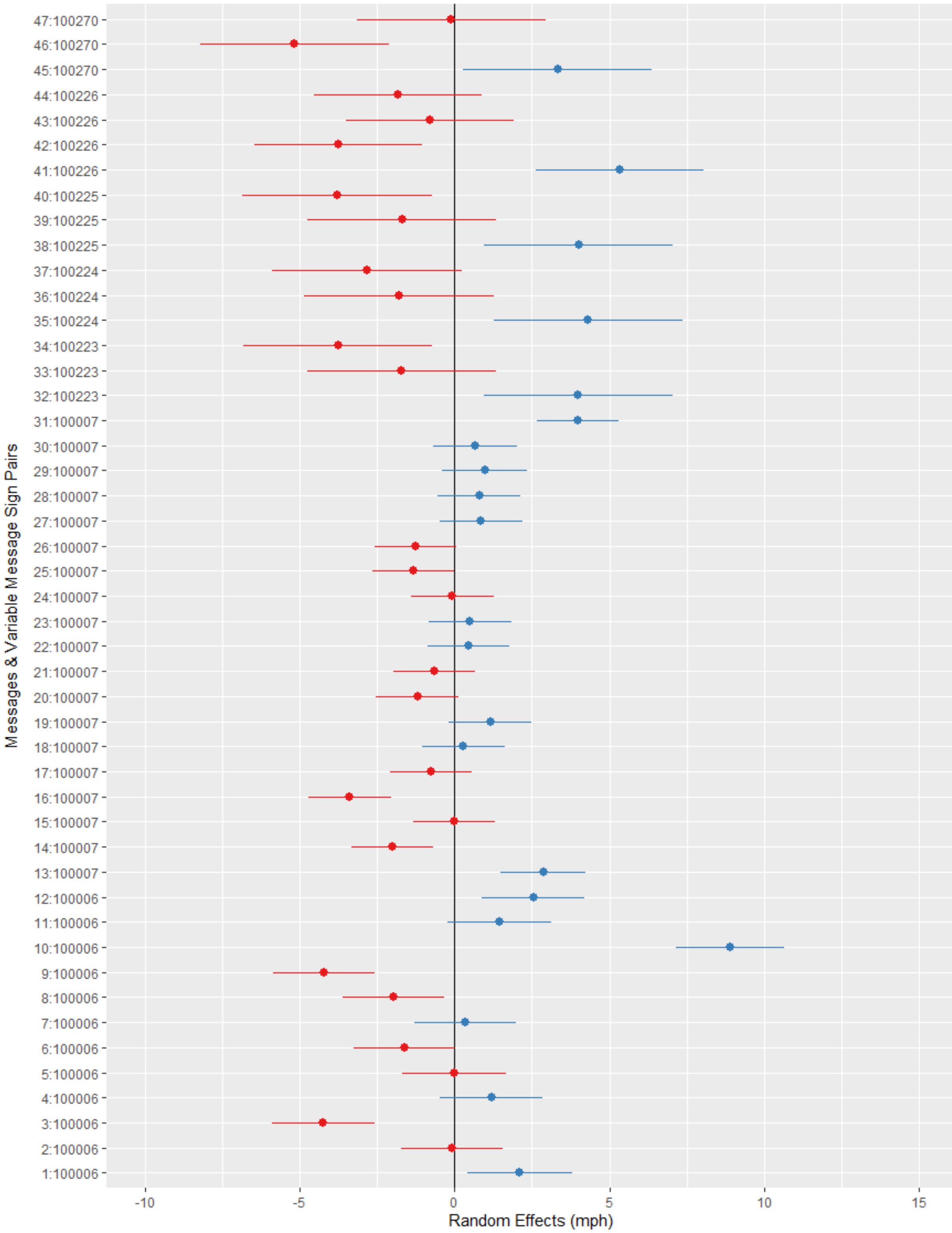


Figure 4.6: Random effects for VMS and message pairings.

In further exploring this point, Figure 4.7 illustrates the speeds observed from the data as box plots for when the VMS was "Off" or "On." There appeared to be a slight increase in speeds when VMS were turned "On," but there was little practical difference between these plots. These plots further illustrated that although all variables were statistically significant influences on driver speeds, the practical significance was likely minimal. As a warning, it should be noted that the number of observations for the "On" and "Off" stages are vastly different, and these observations may be overly simplistic.

Table 4.4: Comparison of Summary Statistics

Data	*Off*	*On*
Minimum	0.391	1.273
1st Quartile	53.453	54.492
Median	61.648	60.02
Mean	59.656	60.702
3rd Quartile	68.152	68.32
Max	101.445	104.856
Standard Deviation	12.383	10.636
Count	147,485	1,278,620

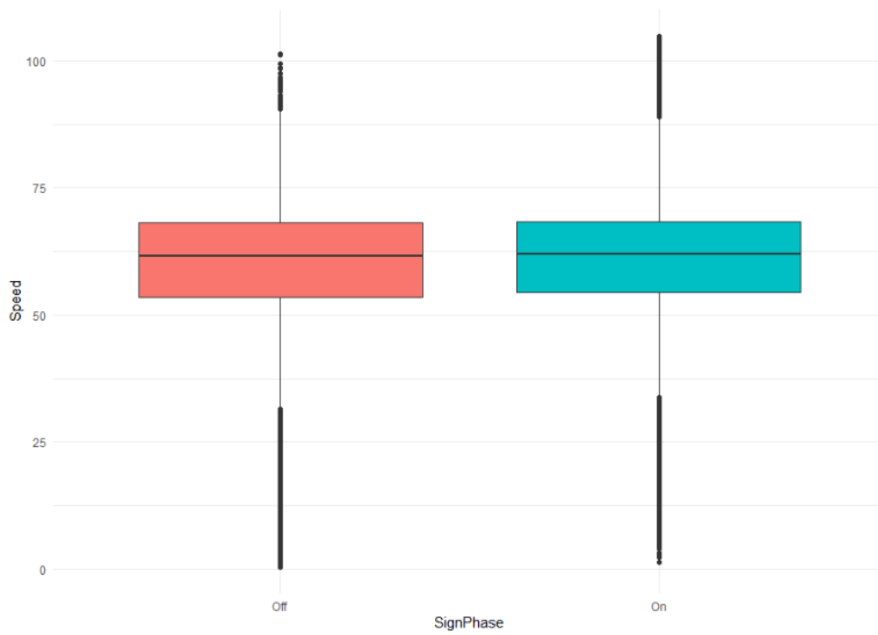


Figure 4.7: Boxplots of speeds under sign phase on and off.

4.3.2 Mixed Effects Model Verification

Additional results from the model were investigated to verify the fit of the model to the data. One such estimator of fit is the distribution of the residuals, as presented in Figure 4.8. As shown, the residuals for the model are centered around "0" and are normally distributed. This shows that the model was generally a good fit for the data. The spread of the data is large, but that is to be expected with the large number of observations.

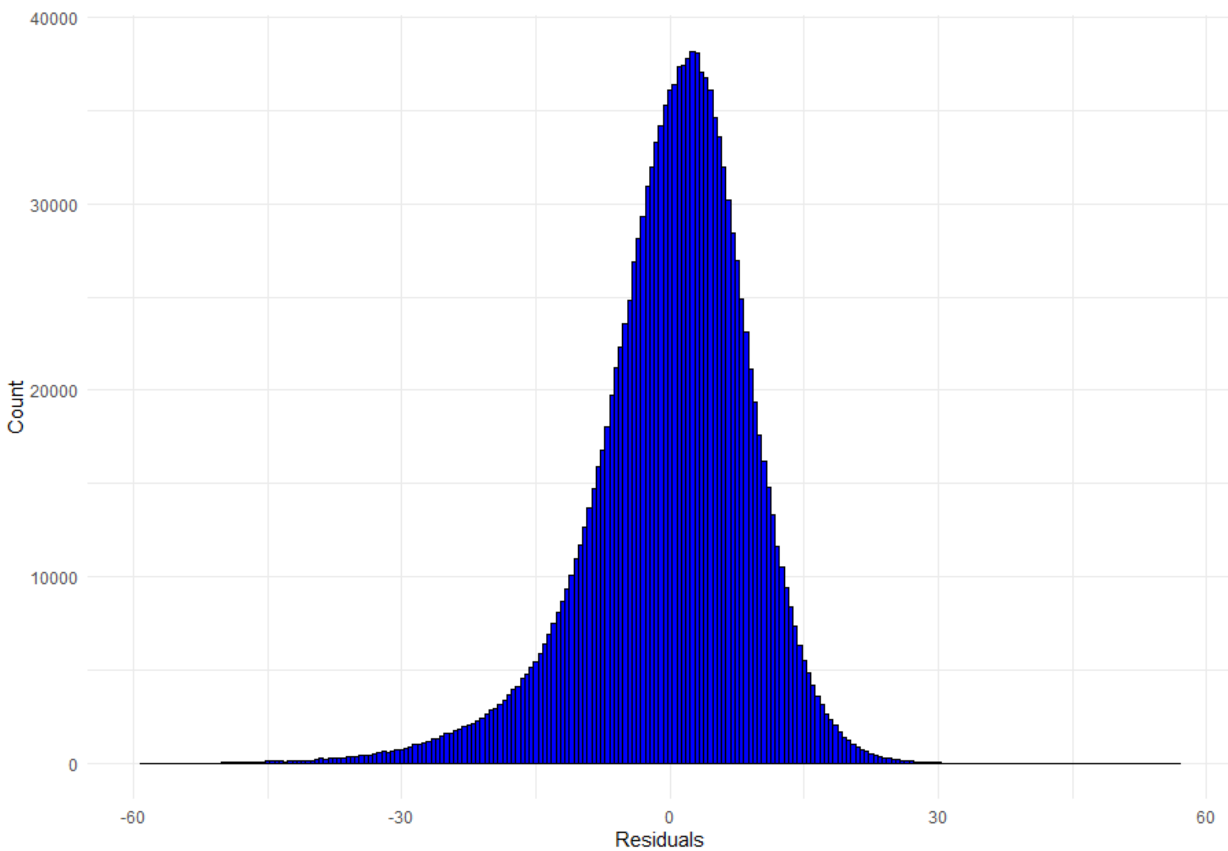


Figure 4.8: Weather model residuals.

To further explore the relationship between road grip factor and vehicle speeds, Figure 4.9 plots the residuals by the road grip factor. If a non-linear correlation was optimal for a variable, such a residual plot would exhibit a non-linear relationship. The results shown in Figure 4.9 vary widely from zero. As road grip increases, the residuals develop a wider spread, correlated to an increase in observations at higher road grip levels. It is possible that road grip may be better fit by a non-linear model, but as shown previously in Figure 3.8, such models do little to better the model fit.

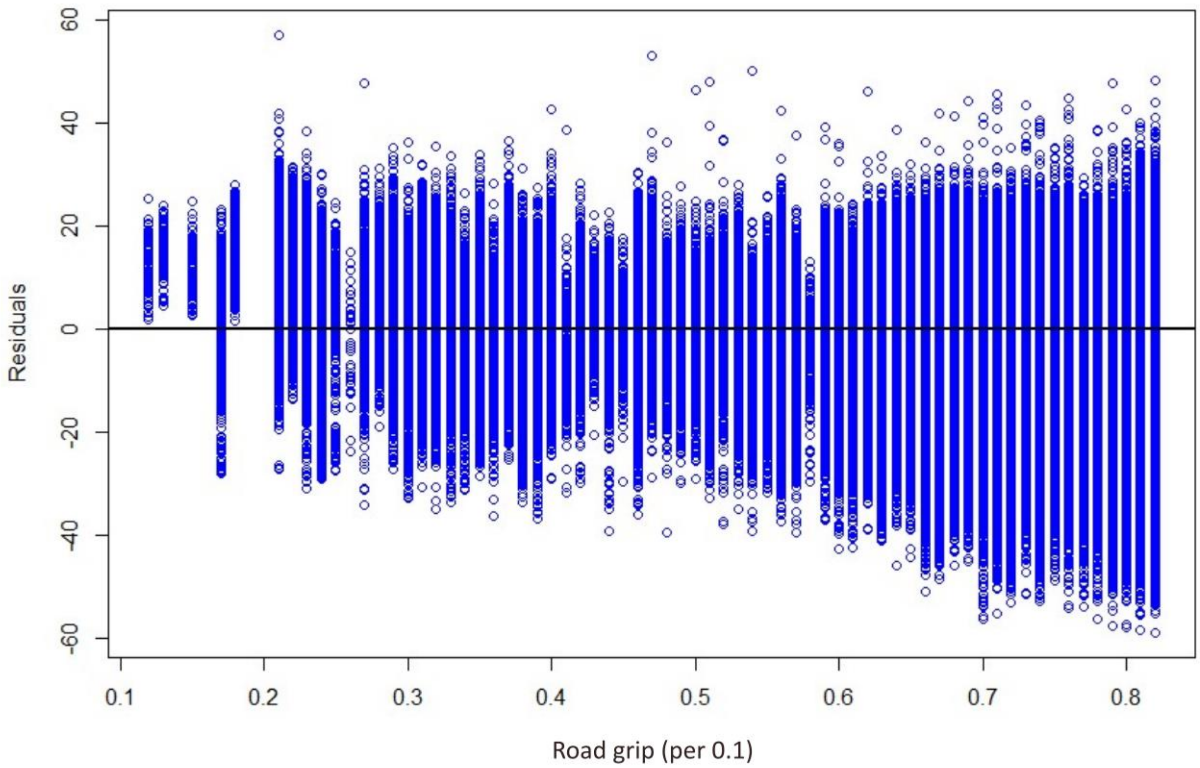


Figure 4.9: Road grip vs residuals.

