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Evaluation of the Effectiveness of a Variable Advisory Speed System on Queue Mitigation in Work Zones

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Evaluation of the Effectiveness of a Variable Advisory Speed

System on Queue Mitigation in Work Zones

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A thesis submitted to the faculty of
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Master of Science

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ABSTRACT

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System on Queue Mitigation in Work Zones

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Construction is increasing due to increased demand and degradation of existing infrastructure. This construction often results in a reduced number of traffic lanes or lane width during construction, which often creates queue at the entrance to work zones. Variable Advisory Speed Systems (VASS) provide drivers with advanced warning regarding traffic speeds downstream to help them make better decisions in advance of problems that may exist downstream. The purpose of this study was to evaluate the effectiveness of a VASS at mitigating queues in work zone entrances during peak hour conditions. It was anticipated that by implementing a VASS queues would be reduced and vehicle flow increased in work zone areas. Three objectives of this study were: (1) research VASS systems that are available to be tested, (2) select and deploy a VASS in Utah at a long-term work zone, and (3) perform a statistical analysis on traffic flow characteristic data to evaluate the effectiveness of the VASS on queue mitigation.

A literature review on the use of VASS for work zones returned minimal studies on advisory speeds in work zones. Most of the advanced speed notification systems, found during the literature review, used variable speed limit (VSL) applications. A VASS was selected and deployed at the northbound approach to the I-15 Beck St. widening project in North Salt Lake City. In this study the VASS consisted of five sensors and two variable message signs (VMSs). To determine if the system was effective at reducing queue the speed data were analyzed in detail to come to statistical conclusions.

The collected data shows that the VASS investigated was effective on weekends during evening peak hours when there was a slow down. No consistent significance was seen on week days during the evening peak. There was no statistical difference between before and after speed data on any day of the week when there was no slow down. This study is valuable because it is unique in studying an advisory speed using VMSs and other ITS technology. This study recommends that further studies be conducted without a movable median barrier system, as was used in this construction project, to evaluate further about the effectiveness of VASSs. It is recommended that, if a VASS is considered, studies be done to see whether queues are expected to form at the work zone entrance, as VASSs will not be effective if queues do not form.

Keywords: variable, speed, advised, VASS, VMS, VSL

ACKNOWLEDGEMENTS

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1 INTRODUCTION

With an increase in population comes more traffic, and with more traffic comes the need to upgrade, rehabilitate, or replace existing transportation infrastructure. During the necessary construction there is a need to control the amount of delay that drivers will experience. An integral part of controlling delay is to look at the cause of delay. One such cause of delay, addressed in this thesis, is that associated with the approach to a work zone. During construction, various methods of traffic control measures are necessary to get the work done efficiently and on time. They range from systems that are strictly mechanical to those that require complicated electronics applications. One such technologically advanced system is a Variable Advisory Speed System (VASS).

Often times the research done on VASSs includes a discussion on variable speed limit (VSL) systems. Due to limitations on the policy established by the Utah Department of Transportation (UDOT) a VSL system is not practical to investigate at this time. The UDOT policy that addresses speed reductions in work zones is UDOT 06C-61. The policy allows for a reduction in speed on a road with a speed limit at or above 60 mph to be reduced by 10 mph for up to 20 calendar days without a Traffic Engineering Order (TEO), and on roads with speed limits less than 60 mph the speed can be reduced by 5 mph for up to 20 calendar days. Obtaining a TEO has a somewhat lengthy process and for the purpose of this study it was not practical to try and get a TEO that would allow speed restrictions below those of UDOTs standard policy because this study was not testing a VSL system. One reason a VASS was chosen for this study

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is that because speeds often drop near or below 30 mph in work zones it would be very difficult to get a TEO to allow regulated speed limits at or below this speed. A VASS is ideal for this study and does not require a TEO by allowing lower speeds to be advised to drivers without making them enforced speed limits.

The VASS explored in this study consists of multiple microwave sensors and Variable Message Signs (VMSs) that can be placed along a certain section of a highway work zone. A work zone is defined as the area in which road construction occurs. The work zone area includes the area before the actual work begins, referred to as the work zone entrance (FHWA 2009). The expected benefit of providing variable advisory speed is a decrease in the chaos directly upstream of the entry to the work zone, thus reducing the queue that is often associated with upstream sections of work zones. The presence of a large number of vehicles trying to enter the work zone is a typical picture of the approach to a work zone during peak hours when higher traffic volumes are anticipated. This problem is further influenced by the need to slow down in work zones. By implementing a VASS in the approach to the work zone entrance researchers hope to reduce the level of the chaotic traffic condition, ensure that the vehicles travel at a safe speed as they approach the work zone, and increase the throughput of vehicles in the work zone, thus decreasing the delay to drivers. Implementing a VASS may help reduce queue and make driving through work zones less stressful for drivers and, as a by-product, decrease the potential for traffic crashes, primarily rear-end collisions in the work zone approach area.

1.1 Purpose and Background

In order to better serve the drivers of Utah, UDOT needs to make informed decisions about how to best organize and plan for construction projects. These projects often bring

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decreased number of lanes and, in time, increased traffic congestion. Thus there was a need to find ways to alleviate some of this congestion. The existence of VASS concept was presented at the 2007 Annual Meeting of the Transportation Research Board (Kwon et al. 2007). VASS has not been used around the country like many VSL systems, which have similar components. UDOT was interested in evaluating whether a VASS would work at work zones on Utah's highways to help mitigate congestion problems as well as possibly improve the safety of Utah highways. The purpose of this study was to deploy a VASS at a work zone entrance area and evaluate its effectiveness at mitigating queues.

1.2   Research Objectives

The research was funded by UDOT to investigate whether implementing a VASS in work zones would reduce queues, and therefore be an effective option for queue mitigation in future construction projects. The first objective of this project was to investigate VASSs that were available for use by UDOT. The second objective was to select one VASS that was appropriate for the needs of UDOT and test that system in a long-term work zone. The third objective was to conduct a statistical analysis of the data from the VASS to evaluate its effectiveness on queue mitigation and provide appropriate recommendations to UDOT regarding the possible application of VASS at work zones on Utah's highways.

1.3   Organization of the Report

This thesis consists of six chapters. Chapter 1 presents the purpose and background, and research objectives. Chapter 2 summarizes the findings from a literature review and explores how the concept of data collection and information dissemination used in VSL system could be used as a VASS at work zones. Chapter 3 describes the location of the work zone used to

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evaluate the VASS in this thesis and the method of deploying and calibrating the VASS in the selected work zone. Chapter 4 discusses data collection and reduction processes and how raw data sent from the VASS supplier were reduced to a spreadsheet database that could be analyzed by statistical software. Chapter 5 presents the results of a statistical analysis on traffic flow characteristic parameters, performed to evaluate whether the VASS system was effective in mitigating queues at work zones. Chapter 6 concludes the thesis with the conclusions of the study and a set of recommendations for UDOT regarding the use of VASSs in work zones.

2   LITERATURE REVIEW

The purpose of this literature review is to examine different strategies of queue mitigation and compare them to VASSs. There are many different methods currently utilized that can help reduce queue in work zone areas. These will be discussed briefly as well as an in-depth discussion on VSL and other similar systems. Part of the reason for having an in-depth look at VSL is that much of the research has been done in this area and the equipment used and information presentation concept used for VSL are similar to those of VASS. Hence, discussions on VSL concept can give some insights into the potential benefits of VASS used at work zones.

This chapter discusses the various methods of queue mitigation that are currently available. These methods include those that have been used in various capacities for many years as well as those that use the newest technological advances. The chapter then concludes with a section on VSL, which is the most widely used system that is similar to a VASS.

2.1   Methods of Queue Mitigation

The most challenging problem associated with construction zones is the fact that vehicles still must travel through the work zone during the construction. This is more easily understood in large projects that affect the major roads such as interstate highways. There are many techniques that are utilized in various situations to help lessen the effect of the construction on the drivers traveling through work zones. These different techniques can be used to relieve queue and other undesirable effects at a work zone on drivers. A list of several such techniques

was presented in UDOT report UT-08.30 (Saito et al. 2008). A list of these findings is presented in the next sub-section to help understand ways that are mechanical and do not use advanced technologies.

2.1.1   Non-Technological Approach to Queue Mitigation

The traffic in work zone that normally has three lanes will be much more congested if the number of lanes are reduced, so one technique is to reduce lane width and/or push traffic onto the shoulder to maintain the same number of lanes that the drivers are accustomed to. The hope here is that although drivers must slow down due to decreased lane width, they will not have as many delays or queues that are associated with reducing the number of lanes. When the number of lanes must be reduced, there are varying techniques to deal with this problem. One is to have an organized merge at the point where the lanes are reduced with equal queues in each of the two affected lanes. This is accompanied with signs that instruct drivers not to merge until the merge point. Another similar technique is where the lane numbers are not reduced but signs are installed that have flashing lights. The lights are activated to restrict drivers from merging and therefore reduce crashes and other situations causing delay associated with the merge can be avoided (Saito et al. 2008).

Although a little more abstract, there have been some studies done on complete road closures (Saito et al. 2008). This method could be well utilized in many cities but on major interstates it may not work, particularly in Utah due to lack of sufficient alternate routes. It may be able to be implemented on a small scale where lanes are closed during the night. However, this still creates a problem due to the lack of sufficient alternate routes for traffic. In conjunction with road closures or construction projects Saito et al. (2008) mentions the use of incentives to

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promote the use of currently available mass-transit or bus systems including offering drivers some sort of discounted rate or other incentive that can be worked out with the transit company. This could be effective because of the decreased amount of single occupancy vehicles on the road. Their study also mentioned that some people continue to use the transit system even when the construction is done. This could be considered an added benefit to the community by having reduced vehicle emissions and reduced traffic flow after all roads are reopened.

Traffic flows in work zones typically go down at night, opening up a new opportunity to have more room and less worry about delay. Therefore, another technique that has been utilized is night construction. This allows the construction crew to reduce the number of driving lanes and give them the needed space to work when there is low demand on the road. Then, during the day the road can remain open to traffic unimpeded by the construction project. This method appears to have great potential; however, it has been reported that due to reduced visibility the night work is sometimes not as good as the work done in the day (Saito et al. 2008).