To further explore the relationship between the milepost difference variable and vehicles speeds, a plot of residuals by milepost difference is illustrated in Figure 4.10. This distribution exhibits a “bell” shape, where residuals are smaller on either side of the spectrum, but larger in the middle. Due to a lack of curvature or abnormal peaks, it is unlikely that a different fit would be better and it is difficult to say if the milepost difference is a reasonable indicator of driver speeds due to a lack of trend and the wide spread in results.

Due to the large number of observations, all relationships between vehicle speed and the independent variables are statistically significant. However, the practical significance of VMS activations in canyons is limited with a measured reduction of speeds of 0.2 mph and with many other more practical influences including road grip and time of day.

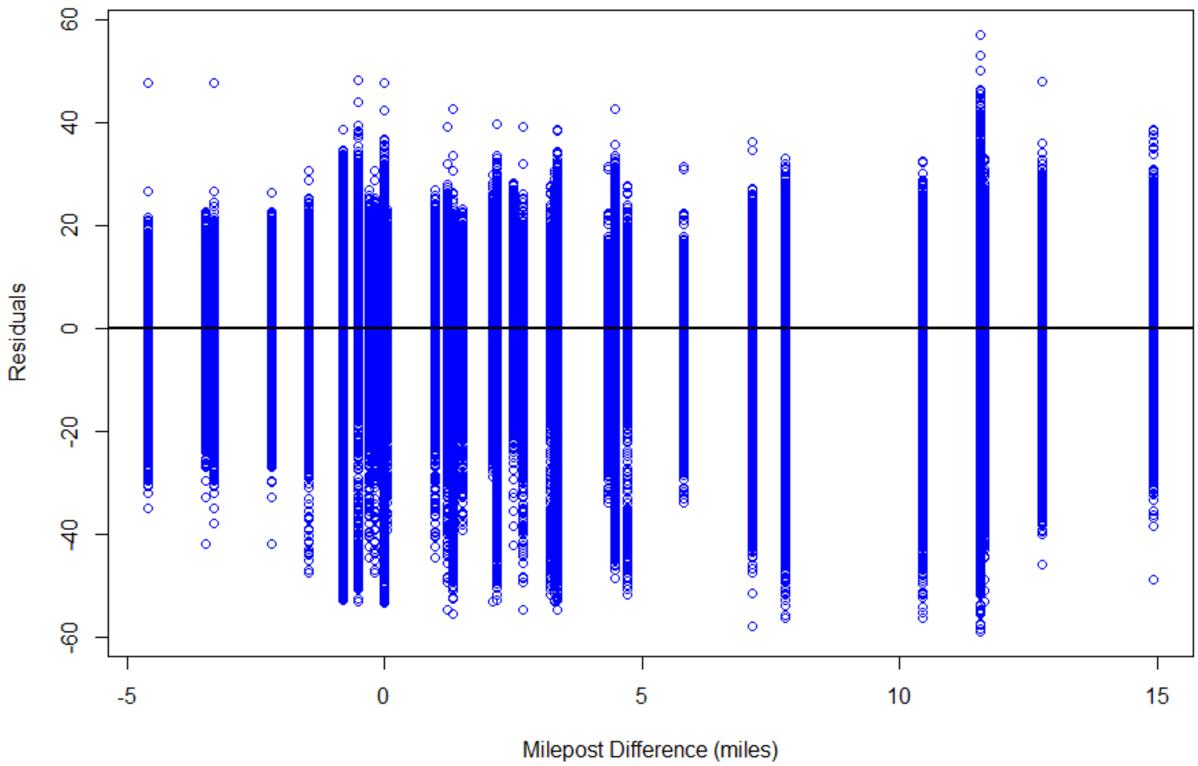


Figure 4.10: Milepost difference vs residuals.

4.4 ITS Attitudes Survey Results

The research team distributed the ITS attitudes survey with the goal of measuring the usage of, attitudes toward, and potential improvements to UDOT's current ITS device deployment. Overall, 435 complete responses were collected, with 186 partial responses as shown in Figure 4.11. Note that all numbers presented in Figures 4.10 to 4.22 are the number of responses unless otherwise indicated, as different amounts of responses were collected for each question. The median response time was slightly over 11 minutes, and with approximately 1,200 UDOT employees, the response rate was over 30 percent. Because the survey was a self-selecting survey, meaning that the choice to take the survey was up to the individual, the results cannot be applied to UDOT as a whole or to certain departments, the results can only be applied to the sample size of respondents.

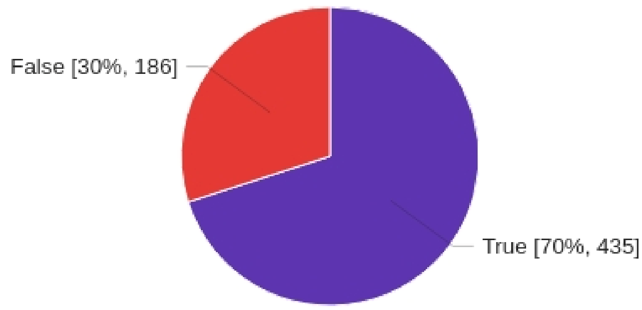


Figure 4.11: Survey completion rates

Five main sections were included in the survey to comprehensively understand the attitudes of UDOT employees toward and usage of various ITS devices. These sections were general employee information, traffic camera use, RWIS use, VMS use, and free response. The free-response section included at the end provided an opportunity for individual comments, but multiple free-response questions throughout the survey were also available for more device-specific feedback. The combined responses from all free-response questions were provided to UDOT in a shared folder at the conclusion of the survey administration. This section reviews the results for the five main sections individually to provide the most relevant findings.

4.4.1 General Employee Information

The largest group of respondents to the survey were from Engineering, but individuals with a variety of roles completed the survey. Respondents from groups other than Engineering included 126 individuals from Maintenance, 88 from Administration, 23 Engineering Technicians, and 135 in various other roles. In the "Other" category, roles such as GIS, Port of Entry, Motor Carrier, Planning, and Environmental were listed.

Many of the respondents were mid to late-career employees with more than 20 years of experience in their profession, as shown in Figure 4.12. When asked for the number of years a respondent had worked in the profession, an upward trend was observed, with more respondents with more experience and fewer respondents with less experience. When participants were asked for the number of years the respondent had worked at UDOT, the same trend was evident, but to less of an extreme.

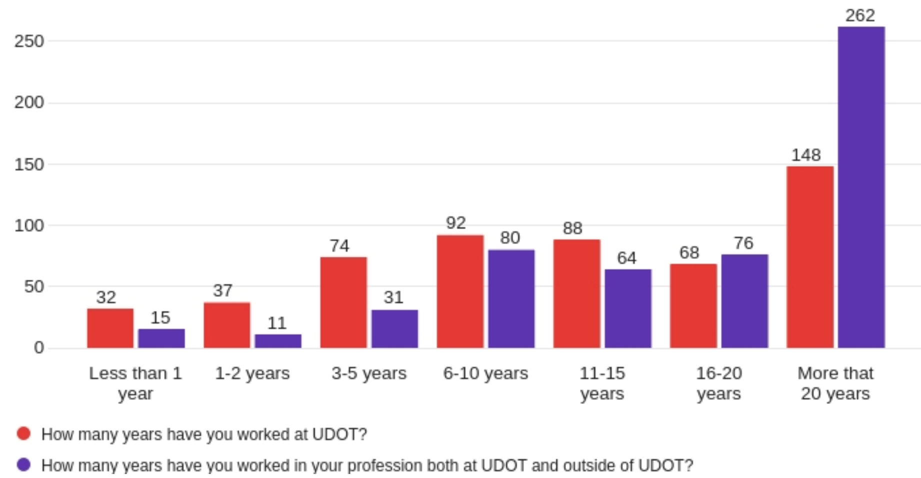


Figure 4.12: Respondent UDOT employment and career duration.

4.4.2 Traffic Cameras

Respondents were asked how much access they have to traffic camera feeds and of 501 respondents, 44 percent have access to a live feed in office, 22 percent have access to a live feed on a personal device, 21 percent can adjust camera angles, and 5 percent can record video as shown in Figure 4.13. The respondents were asked what kinds of access they would like to have to cameras, and the most desired type of access was to a live feed on a personal device (70 percent). Access to a live feed in the office (42 percent) and ability to change camera angles (36 percent) tied for second most desired with approximately an equal number of responses. The least desired was the ability to record video (14 percent).

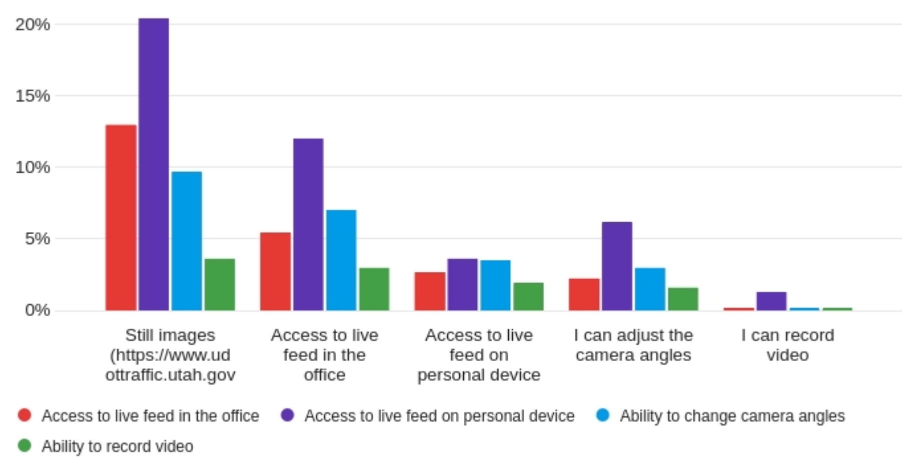


Figure 4.13: Respondents desired access as grouped by current access.

Respondents were asked if they use cameras for work and/or personal use and 67 percent said they use cameras for work and/or personal purposes whereas 22 percent said they only use cameras for personal use. For work purposes, the highest number of respondents indicated that use of traffic cameras in a work setting was for maintenance reasons, followed by live traffic/incident monitoring and work site management. Research/data collection was the least cited and least frequent use of cameras for work purposes, but with 81 out of 340 respondents (24 percent) indicating that they do use cameras for this purpose, it seems to be a useful advantage of the technology, as shown in Figure 4.14. Overall, users felt that traffic cameras were "extremely useful" for the purpose(s) they selected, as shown in Figure 4.15.

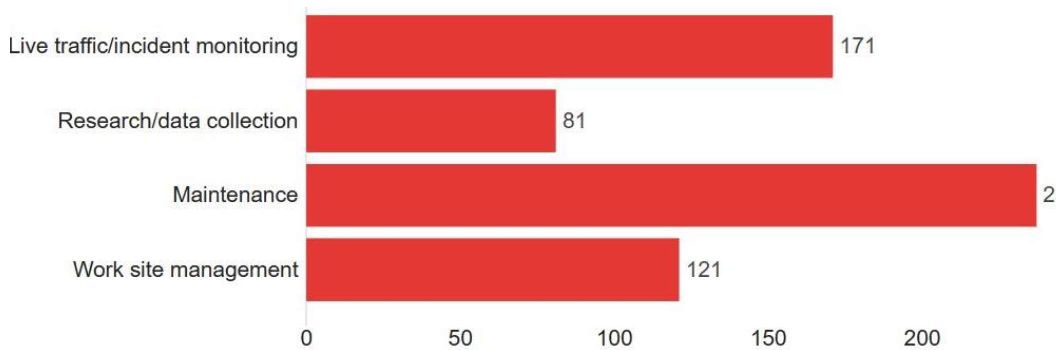


Figure 4.14: UDOT-related uses of traffic cameras.