A new method that is more preventative than anything is that of paving for 12-foot lanes by placing 14 feet of pavement. This is in anticipation of the need to decrease lane width during future construction projects while still maintaining a certain number of needed lanes. This technique will allow more road width of previously paved road that will be available during the next construction project on that particular road. This strategy initially appears to be a good idea; however, a few flaws were identified with this method. Based on the fact that extra lanes will be paved it is not anticipated that the pavement will be used to carry traffic for a long period after it is placed. Therefore, paving more than necessary may be considered a waste of money, materials, and the environment. In addition, the road must be kept and maintained until it is time to be used and theoretically it may not be needed until it is worn out from the weather or other

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distresses, such as shoulder drop off, freeze-thaw cycles, and other extreme environments including frost heave. These concerns may not be enough to prevent some projects from placing extra lane widths. Due to limited study of this technique, it is unknown if the flaws discussed here are an actual concern or if they are not a problem that should be considered before paving extra width when reconstructing a road.

2.1.2 Technological Approach to Queue Mitigation

With the continued growth of technology including smart phones and the Internet, if the information on road construction or even information on delay could be given to drivers before they enter the freeway or get caught up in the queue, much of the problems associated with delay could be avoided. This is an approach that incorporates the use of a web site to give drivers real time data, such as road closures and delay. This method can be useful in many areas as well as other techniques, such as lanes closures, and especially intelligent transportation systems (ITSs). ITSs include but are not limited to any system that utilizes multiple forms of dynamic automated data collection and information dissemination systems including but not limited to VASS and VSL applications, websites, texting, and email updates (Saito et al. 2008). The I-15 CORE project, currently under construction in Utah County is a good example of using these technologies (UDOT 2010). The contractors for the I-15 CORE project are currently using many of these methods including but not limited to website, email and texting updates.

2.2 Variable Speed Limit Applications

Similar systems to the VASS have been implemented and used in various locations in and out of the United States, including, but not limited to, the Netherlands and Finland. These

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systems range from weather related systems such as that implemented along the E18 test site in Finland (Rama 1999), to systems that are complicated enough to use a photo enforcement technique used in Illinois in work zones (Benekohal et al. 2008). In addition, many studies have been done that are simply a computer simulation of a real highway such as one done on a section of I-4 in Orlando, Florida (Abdel-Aty et al. 2006).

The use of "variable speed limit control has long been recognized as one of the most promising tools for managing work zone traffic flows" (Kwon et al. 2007). This statement suggests that the use of VSL is not a new concept and that VSLs are an effective method of helping alleviate congestion in work zones. The Finland study of E18 was done in 1999, which suggests that this research on VSL is not a new concept. This study was a weather related study that focused on the effects of VSLs during inclement weather. The study had a control road and an experimental road that they compared the difference in lowering the speed limit due to the weather versus using a VSL system. The study found that in moderate to severe weather conditions the mean speed on the control road was less than on the experimental road. This could have been due to the fact that the control road had more severe weather that lasted longer. The study also concluded that the VMSs were not feasible due to the low volumes of cars on the road, and it suggested that in higher volume areas VMSs could be very appropriate (Rama 1999).

Much of the research on VSL systems suggests that they must be implemented in such a way that the drivers can have adequate time to adjust their speed. It was found, in a study done using a driving simulator, that drivers did not follow VMSs and VSLs particularly when they were given an abrupt change in speed limit. However, when the speed limit was changed gradually, drivers were much more likely to follow the VMS or VSL and speed variations were reduced (Lee, Abdel-Aty 2008). It seems that this could be due to the fact that drivers may not

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feel that an abrupt change in their speed is necessary, whereas a gradual change in speed limit seems much more reasonable to drivers. In addition, VSL research tends to focus on crash mitigation, compared to other measures of effectiveness (MOE) such as queue mitigation.

Another area of research that has been done regarding VSL systems is the area of enforcement. If a speed limit is implemented it must be enforced somehow. An area that has been recently researched is that of automated enforcement. Automated enforcement is simply a way to automate the enforcement of speed limits by using a system that takes photos of the vehicle and then a ticket is mailed to the owner of the vehicle. According to a literature review done by UC Davis (Rodier et al. 2007) "in the U.S., automated speed enforcement programs are currently operated in only 11 states and in Washington D.C., most of which are located on residential streets and not highways." Here, the authors suggest that the use of an automated enforcement is not widely used in the US.

The first state to authorize the use of automated speed photo enforcement (SPE) was Illinois (Benekohal et al. 2008). The study used a van that is equipped with two radars. The first radar checked the vehicles speed and sent a warning to the driver if they are speeding, similar to a radar trailer. If the driver did not slow down by the time they passed the second sensor the van would automatically take a photo of the vehicle and a ticket could be issued to the driver or owner. The study was done to find out the effectiveness of the SPE van system in work zones. The study found that the percentage of vehicles exceeding the speed limit was reduced from 39.8 percent to 8.3 percent just by the presence of the SPE van (Benekohal et al. 2008). This suggests that using an automated photo enforcement system may be very effective in reducing the number of speeders in work zones. The presence of the SPE van may simply remind drivers that they need to slow down in work zones. In addition, Benekohal et al. (2008) expected that people who

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would receive tickets would tell their friends about the system and possibly the media would cover a story informing drives beforehand that speeding in a work zone is a serious violation.

Available research focused on the idea of reducing the risk of crashes in either a work zone, or in other areas where a VLS system may be implemented. If vehicles are warned of slower traffic ahead they have a better chance of slowing down and avoiding rear-end collisions. VSL has been effective in reducing speeds in dangerous areas of the road due to weather related problems. In order to evaluate the ability of a VSL system to reduce crash risk a micro-simulation program was developed and the concept of homogenous speed zones was introduced on an area of I-4 in Florida (Abdel-Aty et al. 2006). In addition to the reduction of speeds in a work zone, the study showed that greater safety could be achieved by raising the speed limit of vehicles exiting the work zone (Abdel-Aty et al. 2008). This study showed that when using a VSL system it could be effective to increase the speed of vehicles as they left the work zone. Increasing the speed downstream of the work zone could help clear out any congestion that might have built up in the system from the decreased speed. This could be particularly useful in a work zone where vehicles may slow down due to many variables such as decreased lane width, weaving from one side of the road to the other, or even rubber-necking.

Most research found during the literature review was done using a VSL system. Although similar in concept a VSL is more restrictive than the scope of the VASS evaluated in this study. Therefore, this study is concludes that minimal research has been done on VASSs used for queue mitigation in work zones. Due to the increasing need to find ways to better control traffic flow in work zones more research was needed on the topic of advisory speeds. This study used a VASS in a work zone entrance to evaluate the effectiveness of the VASS at mitigating queues. A similar study was done using the resemblance of advisory speeds (See Figure 2-1) by Kwon et

al. (2007). The use of orange signs instead of white was a step in the right direction. More specific direction on the fact that the speed was advisory would be helpful for drivers. Therefore, in this study on VASSs VMSs will give the drivers the advisory speed for approaching the work zone entrance.

Figure 2-1 Example of variable message sign on study site (Kwon et al. 2007).

2.3   Chapter Summary

There are many techniques that have been implemented to help mitigate queue in work zones. Due to the fact that there are so many techniques it can be a daunting task for engineers and construction managers to decide which method to use. Each method may work differently in different conditions and therefore each technique must be adapted to the specific work zone. For example, systems that are very complex may not work well for small scale projects but may be feasible for large scale projects. Due to the fact that technology is playing an increasingly important role in the lives of individuals, it is necessary that new systems and techniques incorporate technology that is most beneficial and effective at conveying messages to drivers. It is also important for engineers in charge of traffic control for work zones to consider new technologies that could be more efficient or even more cost effective in new projects. This literature review has covered various techniques currently available for mitigating queue with an emphasis on VSL which has similar components as a VASS. The study of a VASS used at work zones has not fully been investigated; therefore, it is important to conduct a study that fully analyzes an advisory speed system and determine if VASSs are effective at mitigating queue at work zone entrances. Hence, it is worthwhile for UDOT to evaluate if a VASS can mitigate congestion and improve traffic flow at work zones.

3   STUDY SITE DESCRIPTION AND DEPLOYMENT

Due to the increased amount of highway construction work planned and scheduled in Utah it is important for UDOT to find out if a VASS is something that Utah drivers could benefit from. This study was initiated based on the findings of other research studies, as mentioned in the literature review section, which claimed VASSs potential benefit for drivers and the highway agency. Many studies found that a VSL system was beneficial; therefore, this study explored the possibility of a VASS, which was based on a similar data collection and information dissemination concept as those of VSL, being of some benefit for mitigating queues and controlling speeds in work zone areas.

Chapter three first introduces the system that was selected for implementation, and then a description of the work zone that was selected to install the VASS is given with a map of the area and locations of sensors and VMSs used in the system. Then a brief discussion on the way the message for the VMS was selected by the system is given. Next a discussion on the deployment of the VASS is given including discussion on calibrating and monitoring the system. Next issues raised by UDOT engineers with turning on the VMSs are addressed and a section on turning on the system is presented describing some issues with the actual messages shown that were quickly resolved. The chapter concludes with a summary of the details that were discussed.

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3.1 Study Description

A VASS was selected, which fit the needs of this study. The system equipment and software were owned and operated by ASTI-Transportation (ASTI). The system consisted of five microwave sensors that measured speed, volume, and occupancy for each of the lanes of traffic. The speed was measured as the average speed for the time intervals (between one and two minutes) at a given sensor for a specific lane of traffic. The average speed for a given lane was then calculated using the standard formula for an average, using the volume of vehicles that passed the sensor. The occupancy was calculated as the percent of time that the vehicles were in the path of the sensor. The system also includes two VMSs that displayed an advisory speed according to the data sent to a server at the ASTI headquarters in the state of Delaware from each of the five sensors. The advisory speed displayed is determined by ASTI's proprietary, computerized highway information processing system (CHIPS). The system consisted of five sensors and two VMSs.

3.2 Site Description

The site was selected at the work zone located on the north end of Salt Lake County: I-15 Beck St. widening work. This construction project replaced several bridges and widened the road for about 3 miles, including the addition of a high occupancy vehicle (HOV) lane in each direction. The work zone was selected because it was a long-term work zone, its traffic control plans did not change significantly in the approach to the work zone entry, and the majority of drivers would be familiar with the work zone area. Construction began in January of 2008 and concluded in August of 2010. The VASS equipment was placed at the northbound entrance to the work zone prior to the active construction area south of the 600 North interchange. The

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decision was made to number the sensors and VMSs from south to north, one to five and one to two respectively to lessen confusion when referring to particular sensor or VMS.