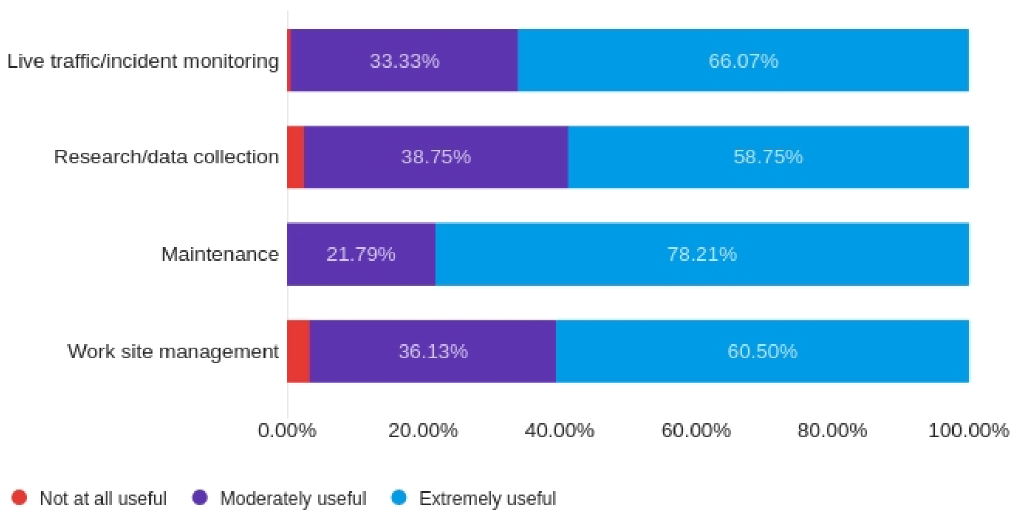


Figure 4.15: Usefulness of traffic cameras for UDOT usage

For personal uses of traffic cameras, 92 percent of respondents said they use it for checking weather conditions, 83 percent use it to check traffic conditions, 60 percent use it for trip planning, and 40 percent use it for checking construction status as shown in Figure 4.16. Over 60 percent of respondents said that traffic cameras are "extremely useful" for checking traffic and weather conditions, and for trip planning and checking construction status, closer to 50 percent of respondents selected "extremely useful" as shown in Figure 4.17.

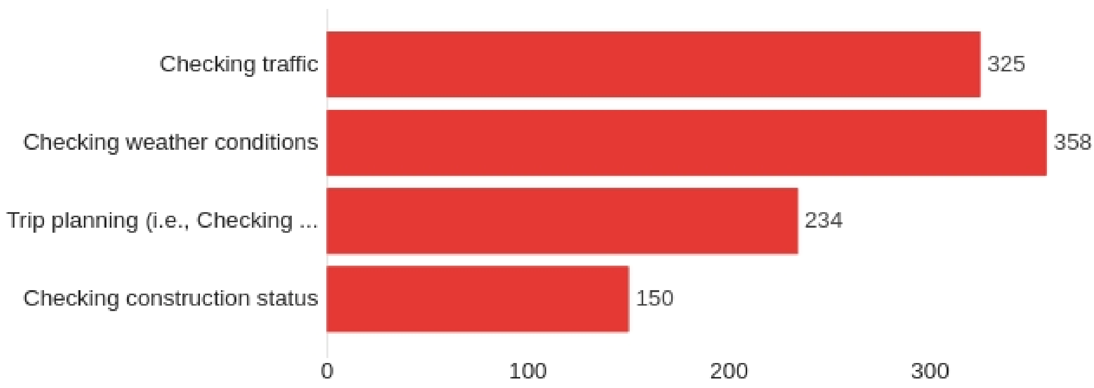


Figure 4.16: Personal use of traffic cameras.

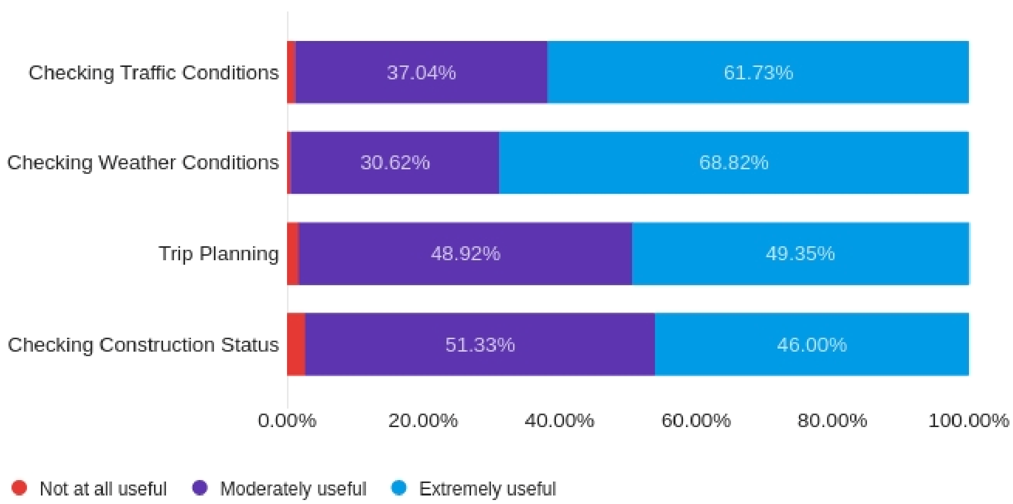


Figure 4.17: Usefulness of traffic cameras for personal use.

4.4.3 RWIS

Respondents were asked how they access RWIS data and as shown in Figure 4.18, the UDOT Traffic Road Weather page was cited as the most used interface of RWIS information, with 321 responses. About a third less, or 117 and 105 respondents, reported using the Statewide Maintenance Forecast page as well as the National Weather Service (NWS) page, respectively, and a tenth less, or 32 respondents, reported usage of the University of Utah's MesoWest page.

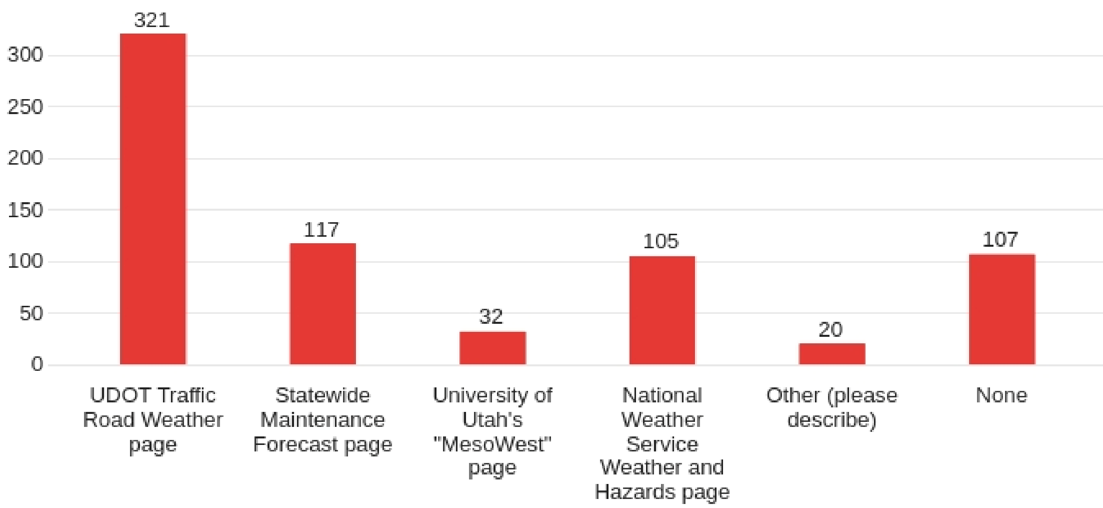


Figure 4.18: Tools for RWIS usage.

Respondents said they use the UDOT and NWS pages slightly more for personal use than for work purposes, while the Statewide Maintenance and MesoWest pages were used more for work purposes than for personal purposes, as shown in Figure 4.19. Winter weather planning and weather tracking were nearly equally cited as the most common uses for RWIS data, followed by route detour planning and public weather alerts. Respondents reported that they use RWIS on the most frequent basis for public weather alerts and least frequently for route detour planning. To a question asking when during the year respondents tend to use RWIS, 324 of 334 respondents (97 percent) said they use it during the Winter/Snow season and 70 respondents (21 percent) reported use during the Summer/Construction season. Nearly 60 percent of all respondents claimed that for the purpose(s) they use RWIS, it is "extremely useful," as shown in Figure 4.20.

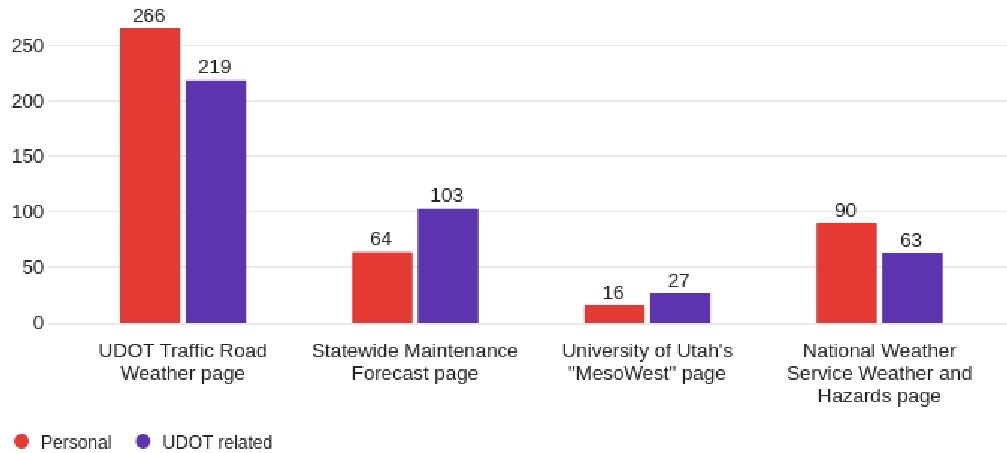


Figure 4.19: Implementation of RWIS tools.

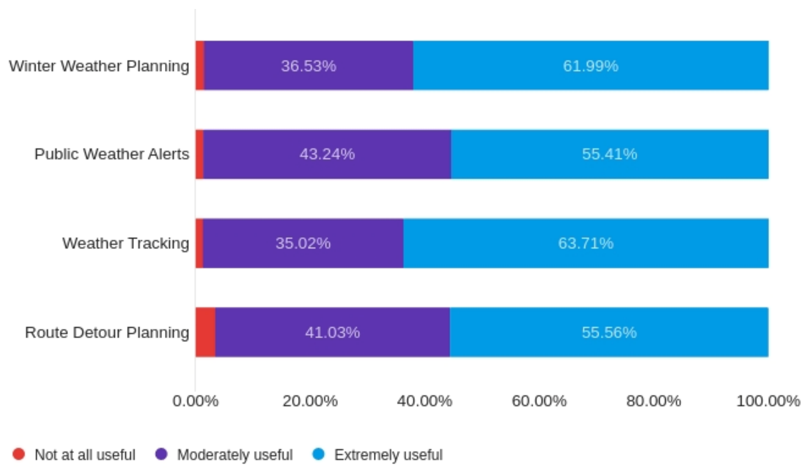


Figure 4.20: Functionality of RWIS uses.

In terms of those who did not use RWIS, out of 108 responses, 40 percent of respondents said it was because RWIS was not applicable to their jobs and 22 percent reported not knowing about RWIS, not knowing it was available to them, or not knowing how to access it.

4.4.4 VMS

The survey asked users about their implementation of VMS devices in UDOT and also gauged opinions on VMS implementation and public response.

In general, 57 percent of respondents said that they use VMS for their work at UDOT and 84 percent of those who said they do not use it for their work indicated that it is either not applicable for their work or did not have an opinion on why they do not use it. Of the possible related uses of VMS, the highest selected use case was Incident Management Progress closely followed by Travel Time Predictions, as shown in Figure 4.21. Additional user responses included uses for Construction, Work Zone, Road Closure, and Special Event messaging. Users of VMS devices for these purposes generally found them to be "moderately" or "extremely useful," as shown in Figure 4.22.