Inside the study site, there was a freeway transition ramp from eastbound I-80 to northbound I-15 and an off-ramp for 600 North. These locations for the VMSs and sensors were chosen after site visits were made, after reviewing an aerial image of the study site, based on the knowledge that the first VMS could not be placed further south than 400 South (which was the south end of the work zone), and based on the desire that the last sensor be placed somewhere within the construction zone. The original study site was almost two miles long prior to some changes that were made due to necessity. During a site visit on February 23, 2010, it was determined that the location for sensor 5, identified in the active construction area, would not be a feasible location to place the sensor due to a steep and soft shoulder in that area. A new location was identified in the shoulder at the old 800 North bridge area. The new location initially looked suitable because there was a flat area to place a sensor out of the way of traffic and construction activities.

The relatively short distance of the system included all sensors and VMSs. The main reasons for the short distances were: limited space available at the work zone entrance, relationship with other highway configurations in the work zone, and compliance with the Manual on Uniform Traffic Control Devices (MUTCD) rules and regulations for placing VMSs in work zones (FHWA 2003), discussed in detail in Section 3.5 of this chapter.

During the site visit on February 23, 2010, general areas were outlined and specific locations for the sensors and VMSs were selected. The layout found in Figure 3-1 was then updated to reflect the actual locations where sensors or VMS boards would be placed. In addition to designating the location of sensors and VMSs the specific locations were painted so it

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would be easy to know where to place the sensors and VMSs at the time of deployment. All locations for VMSs and Sensors were then approved by UDOTs Resident Engineer for the project as well as the other technical advisory committee (TAC) members prior to deployment.
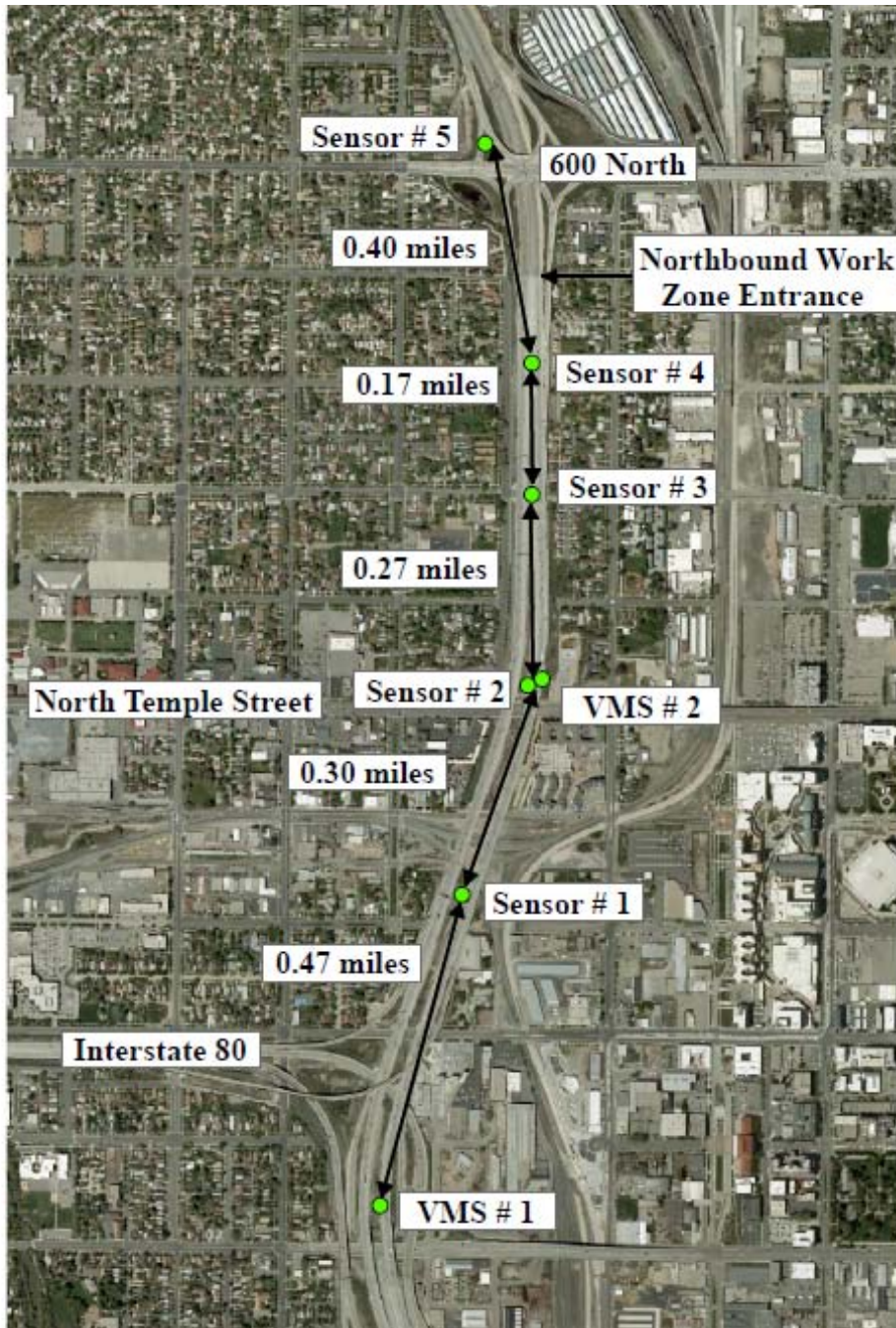
Figure 3-1 Sensor locations (background image by AGRC 2011).

3.3   VMS Message

In a TAC meeting on February 9, 2010, the decision was made regarding the message that the VMS would display during different degrees of slowdown. It was decided that at speeds at or above 55 MPH the VMS would display, in three lines of text, "55 MPH TRAFFIC AHEAD," for speeds between 15 mph and 55 mph the message would round down to the nearest 5 mph speed and display, again in three lines, "XX MPH TRAFFIC AHEAD," where the "XX" represented the lowest average speed rounded down to the nearest 5 mph. For speeds below 15 mph the VMS would display, again in three lines, "STOPPED TRAFFIC AHEAD."   An example of what the VMS would look like is presented in Figure 3-2.
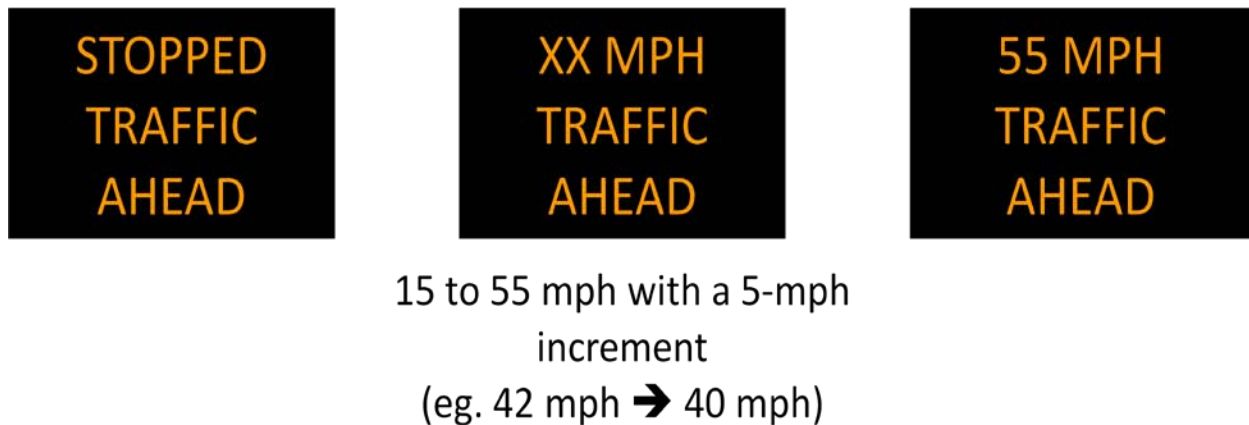
Figure 3-2 Sample of VMS sign images.

3.4   Deployment and Calibration

The sensors and VMSs were deployed with the assistance of the UDOT Research Division and the I-15 Beck Street UDOT construction crew on Tuesday, March 9, 2010. Two UDOT trucks were utilized to transport the equipment to the pre-determined locations with the exception of sensor 5. As noted earlier it was difficult to find a location in the active work zone to place a sensor that would be out of the way of the construction and also be a good location to

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gather data. Upon driving to the proposed location it was quickly determined that the location was not suitable. The major problem with this location is that the area, although flat, was lower than the pavement surface and the sensor only had a mast that was 20 feet tall, meaning that due to the large amounts of truck traffic traveling in the southbound direction the sensor would have great potential to give false readings if placed in that location. Other areas were investigated in the area. The investigated locations included: the approach fill of the old abutment on the east side of the freeway, the northbound 600 North on-ramp, and the southbound 600 North off-ramp. After consulting the engineers available at the project office, it was determined that the best location would be between southbound I-15 and the off-ramp at 600 North. Figure 3-3 shows this area with the off-ramp on the left side of the figure and I-15 on the right side of the figure. There was a flat spot, protected by the concrete barrier that provided the necessary view of the northbound traffic over the truck traffic traveling southbound to get accurate readings from the northbound traffic. The final sensor locations can be seen in Figure 3-1, which also shows changes in the location of sensor 2 and VMS 2 that will be discussed in more detail in section 3.5.

After the sensors were placed in the designated locations each sensor had to be aligned, leveled, and calibrated to gather data from only the lanes of active traffic. This was done using software provided by ASTI. The sensors had to be perpendicular to the vehicles that passed by and the software could tell if the sensor was properly aligned. Additionally the sensor trailers were leveled using a carpenter's level. After the sensors were aligned and leveled they then needed to be calibrated to gather only the data from the lanes with active traffic.

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Figure 3-3 Final location for sensor 5 (taken by Mitsuru Saito).

The calibration was done by using a radar gun to measure the speed of an approaching vehicle and then verifying the correct speed showed up on the sensor. Figure 3-4 shows the radar gun being used to verify the speed of approaching vehicles. Figure 3-5 shows the lane configuration of sensor 2 during calibration. Using Figure 3-4 and Figure 3-5 as an example, the radar gun was used to measure the speed of a vehicle in lane four traveling about 65 mph and then the lane configuration was monitored on the computer to verify that the sensor recorded a

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vehicle traveling about 65 mph in lane four. This process was repeated for all sensors before the system was activated. There was no calibration necessary for the message boards and after all sensors were calibrated the system was ready to receive data and be activated.

Once the system was deployed and the system activated ASTI set up a private website where Brigham Young University (BYU) researchers and TAC members could view the speed of the sensors and the current message displayed in the VMS boards. Figure 3-6 is a screen shot of the ASTI web site looking at sensor 2. The web site provided a way to remotely verify that the system was functioning properly in conjunction with BYUs access to UDOT cameras in the study area from the BYU transportation laboratory. Shown in Figure 3-7 is the web site provided by ASTI illustrating the message displayed at VMS 2 when speeds were slowed to 35 mph.

3.5   Issues with Sensors and Questions with Turning on the VMSs

After the system was initially deployed and the data from the sensors was investigated, a few minor problems were discovered. Sensor 2 and sensor 4 were placed in a location where vehicles are on a horizontal curve and sometimes false data were received. These problems were easily fixed by relocating the sensors to avoid horizontal curves. Sensor 2 was moved to the north side of the North Temple bridge and sensor 4 about 50 feet south of its previous location. No other problems were encountered with these sensors after they were relocated. After the collection of the before data, it was discovered that sensor 3 was out of alignment. The alignment of sensor 3 was corrected in the field and all other sensors were checked to verify proper alignment.

Figure 3-4 Sensor calibration using radar gun (taken by Mitsuru Saito).
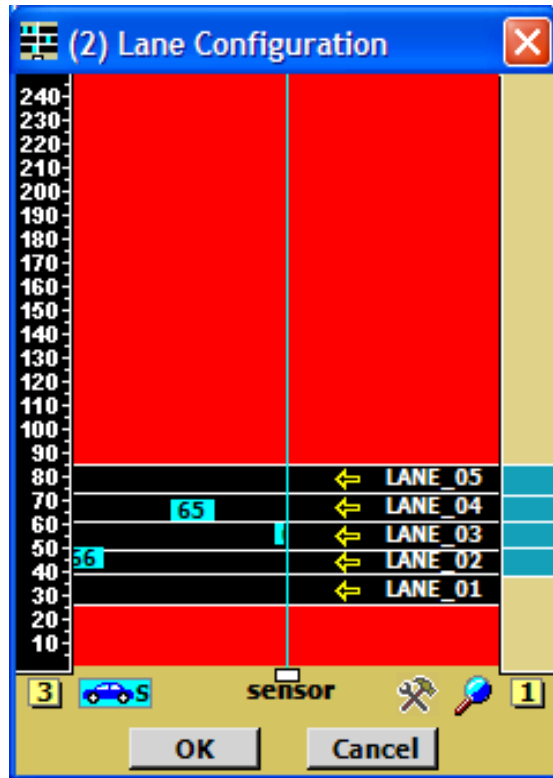
Figure 3-5 Calibration of sensor 2 using computer.
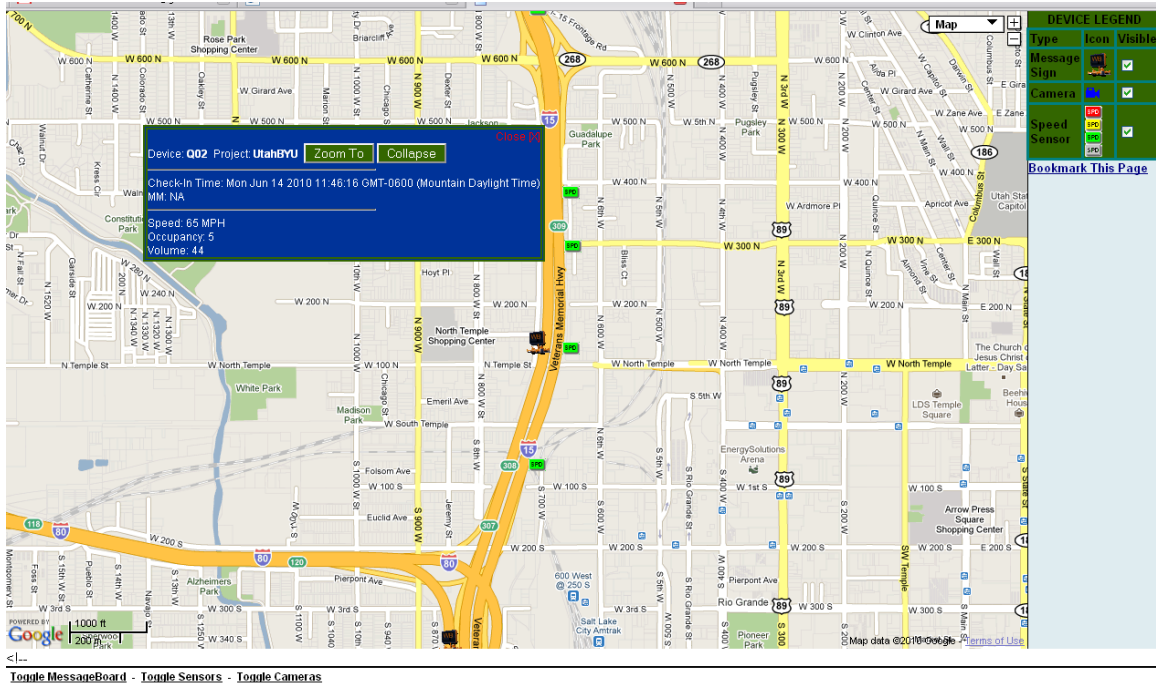
Figure 3-6 Example of system web site for sensor verification.
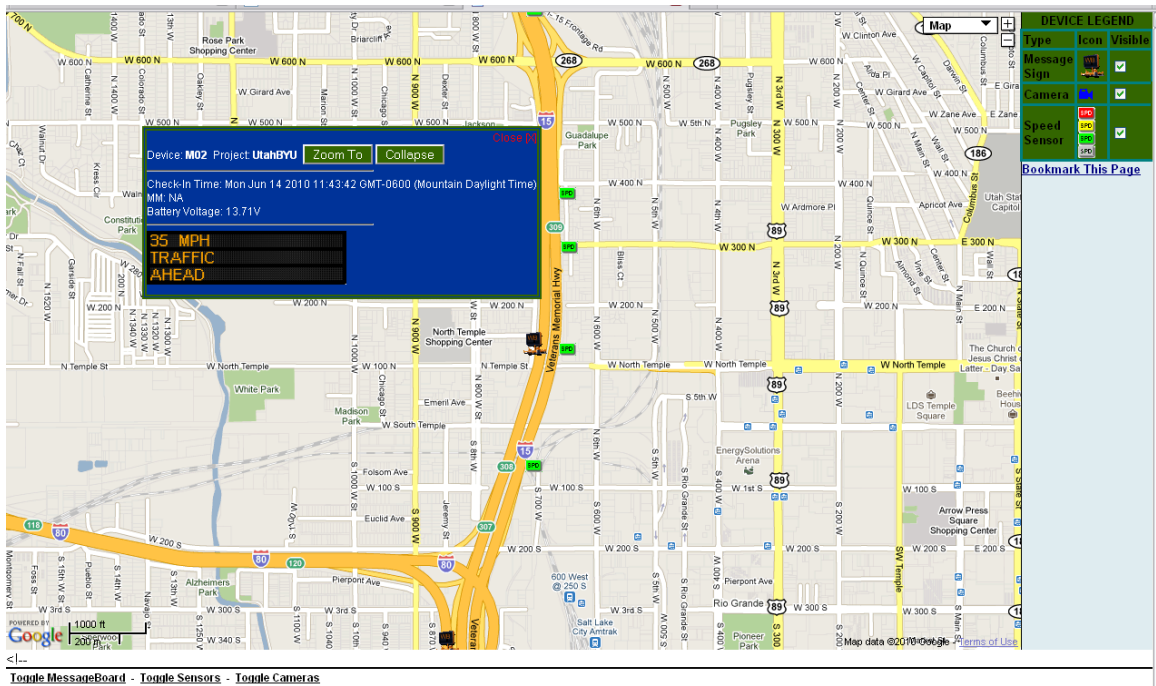
Figure 3-7 Example of system web site for VMS verification.

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www.manaraa.com

The data collection consisted of two parts, collection of before data and collection of after data. During the before data collection the VMS boards were overridden to show a blank screen, and the system did not show an advisory speed. It became apparent that there were a few questions that would need to be answered prior to turning on the VMS boards, to ensure safety in the test area:

- Is the message clear to drivers?

- How does the public know what the message means?

- Does the Utah Highway Patrol (UHP) consider this speed an enforceable speed limit?

- Does the system meet current MUTCD requirements?

- Are the VMSs placed in the best location to reach all drivers? and

- Will crash potential increase with more traffic control devices?

All of these questions were very important and it was assumed that they had previously been addressed. However, not all of the UDOT personnel who had some stake in this study were informed. Efforts were made to ensure that that these questions were answered to ensure safety in the work zone, prior to turning on the VMSs. The results of the research on these questions are presented in the remainder of this chapter.

3.5.1 Clarity of Message Resolved and UHP Informed

The messages that were to be shown on VMSs were given to the director of UDOTs Traffic Operation Center (TOC), who is familiar with messages that are given to drivers, to verify that the proposed messages as shown in Figure 3-2 would send a clear message to drivers. After the messages were approved by the TOC director, other concerned UDOT engineers were comfortable with the message. From the beginning of this project it was determined that no

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speed would be an enforceable speed limit. UHP was not directly told in the beginning of the project; however, they were informed before the VMSs were turned on that the speeds on the VMSs were only there as additional information for drivers and the speeds were not an enforceable speed limit.

3.5.2 MUTCD Requirements Addressed

A search was done to discover the compliance of our system with the current MUTCD requirements. Both the 2009 and 2003 versions of the MUTCD were reviewed. There was little information regarding the specific use of VMSs in work zones other than that found in the 2003 MUTCD which states "Highway and transportation organizations are encouraged to develop and experiment with changeable message signs (FHWA 2003). The 2009 version says that portable message signs are used in construction zones to display information such as what this study would give to drivers, i.e. real time information about traffic upstream of the driver's current position on the road (FHWA 2009). Additionally, the 2009 MUTCD recommends that VMSs be placed off of the shoulder or behind barriers to protect them and drivers (FHWA 2009). Many of the recommendations from both 2003 and 2009 were already reflected in the layout of this study.

3.5.3 VMS Locations and Crash Potential

The issue of the VMSs being in the best location for drivers came in part to one of the UDOT engineers driving through the construction zone from I-80 Eastbound driving onto I-15 northbound through the study site. As he drove through the study site he found that he never saw the VMSs. This was due to the fact that VMS 1 was located at least 0.5 miles prior to the merge from I-80 eastbound to I-15 northbound, and VMS 2 was placed on the left side of the road to

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help keep it safe as the only protection on the east side of the road would be orange barrels. Before simply moving the VMS to the east side of the road the option of placing a third VMS was explored. UDOT offered to place one of its own VMSs and pay for its use if it could be linked to the ASTI system. Attempts were made on several occasions and they were not successful enough to allow the use of UDOTs VMS. This was the last issue to resolve. As a result of this issue VMS 2 was placed on the right shoulder just north of sensor 2, with barrels to protect it. Figure 3-8 shows VMS 2 in its final location with barrels to protect it on the east side of I-15 just north of the bridge over North Temple St.