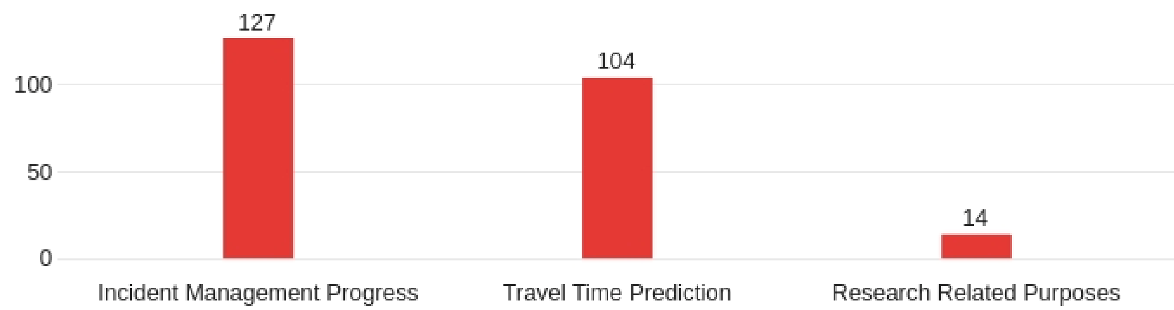


Figure 4.21: UDOT respondent uses of VMS.

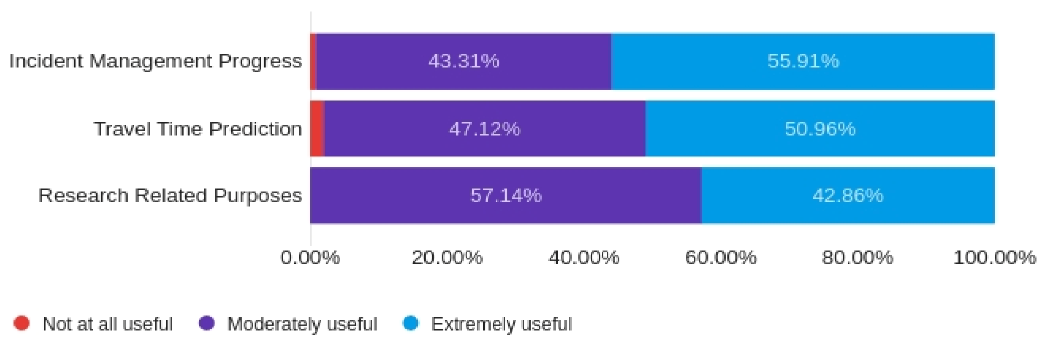
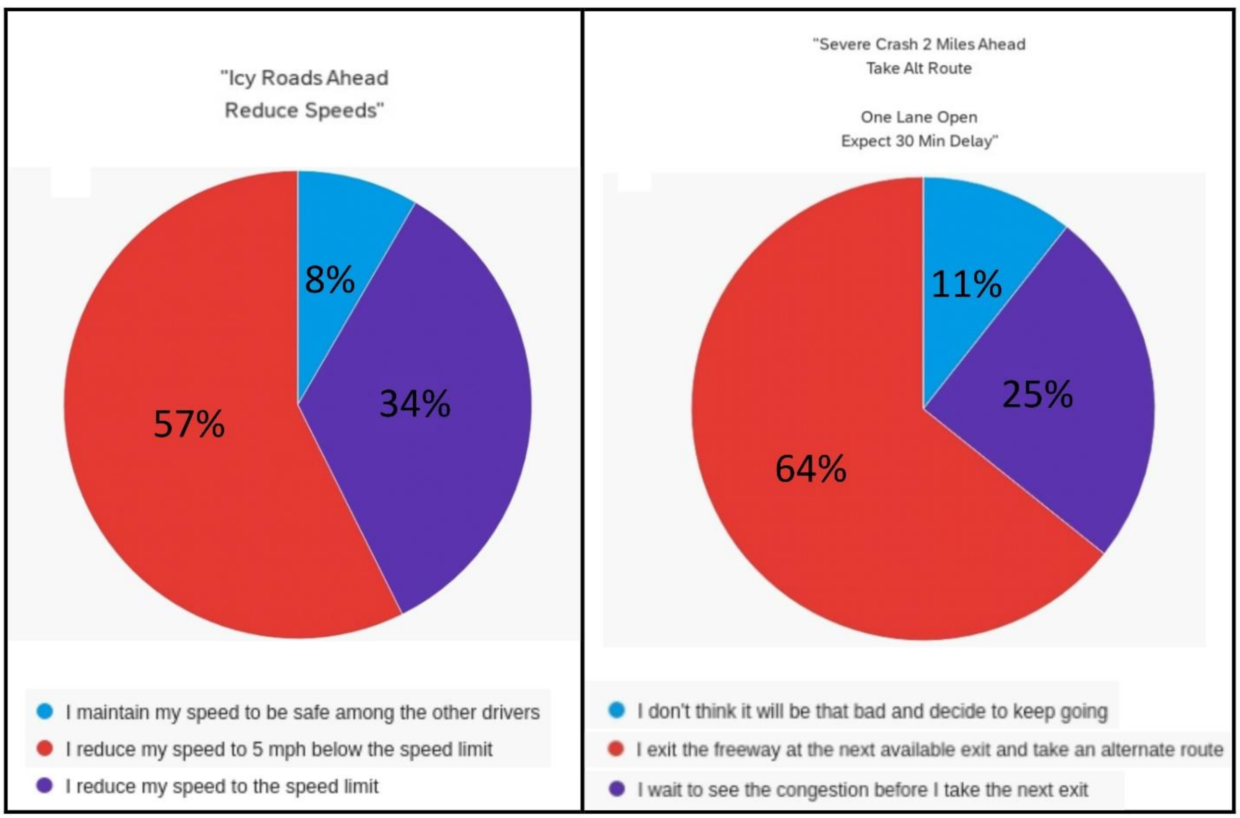


Figure 4.22: Usefulness of VMS of UDOT uses.

In addition to asking about uses of VMS, respondents were asked opinion-based questions to gauge responsiveness and perception of public response to VMS messages. Responsiveness was gauged using scenario response questions and other general questions, while public perception was gauged with opinion-based questions. The three situational questions presented hypothetical messages and conditions under which a VMS message was presented to them while on the freeway and the respondents were asked to choose an action they would take in response to the message. Two of those questions related to a situation a driver may encounter in the diversion rates or weather analysis, and those results are presented here.

In the first question, a message was shown prompting drivers to take an alternate route due to a crash with a 30-minute delay 2 miles downstream. Sixty-four percent of respondents said they would exit the freeway at the next available exit to take an alternate route, 25 percent said they would see the congestion before taking the exit and 11 percent reported that they would not think the congestion would be too bad and would continue driving. In the second question, a message was presented asking drivers to reduce speeds due to ice conditions ahead on a day with light snow and 30°F conditions. Fifty-seven percent responded that they would reduce their speed to 5 mph below the speed limit, 34 percent responded that they would reduce their speed to the speed limit, and 8 percent said they would maintain their speed to be safe among other drivers, as shown in Figure 4.23.



(a) (b)

Figure 4.23: VMS reaction polls for (a) weather-related and (b) crash diversion scenarios.

In addition to these findings, Figure 4.24 shows that 39 percent of respondents said they trust VMS “extremely well” and 59 percent said they trust VMS “moderately well.” Sixty-eight percent of respondents said that they follow VMS messaging most of the time and 30 percent said they follow VMS messaging about half of the time. In contrast, respondents said that they think the traveling public responds to VMS less favorably. Only 8 percent said that they think the public responds “extremely well” to VMS, 70 percent said, “moderately well,” and 23 percent said “not well at all.” When asked to fill in the blank (“VMS messages are …”), 56 percent said that VMS messages are “extremely useful,” while 43 percent said that VMS messages are “moderately useful.” The other 1 percent said that VMS messages are “not at all useful.”

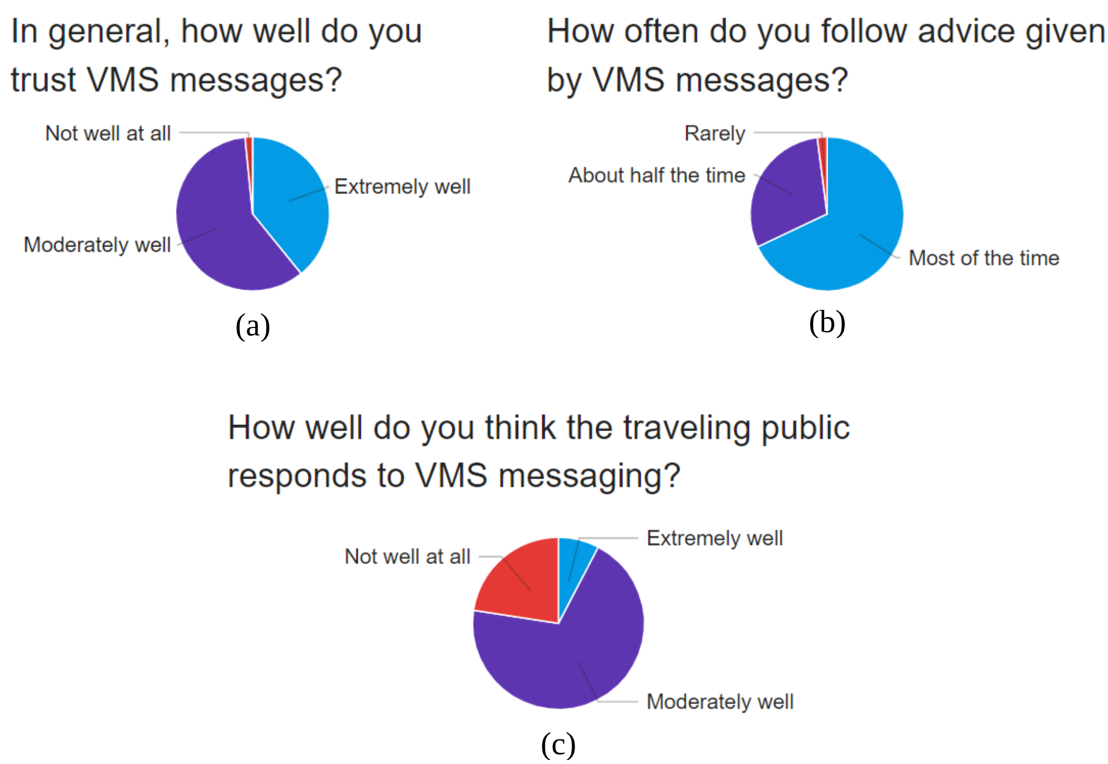


Figure 4.24: Responses and beliefs about VMS impacts.

4.4.5 Free-Response Questions

Throughout the survey, opportunities for free-response answers were provided to respondents. Detailed lists of free-response answers from respondents were provided to UDOT for further review and action. Responses were highly constructive, and respondents engaged with the prompts to provide valuable feedback for UDOT. Most commonly, users requested greater access to data and improvements to existing infrastructure before implementation of new infrastructure.

UDOT employees showed great ingenuity in applying various ITS technologies to their various roles and reported these usages in this section. Traffic cameras were used to estimate snow cover, field observations, testing whether a VMS was working, answering questions from the public, remote viewing of incidents for IMTs, and even for measuring structural performance during wind or storm events. Reported concerns with cameras were that they tended to fail, coverage was spotty, poor visibility during nighttime and storm events, and employees did not have the necessary access to fully utilize the cameras (e.g., live feed, image manipulation).

RWIS and VMS had a more specialized audience for use at UDOT, but various use cases and feedback were provided. For RWIS, reported uses included land and snow slide prediction, checking if local roads had been plowed, and communication with the general public. Suggestions for improvements included better geographic coverage, direct links to RWIS data websites on UDOT computers, addition of flood or fire potential measurements, and improved access to historical data. Unique utilizations of VMS reported in the survey included warning users of animals (cows) on the road, air quality warnings, and warning drivers of damaged roads. Many recommendations on future VMS uses were provided, including providing better warnings of construction, weather conditions, message campaigns for UDOT initiatives, specific targeting during weather conditions, and incorporating messages in other languages, specifically in Spanish. Overall, for VMS messages, respondents wanted VMS messages to be updated regularly to avoid incorrect messages being posted to the public, and to limit urgent messages about crashes and weather conditions to only when such events are ongoing.

The free-response section was well-used by participants to provide recommendations for improved implementation of ITS devices, with dozens of constructive comments, and hundreds of recommended locations for future ITS implementation.

4.5 Summary

In this chapter, the results for the diversion rates analysis, the weather analysis, and the ITS attitudes survey were discussed. For the diversion rates analysis, an approximate 18 percent increase in diversion rates was observed when VMS were activated. The mixed effects model controlled for the ratio of mainline speeds, if the VMS was “On” or “Off,” and the interaction between the VMS variable and the speed ratio. For the weather analysis, the activation of a VMS sign was found to lead to an increase in speeds of approximately 0.2 mph. While this finding was statistically significant, it may not be practically significant due to the large number of observations included in the analysis. For the ITS attitudes survey, 435 complete responses were collected with 186 partial responses for a response rate of over 30 percent. Because the survey was self-selected, the results cannot be applied to UDOT as a whole, but they offer insights into the limitations, benefits, and usage of ITS devices.

5.0 CONCLUSIONS

5.1 Overview

The primary objective of this research was to evaluate the effectiveness of commonly deployed ITS treatments in terms of mobility and/or safety on roadways in Utah. This was done through three analyses. First, the effectiveness of VMS on Utah freeways in diverting drivers off the freeway during incidents was measured. Second, the effectiveness of VMS in Utah canyons in encouraging drivers to reduce their speeds during winter weather was evaluated. Third, a survey was conducted to measure the usage of, attitudes toward, and potential improvements to UDOT's current ITS deployment of VMS, traffic cameras, and RWIS devices.

This chapter presents a review of the methodology, findings, and limitations of the research. First, an overview of the methodology of each of the three analyses will be described. Second, the major findings from each of the three analyses will be presented. Last, a description of limitations encountered in each of the three analyses will be discussed.

5.2 Methodology

The methodologies of each of the three analyses conducted during this research will be presented in the following subsections. First, a review of the diversion rates analysis will be conducted. Second, a review of the weather analysis will be described. Finally, a review of the ITS attitudes survey will be presented.

5.2.1 Diversion Rates Analysis Methods

A before-and-after study was conducted to measure the effect of VMS on Utah freeway diversion rates during incidents. VMS data were collected from UDOT's TransSuite database and crash data from March to August of 2018 and 2022 were used from UDOT Report UT-23.05 (Schultz et al., 2023b). Four crash selection criteria were determined by the research team to guide selection of appropriate crashes for this type of analysis and a total of 8 crashes were identified for analysis. In total, 650 flow and speed observations were obtained from UDOT's PeMS database (https://udot.iteris-pems.com/) for the crash day and a control day, which was one week before or after the crash. A mixed effects model was built to evaluate the effect of

VMS during each incident and the dependent variable was selected as the ratio of diversion rates on the crash day compared to the control day. The ratio of the speed on the mainline freeway on the crash day compared to the control day was included as a predictor variable as well as the reciprocal of the control offramp diversion rate, which was included to measure the stability of the model. An interaction term between the VMS activation and the speed ratio was included to clarify the effect of each variable.

5.2.2 Weather Analysis Methods

A before-and-after study measuring the change in driver speeds due to VMS messages in Utah canyons during winter weather conditions was conducted. Sardine Canyon, Weber Canyon, and Provo Canyon were selected as ideal locations for this analysis. VMS messages from UDOT's TransSuite database were filtered to identify messages from these canyons referencing winter weather that could be used for the analysis. Overall, 47 VMS messages from October 2021 to April 2022 were chosen. Vehicle occurrence and weather data for each VMS message were collected through UDOT's Freeway Performance Metrics Occurrence Data website (https://www.udottraffic.utah.gov/FPM/VehicleEvent/EventReport) and the University of Utah's MesoWest website (https://mesowest.utah.edu/), respectively. Over 1.4 million speed and weather observations were obtained and combined into one dataset. An equation based on the cumulative product of minimum-maximum normalizations for time and distance (Han et al., 2012) was built to assign a weather observation to each vehicle occurrence observation. A mixed effects model was built with eight independent variables from available traffic, time, and weather data as well as including random effect variables for the VMS ID and VMS message number.

5.2.3 ITS Attitudes Survey Methods

The ITS attitudes survey was created to measure the usage of, attitudes toward, and potential improvements to UDOT's current ITS device deployment. This survey was built to provide all UDOT employees with an opportunity to share their opinions and experiences with ITS devices. While there are many ITS devices in the state, three were selected to be the focus of this survey, namely VMS, traffic cameras, and RWIS. The survey was built in Qualtrics$_{XM}$ and routing logic was included to tailor the questions to the participants' experience with ITS devices. Overall, respondents could see a maximum of 65 questions or a minimum of 25 questions with a mixture of multiple choice, rank choice, and free-response questions. The survey was distributed to all UDOT employees on November 8, 2022 and was closed on January 8, 2023.

5.3 Findings

Due to the complexity of analyzing ITS devices, three unique approaches were developed to understand applications of the VMS, RWIS, and traffic cameras under various scenarios. This section will describe the individual findings from each of the three analyses in the research. First, results for the diversion rates analysis will be summarized. Second, results for the weather analysis will be reviewed. Last, results from the ITS attitudes survey will be discussed.

5.3.1 Diversion Rates Analysis Results

It was found that when VMS messages were active during incidents along I-15 warning drivers of future delays, diversion rates from the freeway increased by 18 percent. The interaction between VMS activation and the ratio of speeds on the crash to the control day was included and it was found that as the speeds on the crash day decreased in comparison to those on the associated control day, the effect of VMS on the ratio of diversion rates increased. Fixed effects were controlled for the ratio of speeds and the reciprocal of control day diversion rates to provide clarity to the model. Random effects were assigned to the different crashes and off-ramps and no direct correlation was found between the diversion rate and the position of the offramp relative to the crash. VMS messages were found to provide a tangible benefit to drivers during crash scenarios when used appropriately by the DOT.

5.3.2 Weather Analysis Results

It was found that when VMS messages were activated in non-crash scenarios during the winter season in select Utah canyons, there was a slight increase in speeds of 0.2 mph. The model included interactions due to weather and traffic conditions. To control for the randomness introduced by VMS location and individual messages, random effects due to VMS and message characteristics were also introduced. In total, there were 1.4 million speed observations included in the model. This result has high statistical significance, but likely limited practical significance, as the data suggests that under these conditions and with these specific messages, there was little influence of VMS on driver speeds. As noted in the literature review, each scenario and set of conditions provides different outcomes during VMS implementation. More research could be conducted to better understand the interactions and nuances between VMS and driver speeds.

5.3.3 ITS Attitudes Survey Findings

It was found that UDOT employees are generally favorable of ITS devices for both work and personal use. ITS devices were reported to be utilized in many capacities and to great effect. UDOT employees indicated that for most of the purposes, ITS devices were highly effective and frequently utilized. A few key limitations on the use of ITS devices included maintenance delays, limited device availability and quality, and inconsistent utilization by responsible parties. UDOT employees use these devices to accomplish a wide range of purposes, which would improve with greater functionality and access to ITS data.

5.4 Limitations and Challenges

The conducted research had several key limitations in application and wider use. Understanding these limitations allows for appropriate uses of these findings in future research and practical applications. First, a discussion of limitations of the diversion rates analysis will be presented. Second, a discussion of limitations of the weather analysis will be reviewed. Last, a discussion of the ITS attitudes survey limitations will be summarized.

5.4.1 Diversion Rates Analysis Limitations

While the research team attempted to control for as many confounding variables as possible during the diversion rates analysis, many variables and factors were not able to be accounted for by available, quantifiable data. Some of these factors include driver familiarity of freeways and alternate routes, driver usage of Google Maps and other wayfinding apps, behavior changes based on driver urgency to arrive at his/her destination, and the presence of a visible queue. These factors and numerous others did not have measurable ways to be controlled for in a mixed effects model, but could have very large effects on the diversion rates of drivers. It should be understood that the diversion rates analysis findings only controlled for the mainline freeway speeds and the random effects for each crash and offramp.

In addition, a limitation arose in conversation with a TOC operator about the purpose of VMS. A member of the research team had the opportunity to converse with a TOC operator about the process of creating and activating VMS messages during incidents. The TOC operator explained that most of the time, the primary purpose of the VMS messages is to inform the drivers of the conditions downstream while keeping the drivers on the freeway. The operator continued that only in very specific circumstances, such as a complete freeway closure, do the operators use VMS to divert drivers off the freeway because the diversions cause congestion to expand to arterials and collectors instead of being contained on the freeway. The diversion rates analysis provided interesting and positive results, but if the purpose of VMS is not to divert drivers off the freeway during incidents, the results contained in this analysis may not be a main effect of VMS messages, but simply a side effect of them.

5.4.2 Weather Analysis Limitations

In the selection of VMS messages for the weather analysis, various potential roadway factors were controlled for to provide clarity in the results. These factors included construction, crashes, nighttime messages, and signs outside of the winter season. The research team minimized the effects of these factors for the benefit of the results, but the minimization of these effects implies that the presence of any of these factors would have critical impacts on traffic flow conditions. Thus, by limiting the results of this study to messages without these factors, the results of this study cannot be applied directly to messages posted in scenarios other than those outlined previously in section 3.4.1.

Another limitation of this analysis was that it was impossible to determine whether the driver was aware of or had read the VMS sign, even if it was presented to them. A binary variable was used to indicate whether the sign was active or inactive, but even if a sign was active when a driver approached the sign, a potential change in behavior may have been due to other factors and not the VMS or its message.

5.4.3 ITS Attitudes Survey Limitations

The main limitation of the ITS attitudes survey was that it was not a random sample. To obtain the largest sample size, the research team distributed the survey to all UDOT employees and allowed the employees to self-select into the survey. This means that the findings of the survey cannot be applied to UDOT as a whole, the findings only represent the feelings and opinions of the respondents to the survey.

5.5 Summary

In this chapter, the methodologies, results, and limitations for the diversion rates analysis, weather analysis, and ITS attitudes survey were summarized and discussed. The methodologies presented provided a detailed and multi-faceted analysis of UDOT's current ITS deployment. The research findings indicated that there are many benefits to having an extensive ITS deployment, including communicating critical safety information to drivers, the ability to influence driver behavior, and providing a robust suite of tools to UDOT employees to enhance their ability to effectively complete their work. Although the results of this research are mixed in relation to the effect of VMS on driver behavior, the development and implementation of ITS devices should continue in the future in a continual effort to effectively communicate with the public and improve safety for all users.

6.0 RECOMMENDATIONS AND IMPLEMENTATION

6.1 Overview

Based on the findings of this research, it is necessary to provide recommendations of future steps and implementation for UDOT to pursue. The following section will describe recommendations, an implementation plan, and ideas for future research. First, specific recommendations are described. Second, an implementation plan is provided to guide UDOT's implementation of the most important findings of this research. Last, a list of future research opportunities from this research is provided for the continued improvements of UDOT's ITS deployment.

6.2 Recommendations

Results from the diversion rates and weather analysis should be shared with relevant members of the UDOT TOC to provide feedback on messages that assist drivers and to improve quality and intent of messages. Additionally, the free-response section on the uses of VMS should be reviewed by the TOC to provide insights on methods to optimize usage of VMS messages when warning drivers of crashes or adverse weather conditions. VMS messages are noticed by many drivers and are a powerful way to shape behavior when utilized consistently to a high level. It is telling that although UDOT drivers have a high opinion of their own compliance with VMS messages, there appears to be a lack of confidence in the public to respond similarly. It is recommended that this concern be shared with the UDOT TOC to help ensure quality of service across UDOT.

6.3 Implementation Plan

UDOT will implement the results of this research by thoroughly reviewing the survey results for specific ITS deployment and system improvements and by ensuring that messaging and deployment strategies are consistent with the purpose of VMS.

UDOT will review the results of the survey, and specifically the free-response section, to identify specific improvements that can be made to the current ITS deployment. Such improvements may be in areas such as RWIS data availability, traffic camera operations and technologies, VMS location implementation, and general device access within UDOT by UDOT employees. Greater public-facing access of data with the general public should also be considered. The free-response section will particularly be reviewed for ITS deployment locations recommended by UDOT employees. As UDOT employees use and interact with many of these devices each day, this section contains valuable information on where gaps in the current deployment are.

UDOT will ensure that all VMS messaging and deployment strategies are consistent with their long-term goals and current purpose of VMS. An inconsistency in the purpose of and research about VMS, as described in section 5.4.1, was observed and the research team feels that a focus on consistency will lead to clearer deployment decisions and operations across the state.

6.4 Future Research

Recommended future research includes the following:

- Survey of the general public in relation to VMS compliance and attitudes.
- Reconducted diversion rates analysis focused on construction rerouting instead of incidents.
- Diversion rates analysis that includes weather as a predictor variable.
- Reorganized diversion rates analysis with origin-destination and routing information to microscopically track where drivers enter, exit, and/or divert from the highway.
- With the current limitations on public service announcements presented on VMS from the Federal Highway Administration, reconduct the diversion rates and weather speed analysis to measure changes in driver compliance over time.
- Weather analysis in which aggregated data is considered instead of occurrence data.
- Further exploration between the relationship between the road grip factor and vehicle speeds.