Figure 3-8 VMS 2 final location (taken by Aaron Wilson).

Crash data were obtained from UDOT for the time between the beginning of the project and April 2010. An analysis of the crashes determined that there were no crashes that were the result of traffic control devices. A summary of the crash data was given to UDOT engineers and it was concluded that the traffic control devices would not increase the crash risk in the

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construction zone. The summary in Table 3-1 shows the results of the crash analysis. Where ASB is the approach to the workzone form the South, and ANB is the approach to the workzone from the North. This table shows four things; the percent of crashes in the areas in and around the work zone, the percent of different types of crashes in the different approaches, the driver conditions at the time of the accident, and the percentage of factors contributing to the crash.

Table 3-1. Crash Data Summary

Area	ASB	Active Work Zone	ANB
Number of crashes	373	867	297
Percent of toal crashes	24%	57%	19%

Approach going Southbound (ASB)			Approach going Northbound (ANB)		
Crash Types	Quantity	Percent	Crash Types	Quantity	Percent
Angle	6	2%	Angle	15	5%
Rear End	198	54%	Rear End	118	40%
Head On	5	1%	Head On	0	0%
Side Swipe Same	75	20%	Side Swipe Same	70	24%
Single Vehicle	83	23%	Single Vehicle	90	31%
Total	367		Total	293	
Driver Condition	Quantity	Percent	Driver Condition	Quantity	Percent
Normal	354	96%	Normal	282	96%
Fatigue/Asleep	2	1%	Fatigue/Asleep	3	1%
Under influence	2	1%	Under influence	4	1%
Other	9	2%	Other	4	2%
Road Circumstances	Quantity	Percent	Road Circumstances	Quantity	Percent
None	305	83%	None	204	70%
Traffic device	0	0%	Traffic device	0	0%
Work zone	28	8%	Work zone	8	3%
Road condition	13	4%	Road condition	70	24%
Other	21	5%	Other	11	3%

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3.5.4   System Activation

On Tuesday April 27, 2010 one last attempt was made at UDOTs Region 2 office to see if UDOTs VMS would be able to work. ASTI was able to display a message; however, they could not maintain communication and change the message at will so the system was kept to its original setup, two VMSs and five sensors. Despite only having two VMSs, the decision was made that two would work as long as VMS 2 was on the right shoulder. At about 12:00 pm on April 27, 2010 the VMSs were taken out of override mode and advisory speed messages were displayed.

Although it was anticipated that the system would be functioning correctly from day one it was quickly determined that there were a couple of things that were not properly communicated to ASTI. The VMS began with a display of "63 MPH TRAFFIC AHEAD," as shown in Figure 3-9. The issue here was that UDOT and BYU anticipated the speed would be displayed in 5 MPH increments, and when speeds in excess of 55 MPH were seen, at the sensors, the VMS would only show "55 MPH TRAFFIC AHEAD" so as to not encourage drivers to go faster than the posted speed limit. During the time ASTI turned on the message boards one member of the BYU team was in communication with ASTI at the study site. The problem of showing speeds above 55 mph was quickly resolved while it took a few hours before the system was set up, as originally planned, to show only 5 mph increments. Figure 3-10 shows VMS 1 after the problems were fixed and the correct messages were being displayed.

Figure 3-9 First message displayed on VMS 2 (taken by Aaron Wilson).

Figure 3-10 VMS 1 showing correct message (taken by Aaron Wilson).

3.6 Chapter Summary

This chapter has presented a general overview of the site where the VASS was deployed. The system was rented from ASTI and it was shipped to Utah in early March 2010. The system was then setup in the study site with the help of ASTI, UDOT Research Division, the I-15 Beck Street construction crew, and BYU researchers. The system was then calibrated and verified to ensure proper operation. ASTI prepared a web site for the BYU research team and TAC members of the study, where the system could be monitored and inspected without driving to the sensors. Before data, data before the VMSs were turned on, was then collected. A few questions were answered with respect to turning on the VMSs, and the option of installing one of UDOTs VMSs was investigated to find a better way to inform drivers of the advisory speed. It was determined that the VMS would not be able to be used in this study and in late April 2010 the VMSs were turned on and system was active. Data collection of the after data began after the issues were resolved. Data reduction began as soon as the data were available.

4 DATA COLLECTION AND REDUCTION

This chapter sets forth the process used to collect and reduce these data in order to prepare them for statistical analysis. First, an explanation on how the data were collected is given followed by initial data reduction then additional data reduction that was necessary and finally a summary of the data collection and reduction process.

4.1 Data Collection

With the equipment in the field the system was ready to collect data. Traffic flow data (speed, volume, and occupancy) were collected by the Wavetronix microwave sensors at the study site and aggregated traffic flow data (that is, average speed, volume, and occupancy for pre-set reporting intervals, usually either one-minute or two-minute intervals) were sent to ASTI's server located at the ASTI office in the state of Delaware via cellular phone network. ASTI's computer then determined the correct message to be displayed. The computer then sent the proper speed message to the VMSs at the study site. ASTI would keep a record of the before and after data received from the sensors and also a record of the messages displayed on the VMSs in the after data. During the first few weeks of before data collection, there was no system in place for BYU to receive the data as it was being collected by ASTI. The general setup of the system was changing with the various moves of sensors as described in Chapter 3. In addition, the lane configuration of the various sensors was changed multiple times during the first few weeks to ensure that the system was functioning properly. The first few weeks of

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before data were later collected into one file but upon reviewing this data it was discovered that there were a lot of inconsistencies in the data. Additionally, there were many changes in sensor location and calibration during the time period making the data unreliable. Once the system was stabilized data collection and data transfer were resumed on a daily basis using a file transfer protocol (ftp) site.

4.2   Data Reduction Process

After the first few weeks of data collection an ftp site was set up on a BYU server where ASTI would place a file containing the data from each day. ASTI would update the file throughout the day and the complete file of the previous day would be available to the BYU team for analysis at the beginning of each day. This process started on March 30, 2010 and continued until June 14, 2010. The files were sent to BYU as .xml files and were then manually converted in to Microsoft Excel files for data reduction. Figure 4-1 shows an example of the raw data converted to Excel format.

As may be seen in Figure 4-1 there were many columns that were not needed in order to analyze traffic flow characteristics. Another task was to organize these data for statistical analysis, that is, they were also not in a usable format in the .xml file. For instance, the data obtained by all sensors at a specific time stamp was placed in one vertical column for a given variable (e.g. speed). In order to put the data into a usable format, Visual Basic for Applications (VBA) in Excel was used to extract only the usable columns and place them in a different sheet in the spreadsheet. The columns that were used for the data analysis are pictured in Figure 4-1: name3, check-in time, current message, ID4, speed, volume, and occupancy. The predefined names of the columns were not as easily recognized. Name3 was the name of the sensor or

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VMS; for instance, sensor 1 was abbreviated as Q01. Check-in-time was the date and time in coordinated universal time (UTC) when the device last sent or received changes to or from the ASTI system. Current message applied only to the message boards and was the current displayed message. ID4 applied only to the sensors and described the specific lane the data represent. For instance, sensor 1 had five lanes so there were rows numbered 1, 2, 3, 4, and 5 for the data received from sensor 1.

Speed represented the average speed in the specific lane since the last time a given sensor sent data to ASTI. Volume represented the number of observed vehicles at a specific sensor since the last time data was sent to the ASTI computer. Occupancy represented the percent of time that the vehicles occupied the area seen by the sensor. Once the necessary columns were extracted, the next task was to separate the data by time stamp. However, the time stamp that was recorded in the .xml file was in Greenwich Mean Time (GMT) also known as UTC. The time issue was resolved by writing a program using VBA in Excel. The program would extract only the time portion from the check-in time column in the original data, and then the time was changed from UTC time to Mountain Standard Time (MST). Figure 4-2 presents the result of this operation. Although the time issue was resolved, the data at this stage of data reduction were still not in a usable format for statistical analyses so a program using VBA was again created to rearrange the entire data set. The data were grouped by each sensor at a given timestamp to make the data useable for subsequent statistical analyses. Essentially the data were taken from the original format being vertical to a horizontal format and the data for an individual time were all grouped together. To establish consistency in the data set, the decision was made to use the time stamp from sensor 1 for all other four sensors even if some check-in times for other sensors were slightly different from that of sensor 1.

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Name	Address	DeviceCount	ID	WCFEnabled	WSDLEnabled	WSDLXSD	ID2
UtahBYU	Not Listening	7	6e590286-b675-40aa-bc80-8076a0c31636	TRUE	FALSE		065575a7-a2b0-4536-9a07-c217bc192333
UtahBYU	Not Listening	7	6e590286-b675-40aa-bc80-8076a0c31636	TRUE	FALSE		c2459ef6-8e9f-4eb9-9c7c-eeeac0d31774
UtahBYU	Not Listening	7	6e590286-b675-40aa-bc80-8076a0c31636	TRUE	FALSE		22584f81-c058-4cef-b911-de2290eb6863
UtahBYU	Not Listening	7	6e590286-b675-40aa-bc80-8076a0c31636	TRUE	FALSE		22584f81-c058-4cef-b911-de2290eb6863
UtahBYU	Not Listening	7	6e590286-b675-40aa-bc80-8076a0c31636	TRUE	FALSE		22584f81-c058-4cef-b911-de2290eb6863
UtahBYU	Not Listening	7	6e590286-b675-40aa-bc80-8076a0c31636	TRUE	FALSE		22584f81-c058-4cef-b911-de2290eb6863
UtahBYU	Not Listening	7	6e590286-b675-40aa-bc80-8076a0c31636	TRUE	FALSE		47022369-02e9-49bf-b4e1-9c29a9c31424
UtahBYU	Not Listening	7	6e590286-b675-40aa-bc80-8076a0c31636	TRUE	FALSE		47022369-02e9-49bf-b4e1-9c29a9c31424
UtahBYU	Not Listening	7	6e590286-b675-40aa-bc80-8076a0c31636	TRUE	FALSE		47022369-02e9-49bf-b4e1-9c29a9c31424
UtahBYU	Not Listening	7	6e590286-b675-40aa-bc80-8076a0c31636	TRUE	FALSE		47022369-02e9-49bf-b4e1-9c29a9c31424
UtahBYU	Not Listening	7	6e590286-b675-40aa-bc80-8076a0c31636	TRUE	FALSE		c06652f6-73c1-412e-b9ee-514453224083
UtahBYU	Not Listening	7	6e590286-b675-40aa-bc80-8076a0c31636	TRUE	FALSE		c06652f6-73c1-412e-b9ee-514453224083
UtahBYU	Not Listening	7	6e590286-b675-40aa-bc80-8076a0c31636	TRUE	FALSE		c06652f6-73c1-412e-b9ee-514453224083
UtahBYU	Not Listening	7	6e590286-b675-40aa-bc80-8076a0c31636	TRUE	FALSE		1d046eaa-59fb-410f-812d-c88ce10fdaac
UtahBYU	Not Listening	7	6e590286-b675-40aa-bc80-8076a0c31636	TRUE	FALSE		1d046eaa-59fb-410f-812d-c88ce10fdaac
UtahBYU	Not Listening	7	6e590286-b675-40aa-bc80-8076a0c31636	TRUE	FALSE		1d046eaa-59fb-410f-812d-c88ce10fdaac
UtahBYU	Not Listening	7	6e590286-b675-40aa-bc80-8076a0c31636	TRUE	FALSE		e7a83d9b-e4a9-41c6-a9b6-eda45e402569
UtahBYU	Not Listening	7	6e590286-b675-40aa-bc80-8076a0c31636	TRUE	FALSE		e7a83d9b-e4a9-41c6-a9b6-eda45e402569