- Expansion of weather analysis to segments of I-15 and other arterials, including during periods of inclement weather or standing water.
- Targeted message trials wherein various message phrasings are tested by UDOT during similar weather conditions to determine the effectiveness of different messages.
- Cross-tabulation of survey results to more thoroughly understand how respondents answered throughout various questions and what those answers mean for UDOT.
- Follow-up survey similar to one conducted in this research after improvements within UDOT to ITS devices' functionality and accessibility have been made to compare with results from this study.
- Conducting a weather analysis during times with crash conditions to measure the impact of crashes on vehicle speeds in addition to VMS interactions. An additional study could also be considered on the interactions between VSL and VMS in Parley's Canyon.
- If access to historical weather data can be improved, a before-and-after study of VMS installation could be conducted in Ogden and Weber canyons to compare effects of VMS messages during similar weather conditions. However, such historical weather data was, at the time of writing, challenging to collect through the MesoWest website.
- With the current expanding growth in west Utah and Salt Lake counties, future before-and-after studies could be conducted to measure the effect of VMS messages on diversion rates.

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APPENDIX A: DIVERSION RATES ANALYSIS

This appendix provides crash maps of each of the eight crashes included in the diversion rates analysis. Each map contains the locations of the crash, offramps, and VMS for each crash. Each crash is denoted with a maroon "X," each offramp is denoted with a blue line and a label, and each VMS is circled in red with a label. If an offramp did not have available data, an orange, "N" was placed next to the offramp.

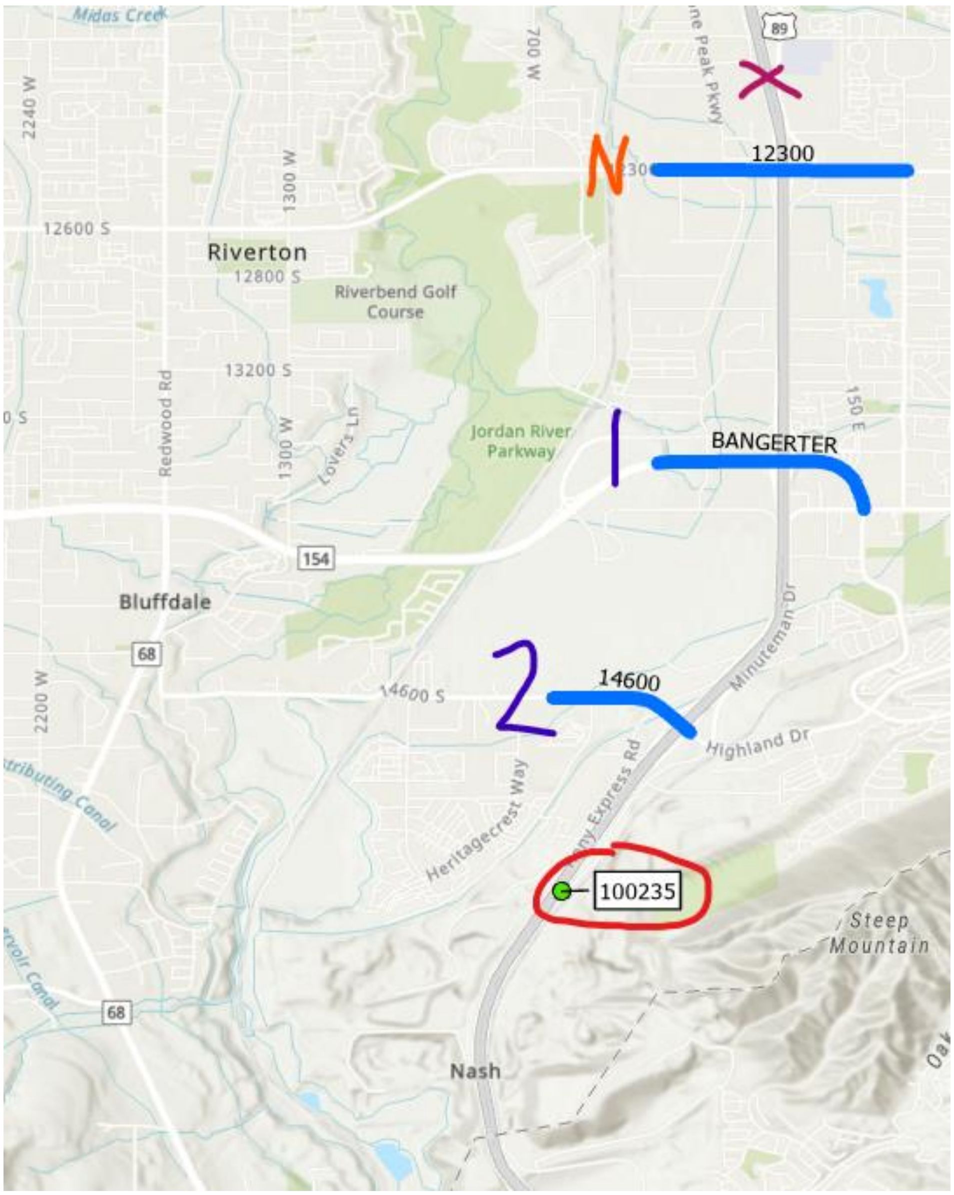

Figure A.1: Crash ID 47 map.

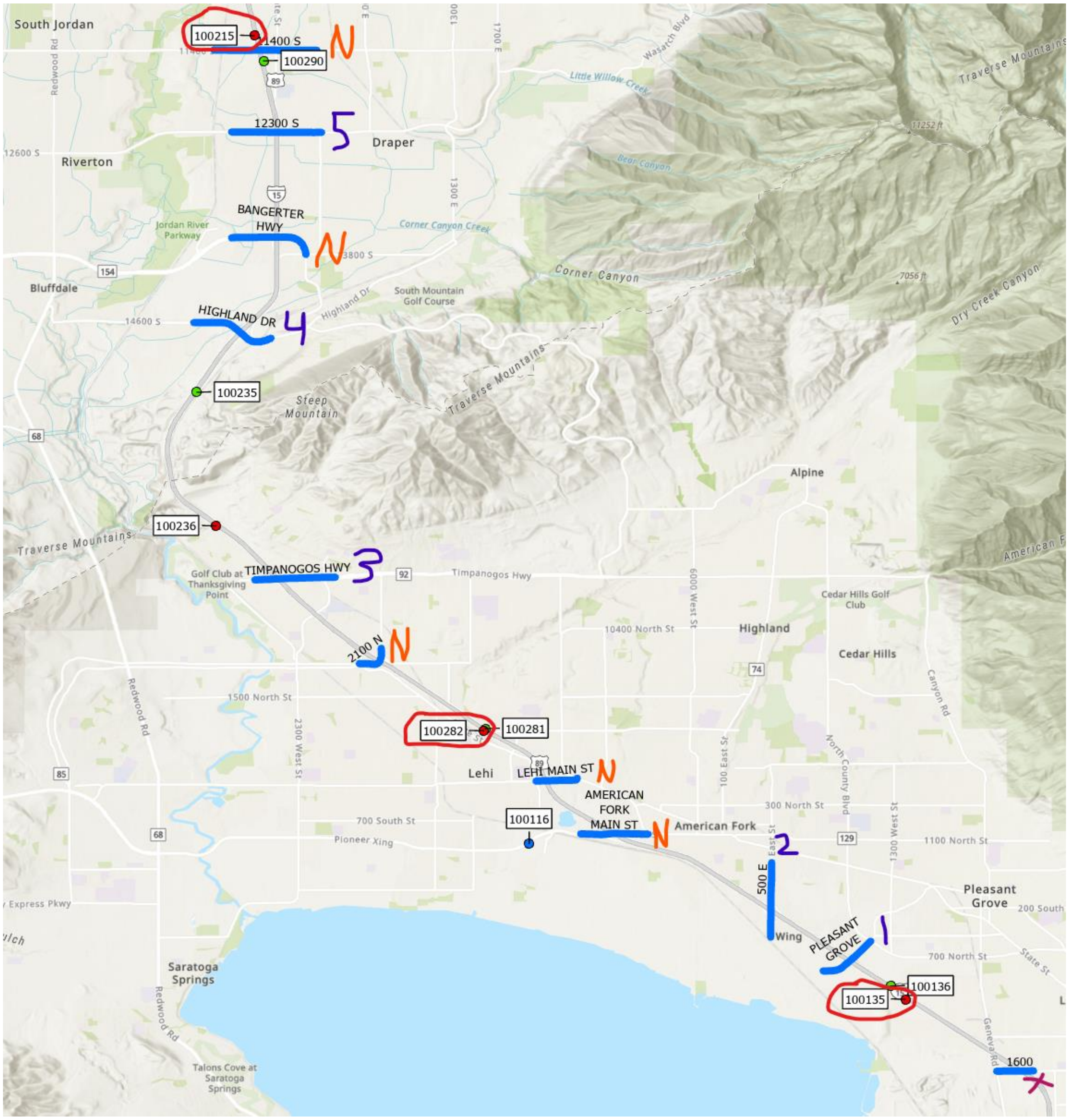

Figure A.2: Crash ID 77 map.

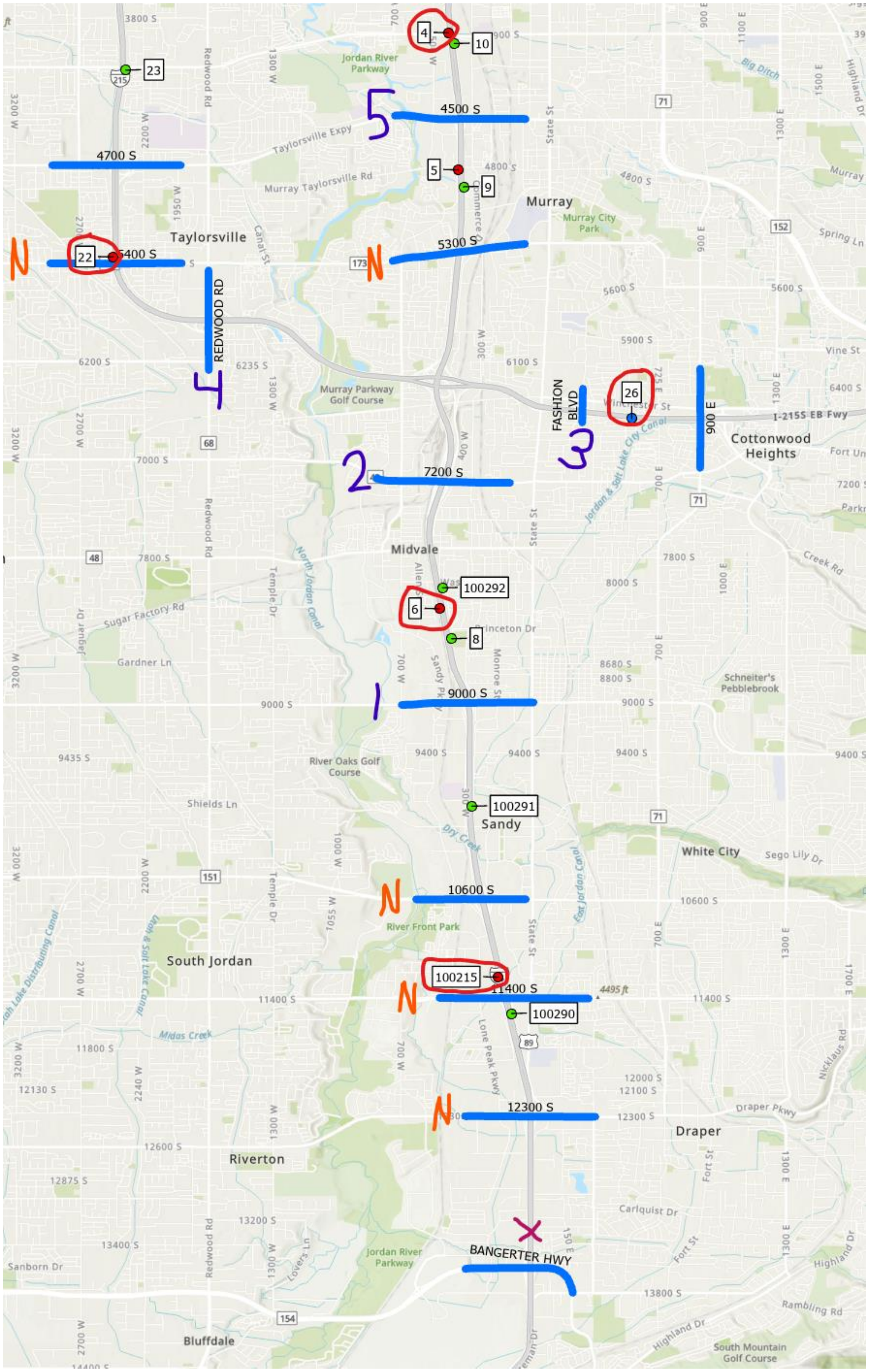

Figure A.3: Crash ID 146 map.