Name3	Voltage	CheckInTime	ProjectID	DeviceType	AuxDeviceFlags	AuxDeviceType
M01	12.42	5/3/2010 12:31:37 PM UTC	6e590286-b675-40aa-bc80-8076a0c31636	Portable	DynamicMessageBoard	DynamicMessageBoard
M02	12.62	5/3/2010 12:31:38 PM UTC	6e590286-b675-40aa-bc80-8076a0c31636	Portable	DynamicMessageBoard	DynamicMessageBoard
Q01	NA	5/3/2010 12:31:36 PM UTC	6e590286-b675-40aa-bc80-8076a0c31636	Portable	RealTimeMeasurementSensor	GenericMeasurementDevice
Q01	NA	5/3/2010 12:31:36 PM UTC	6e590286-b675-40aa-bc80-8076a0c31636	Portable	RealTimeMeasurementSensor	GenericMeasurementDevice
Q01	NA	5/3/2010 12:31:36 PM UTC	6e590286-b675-40aa-bc80-8076a0c31636	Portable	RealTimeMeasurementSensor	GenericMeasurementDevice
Q01	NA	5/3/2010 12:31:36 PM UTC	6e590286-b675-40aa-bc80-8076a0c31636	Portable	RealTimeMeasurementSensor	GenericMeasurementDevice
Q01	NA	5/3/2010 12:31:36 PM UTC	6e590286-b675-40aa-bc80-8076a0c31636	Portable	RealTimeMeasurementSensor	GenericMeasurementDevice
Q02	NA	5/3/2010 12:31:36 PM UTC	6e590286-b675-40aa-bc80-8076a0c31636	Portable	RealTimeMeasurementSensor	GenericMeasurementDevice
Q02	NA	5/3/2010 12:31:36 PM UTC	6e590286-b675-40aa-bc80-8076a0c31636	Portable	RealTimeMeasurementSensor	GenericMeasurementDevice
Q02	NA	5/3/2010 12:31:36 PM UTC	6e590286-b675-40aa-bc80-8076a0c31636	Portable	RealTimeMeasurementSensor	GenericMeasurementDevice
Q02	NA	5/3/2010 12:31:36 PM UTC	6e590286-b675-40aa-bc80-8076a0c31636	Portable	RealTimeMeasurementSensor	GenericMeasurementDevice
Q02	NA	5/3/2010 12:31:36 PM UTC	6e590286-b675-40aa-bc80-8076a0c31636	Portable	RealTimeMeasurementSensor	GenericMeasurementDevice
Q03	NA	5/3/2010 12:31:36 PM UTC	6e590286-b675-40aa-bc80-8076a0c31636	Portable	RealTimeMeasurementSensor	GenericMeasurementDevice
Q03	NA	5/3/2010 12:31:36 PM UTC	6e590286-b675-40aa-bc80-8076a0c31636	Portable	RealTimeMeasurementSensor	GenericMeasurementDevice
Q03	NA	5/3/2010 12:31:36 PM UTC	6e590286-b675-40aa-bc80-8076a0c31636	Portable	RealTimeMeasurementSensor	GenericMeasurementDevice
Q04	NA	5/3/2010 12:31:36 PM UTC	6e590286-b675-40aa-bc80-8076a0c31636	Portable	RealTimeMeasurementSensor	GenericMeasurementDevice
Q04	NA	5/3/2010 12:31:36 PM UTC	6e590286-b675-40aa-bc80-8076a0c31636	Portable	RealTimeMeasurementSensor	GenericMeasurementDevice
Q04	NA	5/3/2010 12:31:36 PM UTC	6e590286-b675-40aa-bc80-8076a0c31636	Portable	RealTimeMeasurementSensor	GenericMeasurementDevice
Q05	NA	5/3/2010 12:31:36 PM UTC	6e590286-b675-40aa-bc80-8076a0c31636	Portable	RealTimeMeasurementSensor	GenericMeasurementDevice
Q05	NA	5/3/2010 12:31:36 PM UTC	6e590286-b675-40aa-bc80-8076a0c31636	Portable	RealTimeMeasurementSensor	GenericMeasurementDevice

DeviceMode	Duration	CurrentMessage	Latitude	Longitude	MileMarker	Location	Count	ID4	Direction	Speed	Volume	Occupancy	Address5
Default	0	[pt20o]55 MPH[nl]TRAFFIC[nl]AHEAD	40.76146	-111.91421	NA	NA							
Default	0	[pt20o]55 MPH[nl]TRAFFIC[nl]AHEAD	40.77211	-111.91009	NA	NA							
Default	0		40.76786	-111.91211	NA	NA	5	1	N	66.891	0	0	166.143.97.40:10452
Default	0		40.76786	-111.91211	NA	NA	5	2	N	74.684	6	2.1210938	166.143.97.40:10452
Default	0		40.76786	-111.91211	NA	NA	5	3	N	72.734	9	3.3710938	166.143.97.40:10452
Default	0		40.76786	-111.91211	NA	NA	5	4	N	72.938	9	3.7773438	166.143.97.40:10452
Default	0		40.76786	-111.91211	NA	NA	5	5	N	70.285	5	2.9335938	166.143.97.40:10452
Default	0		40.77202	-111.91053	NA	NA	5	1	N	74.895	3	1	166.143.97.41:10453
Default	0		40.77202	-111.91053	NA	NA	5	2	N	68.879	11	4.25	166.143.97.41:10453
Default	0		40.77202	-111.91053	NA	NA	5	3	N	67.348	7	2.5039063	166.143.97.41:10453
Default	0		40.77202	-111.91053	NA	NA	5	4	N	67.027	14	5.8984375	166.143.97.41:10453
Default	0		40.77202	-111.91053	NA	NA	5	5	-	66	9	3	166.143.97.41:10453
Default	0		40.77568	-111.91035	NA	NA	3	1	N	75.969	0	0	166.143.97.42:10454
Default	0		40.77568	-111.91035	NA	NA	3	2	N	71.352	14	5.40625	166.143.97.42:10454
Default	0		40.77568	-111.91035	NA	NA	3	3	N	68.684	7	2.6289063	166.143.97.42:10454
Default	0		40.77756	-111.91047	NA	NA	3	1	N	72.266	0	0	166.143.97.43:10455
Default	0		40.77756	-111.91047	NA	NA	3	2	N	67.617	12	4.6523438	166.143.97.43:10455
Default	0		40.77756	-111.91047	NA	NA	3	3	N	64.855	6	2.2578125	166.143.97.43:10455
Default	0		40.7841	-111.91201	NA	NA	2	1	N	60.563	20	16.925781	166.143.97.45:10457
Default	0		40.7841	-111.91201	NA	NA	2	2	N	63.871	6	2.4453125	166.143.97.45:10457

Figure 4-1 Raw data converted to Excel format, and separated into three lines (small part of full data).

The data were separated by each sensor at a given time stamp, then average speeds were calculated using a weighted average formula. The weighted average was determined based on the total volume in each lane at that specific time stamp. An example of the final data reduction can be seen in Figure 4-3; the data are presented in separate rows for each sensor, whereas, normally in the Excel spreadsheet the data are actually in the same row. The VBA in Excel was slightly modified for the after data to include the message from VMS 1 and VMS 2 for the given timestamp. The entire VBA process was connected together into one Excel workbook that would open individual workbooks for each day, make all the changes, save the workbook, and close the workbook. The VBA would then open the next workbook and continue until there were no more to open.

Device Nan	CheckInTime	UTC Time	MTN Time	Lane #	Speed	Volume	Occupancy
M01	3/30/2010 3:08:23 PM UTC	15:08:23	9:08:23				
M02	3/30/2010 3:05:29 PM UTC	15:05:29	9:05:29				
Q01	3/30/2010 3:10:49 PM UTC	15:10:49	9:10:49	1	71.91015625	1	0.33984375
Q01	3/30/2010 3:10:49 PM UTC	15:10:49	9:10:49	2	68.7421875	4	1.5078125
Q01	3/30/2010 3:10:49 PM UTC	15:10:49	9:10:49	3	69.0390625	7	2.7109375
Q01	3/30/2010 3:10:49 PM UTC	15:10:49	9:10:49	4	68.16015625	11	4.69921875
Q01	3/30/2010 3:10:49 PM UTC	15:10:49	9:10:49	5	66.47265625	9	4.5
Q02	3/30/2010 3:11:10 PM UTC	15:11:10	9:11:10	1	70.22265625	3	1.1015625
Q02	3/30/2010 3:11:10 PM UTC	15:11:10	9:11:10	2	67.140625	9	3.45703125
Q02	3/30/2010 3:11:10 PM UTC	15:11:10	9:11:10	3	64	11	4.84375
Q02	3/30/2010 3:11:10 PM UTC	15:11:10	9:11:10	4	67.203125	10	4.23828125
Q02	3/30/2010 3:11:10 PM UTC	15:11:10	9:11:10	5	66	9	3
Q03	3/30/2010 3:10:48 PM UTC	15:10:48	9:10:48	1	64.4453125	0	0
Q03	3/30/2010 3:10:48 PM UTC	15:10:48	9:10:48	2	73.8984375	8	2.64453125
Q03	3/30/2010 3:10:48 PM UTC	15:10:48	9:10:48	3	63.90625	12	5.69921875
Q04	3/30/2010 2:57:48 PM UTC	14:57:48	8:57:48	1	16	0	0
Q04	3/30/2010 2:57:48 PM UTC	14:57:48	8:57:48	2	66	18	7
Q04	3/30/2010 2:57:48 PM UTC	14:57:48	8:57:48	3	60	13	6
Q05	3/30/2010 3:10:50 PM UTC	15:10:50	9:10:50	1	67.3203125	36	15.19921875
Q05	3/30/2010 3:10:50 PM UTC	15:10:50	9:10:50	2	61.19140625	15	11.21875

Figure 4-2 Intermediate data reduction (small part of full data).