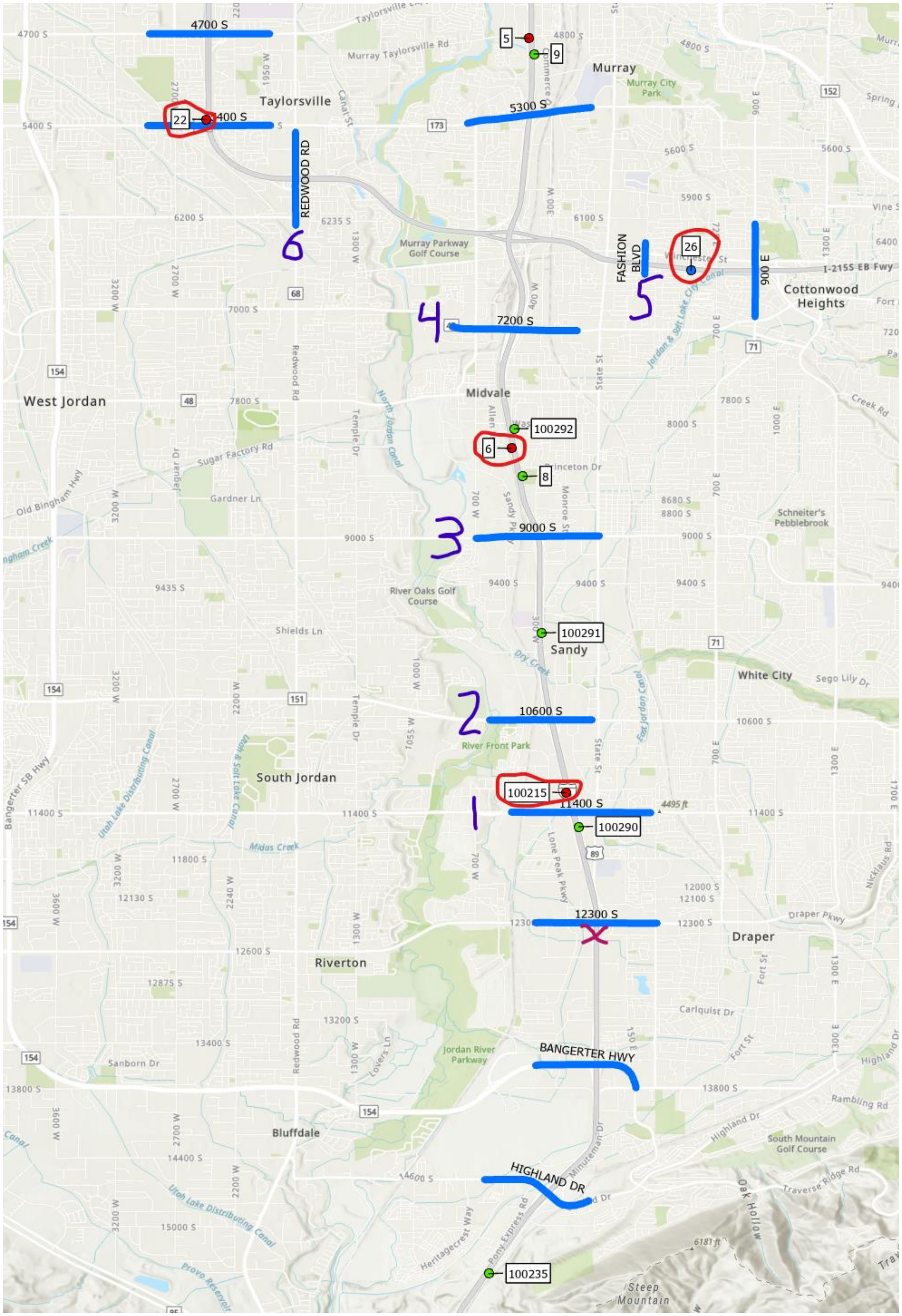

Figure A.4: Crash ID 43 map.

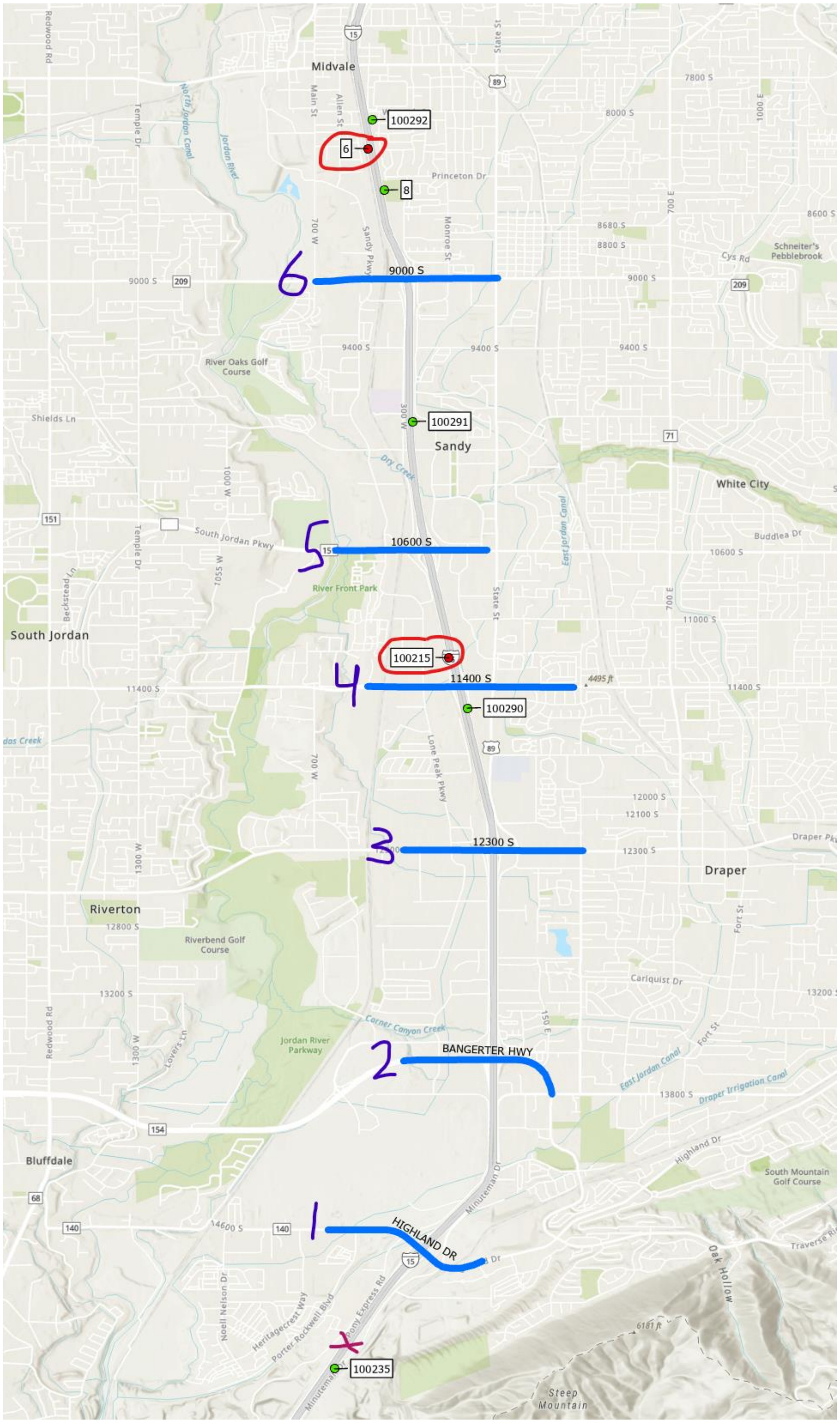

Figure A.5: Crash ID 87 map.

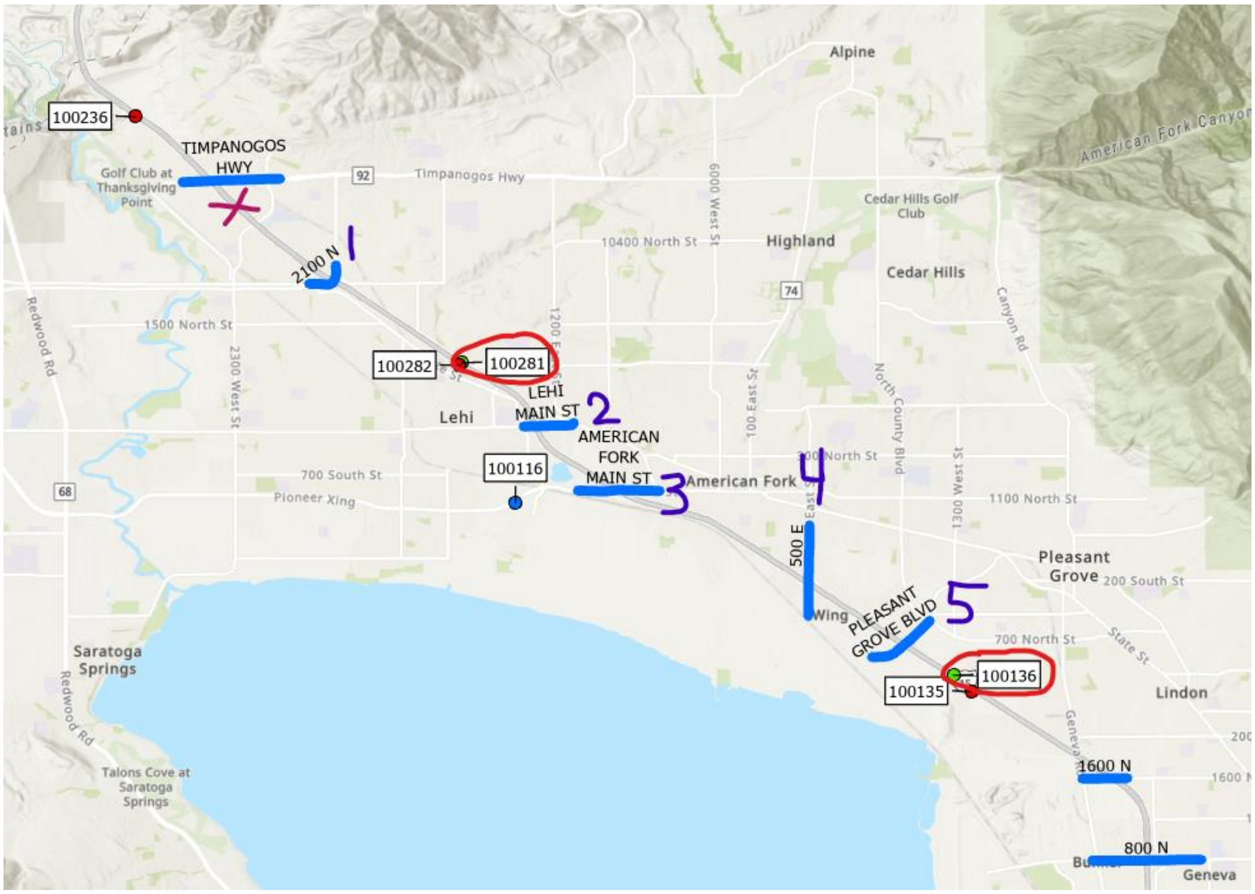

Figure A.6: Crash ID 102 map.

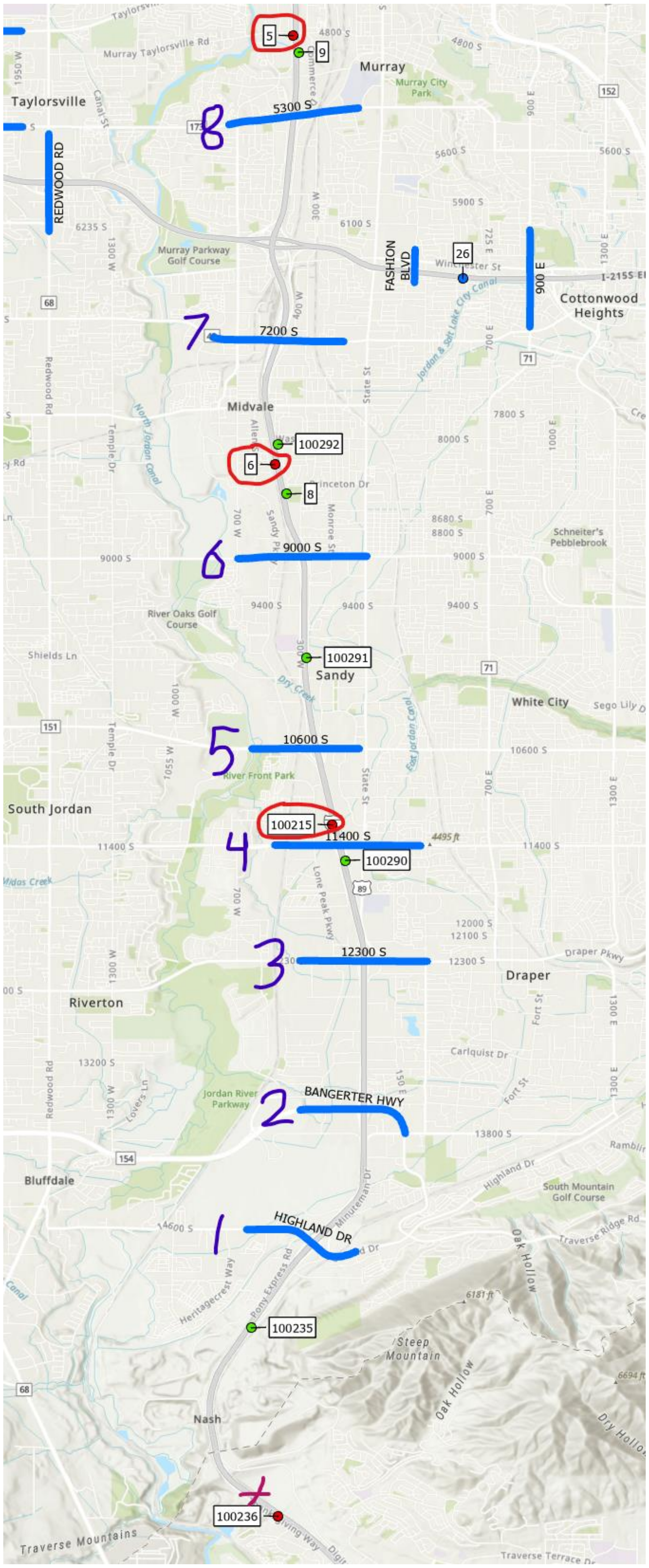

Figure A.7: Crash ID 158 map.

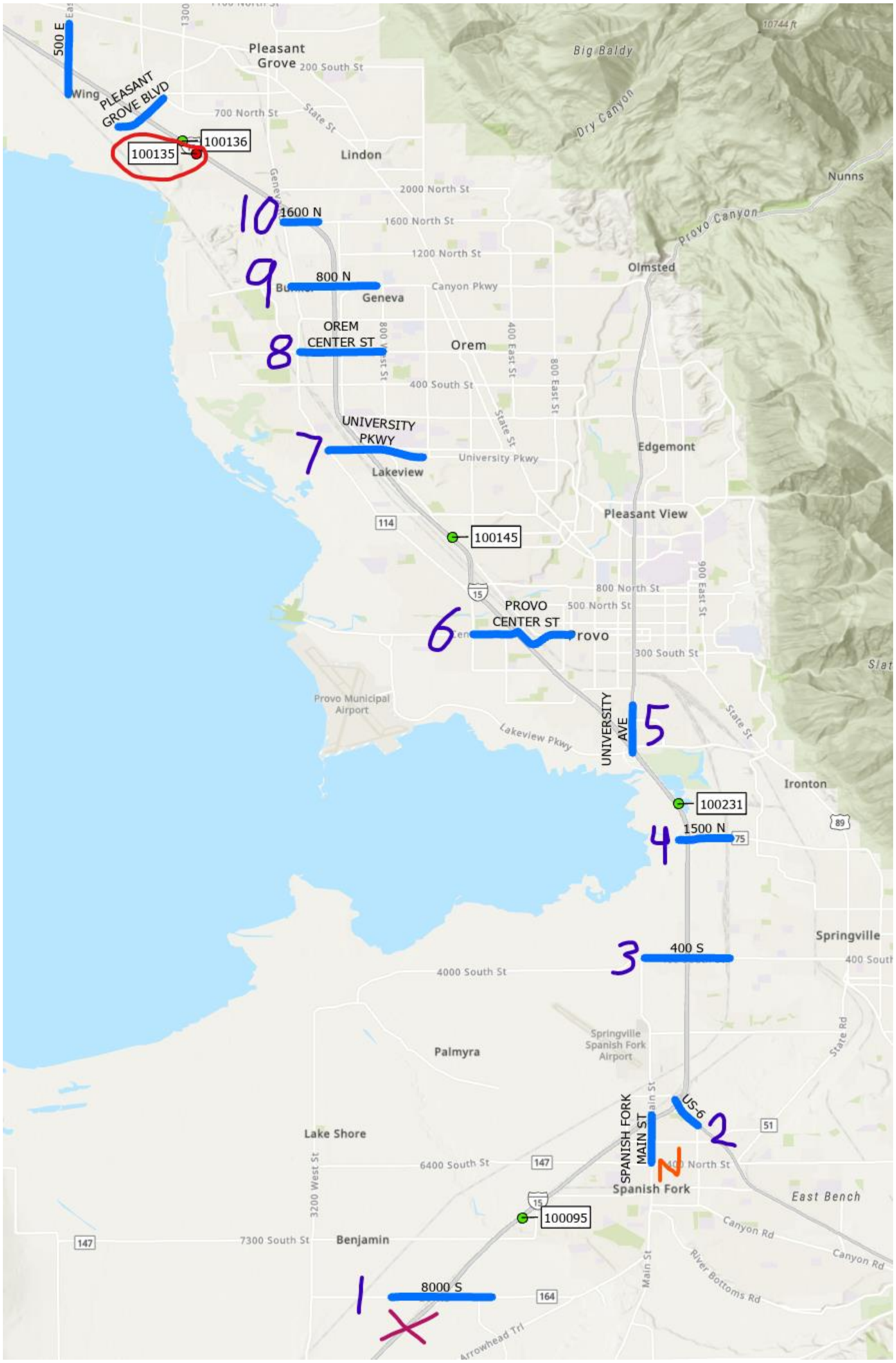

Figure A.8: Crash ID 217 map.

APPENDIX B: WEATHER SPEED ANALYSIS MESSAGES INFORMATION

Table B.1 illustrates the different VMS messages and VMS locations used in the weather analysis. The “Message Number” column is a chronological ordering of the VMS messages by date and VMS. The “Start Time” and "End Time” columns refer to the times that the message was turned on and off. The “VMS ID” column lists the UDOT-assigned ID numbers to the different VMS and correlate to the IDs presented in Figure 3.7. The “Route” column acts as a general location descriptor. Although not used directly in the analysis, the “Message” column lists the message text to provide context.

Table B.1: Message Information From Weather Analysis

Message Number	*Start Time*	*End Time*	*VMS ID*	*ROUTE*	*Message*
1	10/26/2020 15:03	10/26/2020 18:00	100006	US 89	SLOW DOWN SLIPPERY ROAD SECTIONS
2	12/10/2021 9:48	12/11/2021 14:44	100006	US 89	WINTER DRIVING CONDITIONS USE CAUTION
3	12/15/2021 11:17	12/16/2021 4:27	100006	US 89	WINTER DRIVING THRU CANYON REDUCE SPEED
4	12/17/2021 13:19	12/17/2021 22:24	100006	US 89	WINTER DRIVING CONDITIONS SLOW DOWN
5	12/23/2021 17:47	12/24/2021 2:55	100006	US 89	WINTER DRIVING IN CANYON USE CAUTION
6	12/26/2021 10:01	12/27/2021 14:50	100006	US 89	WINTER DRIVING THRU CANYON USE CAUTION
7	12/27/2021 19:20	12/28/2021 13:56	100006	US 89	WINTER DRIVING CONDITIONS THRU CANYON
8	12/29/2021 10:17	12/31/2021 17:00	100006	US 89	WINTER DRIVING THRU CANYON USE CAUTION
9	1/4/2022 8:36	1/5/2022 18:59	100006	US 89	WINTER DRIVING THRU CANYON REDUCE SPEED
10	1/20/2022 19:08	1/21/2022 1:19	100006	US 89	WINTER DRIVING CONDITIONS IN CANYON
11	2/25/2022 19:26	2/25/2022 23:38	100006	US 89	ICY ROADS IN CANYON
12	3/9/2022 10:59	3/10/2022 0:52	100006	US 89	WINTER DRIVING THRU CANYON USE CAUTION
13	10/26/2020 15:03	10/26/2020 18:00	100007	US 89	SLOW DOWN SLIPPERY ROAD SECTIONS
14	12/9/2021 13:02	12/10/2021 8:32	100007	US 89	WINTER DRIVING THRU CANYON REDUCE SPEED
15	12/10/2021 9:47	12/11/2021 14:44	100007	US 89	WINTER DRIVING CONDITIONS USE CAUTION
16	12/15/2021 11:17	12/16/2021 4:27	100007	US 89	WINTER DRIVING THRU CANYON REDUCE SPEED
17	12/17/2021 8:11	12/17/2021 11:15	100007	US 89	WINTER DRIVING THRU CANYON REDUCE SPEED
18	12/17/2021 13:19	12/17/2021 22:24	100007	US 89	WINTER DRIVING CONDITIONS SLOW DOWN
19	12/22/2021 19:20	12/23/2021 17:00	100007	US 89	WINTER STORM THURSDAY EVE PLAN TRAVEL
20	12/23/2021 17:47	12/24/2021 2:55	100007	US 89	WINTER DRIVING IN CANYON USE CAUTION
21	12/26/2021 10:01	12/27/2021 14:50	100007	US 89	WINTER DRIVING THRU CANYON USE CAUTION
22	12/27/2021 19:20	12/28/2021 13:56	100007	US 89	WINTER DRIVING CONDITIONS THRU CANYON
23	12/29/2021 10:17	12/29/2021 19:11	100007	US 89	WINTER DRIVING THRU CANYON USE CAUTION
24	12/30/2021 9:13	12/30/2021 10:57	100007	US 89	WINTER DRIVING THRU CANYON USE CAUTION
25	12/30/2021 13:06	12/31/2021 17:00	100007	US 89	WINTER DRIVING THRU CANYON USE CAUTION
26	1/4/2022 8:36	1/5/2022 5:19	100007	US 89	WINTER DRIVING THRU CANYON REDUCE SPEED
27	1/5/2022 9:58	1/5/2022 15:57	100007	US 89	WINTER DRIVING THRU CANYON REDUCE SPEED
28	1/5/2022 16:01	1/5/2022 18:59	100007	US 89	WINTER DRIVING THRU CANYON REDUCE SPEED

Table B.1 (continued)

Message Number	*Start Time*	*End Time*	*VMS ID*	*ROUTE*	*Message*
29	1/20/2022 19:08	1/21/2022 1:19	100007	US 89	WINTER DRIVING CONDITIONS IN CANYON
30	2/25/2022 19:26	2/25/2022 23:38	100007	US 89	ICY ROADS IN CANYON
31	3/9/2022 10:59	3/10/2022 0:52	100007	US 89	WINTER DRIVING THRU CANYON USE CAUTION
32	10/11/2021 16:20	10/12/2021 13:43	100223	US 189	SLOW DOWN SLIPPERY ROAD SECTIONS
33	1/1/2022 9:12	1/2/2022 9:12	100223	US 189	ICY ROADS POSSIBLE SLOW DOWN
34	2/23/2022 13:54	2/23/2022 19:42	100223	US 189	SLICK ROADS REDUCE SPEED
35	10/11/2021 16:20	10/12/2021 13:43	100224	US 189	SLOW DOWN SLIPPERY ROAD SECTIONS
36	1/1/2022 9:12	1/2/2022 9:12	100224	US 189	ICY ROADS POSSIBLE SLOW DOWN
37	2/23/2022 13:54	2/23/2022 19:42	100224	US 189	SLICK ROADS REDUCE SPEED
38	10/11/2021 16:20	10/12/2021 13:43	100225	US 189	SLOW DOWN SLIPPERY ROAD SECTIONS
39	1/1/2022 9:12	1/2/2022 9:12	100225	US 189	ICY ROADS POSSIBLE SLOW DOWN
40	2/23/2022 13:54	2/23/2022 19:42	100225	US 189	SLICK ROADS REDUCE SPEED
41	10/11/2021 16:20	10/12/2021 7:06	100226	US 189	SLOW DOWN SLIPPERY ROAD SECTIONS
42	12/10/2021 8:11	12/10/2021 9:24	100226	US 189	ICE POSSIBLE SLOW DOWN
43	1/1/2022 9:12	1/2/2022 9:12	100226	US 189	ICY ROADS POSSIBLE SLOW DOWN
44	2/23/2022 13:54	2/23/2022 19:42	100226	US 189	SLICK ROADS REDUCE SPEED
45	12/19/2021 18:39	12/20/2021 14:49	100270	I 84	ICY ROADS POSSIBLE SLOW DOWN
46	12/20/2021 17:56	12/20/2021 23:39	100270	I 84	ICY CONDITIONS IN CANYON SLOW DOWN
47	12/21/2021 18:33	12/22/2021 10:57	100270	I 84	BLACK ICE POSSIBLE NEXT 4 MILES

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