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4.3   Additional Data Reduction

In an early meeting about the statistics it was determined that because the timestamps in the data were not consistent that the data would need to be summarized to a given interval. It was determined that the data would be grouped into approximately 15-minute intervals.

VBA was again used to group the data into the 15-minute intervals and then summarize the data appropriately. The data at each sensor, for a given interval, were then summarized into several different categories: volume, number of data points, number of lanes used, mean speed, max speed, minimum speed, 85th percentile speed, 15th percentile speed, and standard deviation of speeds.

In addition, there were other categories that were added to the categories just discussed to make up the complete statistical data set. These were date, hour, quarter of the particular hour, day, time of day, weather, peak slow down (yes or no), and before or after. An example of the data is given in Figure 4-4 and Figure 4-5. Figure 4-4 shows the categories that are the same for each 15-minute interval and Figure 4-5 is an example of the data for each sensor. Only data for sensor 1 is shown in the figure but the data file that was analyzed contains data for all five sensors.

Though the system collected speed, volume, and occupancy data; only speed and volume data were used for statistical analysis. The ideal set of data to be analyzed statistically would be the volume data, or flow rate. Due to the limitations on volume data, in this study surrogate parameters were considered for evaluating the effectiveness of the VASS at queue mitigation. The surrogate parameters used were mean speed, 15th percentile speed, 85th percentile speed, standard deviation of speeds, and volume. These surrogates could replace the volume data because if the overall speed during a slowdown is increased with the system on it could indicate

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that the VASS was responsible for the better speeds. In addition, if the standard deviation of the

speeds could be reduced this would indicate that the system was responsible for keeping traffic at

a more consistent speed. If the speeds went up or there was less variation in the speeds it could

be inferred that the VASS was effective at reducing queue.

Time	Sensor 1 Speed					Volume						
	Lane 1	Lane 2	Lane 3	Lane 4	Lane 5	Lane 1	Lane 2	Lane 3	Lane 4	Lane 5	Total Vol.	Average Spd. S1
0:01:41	66.28906	72.3125	68.51563	59.86719	67.50391	0	2	8	4	6	20	66.86210938
0:03:41	79.29297	75.42188	69.57422	68.69141	68.07813	1	1	13	12	4	31	69.54158266
0:04:41	79.29297	71.95313	71.54297	70.61328	66.85156	0	4	13	6	5	28	70.56459263
0:06:41	64.21875	72.23047	72.20313	70.09766	65.49609	1	6	12	10	8	37	69.97255068
0:08:41	72.66016	71.25	69.07422	64.41406	75.35938	0	4	11	6	5	26	69.54221755
0:10:41	72.66016	70.59766	65.5625	67.875	63.42578	0	2	5	6	8	21	65.88876488
	Time	Sensor 2 Speed				Volume						
		Lane 1	Lane 2	Lane 3	Lane 4	Lane 1	Lane 2	Lane 3	Lane 4	Total Vol.	Average Spd. S2	
	0:01:41	70.19922	65.60938	62.51953	60.62109	2	8	6	5	21	63.976	
	0:03:41	70.76172	65.36719	65.36719	66.91797	3	12	11	2	28	66.05594	
	0:04:41	66.26172	69.21875	64.35156	64.42578	4	12	7	4	27	66.80874	
	0:06:41	69.31641	68.55859	65.61328	61.85938	6	11	12	5	34	66.66762	
	0:08:41	69.81641	66.80469	60.65625	67.64844	6	12	8	5	31	65.937	
	0:10:41	69.82422	63.46875	66.19141	64.91016	2	6	10	7	25	65.46984	
		Time	Sensor 3 Speed			Volume						
			Lane 1	Lane 2	Lane 3	Lane 1	Lane 2	Lane 3	Total Vol.	Average Spd. S3		
		0:01:41	78.98828	66.39453	59.81641	3	12	8	23	65.74915		
		0:03:41	65.23828	67.98438	63.76172	1	10	10	21	65.84282		
		0:04:41	74.63281	70.01563	69.05078	4	14	6	24	70.54395		
		0:06:41	76.64063	68.10547	70.15625	7	10	10	27	71.07784		
		0:08:41	76.75	69.03516	64.94922	4	10	6	20	69.35234		
		0:10:41	76.67188	66.37109	68.3125	2	5	4	11	68.94993		
		Time	Sensor 4 Speed			Volume						
			Lane 1	Lane 2	Lane 3	Lane 1	Lane 2	Lane 3	Total Vol.	Average Spd. S4		
		0:01:41	71.64063	64.19141	57.16016	5	13	10	28	63.01046		
		0:03:41	65.54688	62.57422	60.62109	1	8	8	17	61.82996		
		0:04:41	67.90625	64.51563	61.94531	5	12	6	23	64.5822		
		0:06:41	72.41797	65.25391	62.18359	3	9	7	19	65.25391		
		0:08:41	70.94922	66.21094	58.31641	2	6	5	13	63.90355		
		0:10:41	72.77344	64.17188	66.54297	2	4	2	8	66.91504		
		Time	Sensor 5 Speed		Volume							
			Lane 1	Lane 2	Lane 1	Lane 2	Total Vol.	Average Spd. S5	Message Board 1		Message Board 2	
		0:01:41	63.17578	60.59766	14	11	25	62.04140625	55 MPH TRAFFIC AHEAD		55 MPH TRAFFIC AHEAD	
		0:03:41	61.71484	62.09375	4	5	9	61.92534722	55 MPH TRAFFIC AHEAD		55 MPH TRAFFIC AHEAD	
		0:04:41	62.05469	62.35156	13	8	21	62.16778274	55 MPH TRAFFIC AHEAD		55 MPH TRAFFIC AHEAD	
		0:06:41	60.55078	61.35938	8	6	14	60.89732143	55 MPH TRAFFIC AHEAD		55 MPH TRAFFIC AHEAD	
		0:08:41	64.10547	58.61328	6	4	10	61.90859375	55 MPH TRAFFIC AHEAD		55 MPH TRAFFIC AHEAD	
		0:10:41	70.84766	58.75391	5	4	9	65.47265625	55 MPH TRAFFIC AHEAD		55 MPH TRAFFIC AHEAD	

Figure 4-3 Final reduced data (small part of full data).

4.4   Chapter Summary

The daily data were made available to BYU researchers by ASTI for analysis using an ftp site established by BYU. Daily raw data were converted to Excel format and VBA programs were written to convert the daily data into a usable format for data analysis. After the data were reduced the decision was made to group the data by 15-minute intervals to establish consistency in the time period for data analysis. After the data were grouped into 15-minute intervals they were added to one spreadsheet and the type of weather was added as recorded by the BYU researchers. The data then became ready for statistical analysis.

Quarter	Hour	Date	Day	Time_of_day	Weather	Peak_Slow_Down	Before_or_After	Before_0__After_1
1st Quarter	9:00	3/30/2010	Tuesday	Morning	Sunny	No	Before	0
2nd Quarter	9:00	3/30/2010	Tuesday	Morning	Sunny	No	Before	0
3rd Quarter	9:00	3/30/2010	Tuesday	Morning	Sunny	No	Before	0
4th Quarter	9:00	3/30/2010	Tuesday	Morning	Sunny	No	Before	0
1st Quarter	10:00	3/30/2010	Tuesday	Morning	Sunny	No	Before	0
2nd Quarter	10:00	3/30/2010	Tuesday	Morning	Sunny	No	Before	0
3rd Quarter	10:00	3/30/2010	Tuesday	Morning	Sunny	No	Before	0
4th Quarter	10:00	3/30/2010	Tuesday	Morning	Sunny	No	Before	0
1st Quarter	11:00	3/30/2010	Tuesday	Mid-Day	Sunny	No	Before	0
2nd Quarter	11:00	3/30/2010	Tuesday	Mid-Day	Sunny	No	Before	0
3rd Quarter	11:00	3/30/2010	Tuesday	Mid-Day	Sunny	No	Before	0
4th Quarter	11:00	3/30/2010	Tuesday	Mid-Day	Sunny	No	Before	0
1st Quarter	12:00	3/30/2010	Tuesday	Mid-Day	Sunny	No	Before	0
2nd Quarter	12:00	3/30/2010	Tuesday	Mid-Day	Sunny	No	Before	0
3rd Quarter	12:00	3/30/2010	Tuesday	Mid-Day	Sunny	No	Before	0
4th Quarter	12:00	3/30/2010	Tuesday	Mid-Day	Sunny	No	Before	0

Figure 4-4 First half of data ready for statistical analysis (small part of full data).

Quarter	S1_Volume	S1_Data_pts	S1_Lanes	S1_Mean_Speed	S1_Max_Speed	S1_Min_Speed	S1_85th_Speed	S1_15th_Speed	S1_Standard_Dev
1st Quarter	136	15	5	69.0890625	76.77734375	63.609375	71.8296875	66.16328125	3.349976536
2nd Quarter	338	40	5	69.79501953	77.68359375	64.0078125	74.38710938	66.06601563	3.869404148
3rd Quarter	306	35	5	69.15859375	76.6015625	62.9453125	73.20117188	65.33046875	3.665048875
4th Quarter	375	40	5	70.20664063	85.3125	60.96875	74.09609375	64.85488281	4.565914273
1st Quarter	285	30	5	69.7390625	76.7734375	60.2578125	74.54921875	65.9671875	3.901250761
2nd Quarter	417	45	5	70.60147569	80.3203125	63.5234375	73.92109375	66.2203125	4.173449397
3rd Quarter	357	40	5	69.8734375	76.9375	63.1640625	73.60839844	65.94511719	3.575945282
4th Quarter	385	40	5	70.60732422	78.2265625	62.83203125	74.71113281	66.72675781	3.8661042
1st Quarter	420	40	5	70.50195313	79.13671875	64.21875	73.06171875	67.56132813	3.502147533
2nd Quarter	466	45	5	70.14791667	77.421875	63.81640625	73.33671875	67.17734375	3.11820457
3rd Quarter	426	45	5	70.39010417	79.42578125	62.09375	74.14765625	65.89140625	3.936391576
4th Quarter	476	45	5	72.13376736	97.89453125	57.77734375	74.65703125	67.30859375	7.379426549
1st Quarter	383	40	5	70.53662109	77.29296875	64.32421875	73.92324219	67.4234375	3.264812557
2nd Quarter	432	40	5	69.48330078	75.2265625	62.2109375	73.2046875	65.60996094	3.614403032
3rd Quarter	491	45	5	71.55494792	81.06640625	65.73828125	74.996875	68.2703125	3.721020281
4th Quarter	401	40	5	71.21865234	80.0234375	65.5390625	74.10332031	68.05097656	3.413675301

Figure 4-5 Second half of data ready for statistical analysis (small part of full data).

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5   DATA ANALYSIS

The data were initially analyzed using SAS statistical software (SAS Institute Inc. 2008) using only days that did not have a slowdown present. For the analysis a slowdown was defined as observed speeds below 50 mph for a period of 30 minutes or more. Interactions that were investigated include weather, daygroup, time of day, and before and after the VMSs were turned on. Since the measurements are not being taken on the same vehicles, the before and after data are considered independent. After this initial analysis was performed it was discovered that there was not sufficient data to analyze the interaction of weather. This might have been foreseen due to the fact that most days were sunny or cloudy but few were rainy or snowy during the study period. In most cases there were not many days in the before data that matched the same type of weather pattern in the after data. Hence, the weather factor was removed from subsequent analyses.

The data were evaluated to see when there were slow downs. Graphs were created for each 24 hour period. Then the graphs were investigated to see what days there were slowdowns and what days there were no slowdowns. It was observed that there was rarely a slowdown in the hours not associated with the evening peak. As a consequence of this discovery, analysis on the data was only done on the peak period. As an example, Figure 5-1 shows the graph of May 15, 2010 when there was no slow down except during the evening peak.
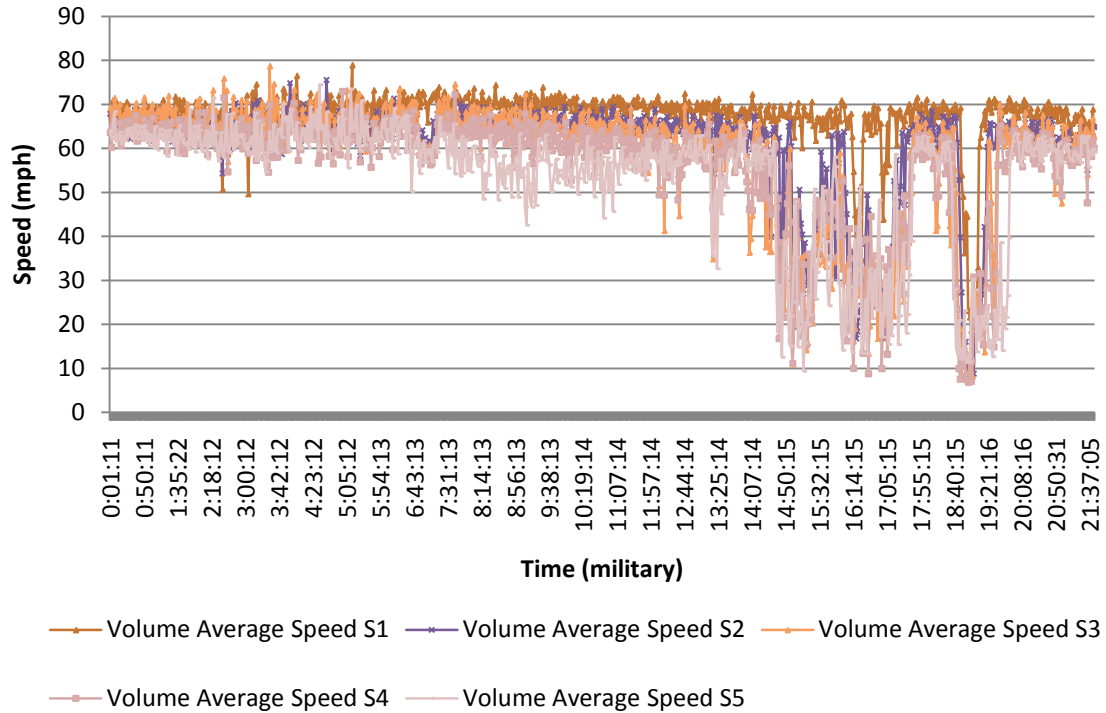
Figure 5-1 Example of daily speed graph.

5.1   Data Analysis Method

The initial analysis, considering only data when a traffic slowdown was not present, showed no difference that was statistically significant at the 95 percent confidence level. This result was expected since when there was no slow down, the VMSs displayed "55 MPH TRAFFIC AHEAD" and traffic would often flow faster than the advised 55 mph. It was not anticipated that the system would impact traffic in any way when there was not a slowdown in the work zone approach area; however, the analysis was done to prove this expectation. After this exploratory data analysis, a more detailed analysis was done using the complete before and after data when there was a slow down during the evening peak. As mentioned in the previous section the data were regrouped into 15-minute intervals. In traffic engineering, 15-minute intervals are a very common interval to group data for analysis.

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After the data were regrouped into 15-minute intervals, one more new factor was added to the analysis. The factor was whether there was a traffic slowdown present during the peak period or not. The peak period, from 3:00 PM to 7:00 PM, was determined by observing hourly distributions of traffic. This was the time period of most concern in this study area. During the evening peak period, the study area could get congested due to the many commuters leaving Salt Lake City going northbound on weekdays. After the data were regrouped, they were analyzed to look for significant difference in before and after data. The data were analyzed using a hypothesis test about the difference between two population means of independent samples; in other words, a means test was performed through an Analysis of Variance (ANOVA). The observational unit used in this study was the mean of all speeds contained in a specific 15-minute interval. The null hypothesis tested in the ANOVA was that there was no difference between the before and after data in speed, volume, or standard deviation of speeds, whereas the alternative hypothesis was that there was a statistically significant difference between the before and after data in speed, volume, or standard deviation of speeds.

The reason why an ANOVA test was performed was to compare the means of the before and after data to determine if the system was effective at achieving smoother traffic flow through the work zone, and possibly contributing to the reduction of queues at the work zone entrance. Figure 5-2 shows a sample of the statistical significance test output from SAS (SAS Institute Inc. 2008). This was a case of the before and after test result for the 15th percentile speed at sensor 4 testing for the existence of a slowdown during the evening peak on a weekend (see A in Figure 5-2). The top of the output shows all the specific information about that particular analysis including the daygroup, time of day, and evidence of a slowdown (see B in Figure 5-2). The section directly under "The GLM Procedure" gives the results of the ANOVA and the

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significance of the model (see C in Figure 5-2). Farther down the output are the results of the before and after significance test (see D in Figure 5-2). A p-value of 0.05 or less indicates significance of the before and after data at the 95 percent confidence level. In this example the weather is not significant at a p-value of 0.0839 while the before and after factor is significant at a p-value of <0.0001.

```
                              The SAS System
14189
              A   Separate Models Analysis for S4_15th_Speed
                                             09:05 Monday, August 23,
2010
   B    --------- Peak_Slow_Down=Yes daygroup=Weekend Time_of_day=Evening Peak ----------

                    C    The GLM Procedure

Dependent Variable: S4_15th_Speed    S4_15th_Speed

                               Sum of
   Source                  DF      Squares     Mean Square     F Value    Pr > F

   Model                    4    8913.70776     2228.42694        7.69    <.0001

   Error                  177   51263.47478      289.62415

   Corrected Total        181   60177.18255


            R-Square    Coeff Var      Root MSE     S4_15th_Speed Mean

            0.148124    41.29083       17.01835              41.21581


   Source                  DF     Type I SS     Mean Square     F Value    Pr > F
 D  Weather                 3   1957.441743      652.480581        2.25    0.0839
    Before_or_After         1   6956.266022     6956.266022       24.02    <.0001
```

Figure 5-2 Sample of ANOVA output, sensor 4, 15th percentile speed (small part of actual output).

Figure 5-3 shows an example of the output of the ANOVA on mean speeds from SAS (SAS Institute Inc. 2008). The output shows the separate model means from the statistical analysis, or the mean of all values in the dataset that have the same factors. On the left side of the figure is the observation number corresponding to the dependent variable as shown and then

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the different factors are shown. The factors of interest were a "yes" in the peak slow down column, all various day groups, the "evening peak" time period, and the before and after means. The figure also shows the sample size, means, and standard deviation used by the ANOVA to determine statistical significance. As an example, the observations of interest in Figure 5-3 are observations 229 and 230. These numbers 229 and 230 correspond to the sensor 1 volume when there was a slowdown, on Mondays, during the evening peak period with no interactions from the weather. The mean volume is shown in the column labeled "mean" on the right side of the figure.

```
                                          The SAS System                                    15670
                                   Separate Model means        09:05 Monday, August 23, 2010

                                                        B
                       P                                e
                       e                                f
                       a                                o
                       k            T                   r
                       _            i                   e
             d         S            m                   _
             e         l    d       e                   o
             p         o    a       _             W     r                                S
             e         w    y       o             e     _                                t
             n         _    g       f             a     A                                d
             d         D    r       _             t     f              M                 _
   O         e         o    o       d             h     t              e                 d
   b         n         w    u       a             e     e              a                 e
   s         t         n    p       y             r     r      n       n                 v

  217  S1_Volume  Yes Monday  Evening               Cloudy         20    237.950000   114.720014
  218  S1_Volume  Yes Monday  Evening               Sunny          45    223.866667   131.698105
  219  S1_Volume  Yes Monday  Evening               cloudy         20    280.650000   115.971991
  220  S1_Volume  Yes Monday  Evening                      After   46    236.391304   135.596539
  221  S1_Volume  Yes Monday  Evening                      Before  39    245.435897   112.910257
  222  S1_Volume  Yes Monday  Evening               Cloudy Before  20    237.950000   114.720014
  223  S1_Volume  Yes Monday  Evening               Sunny  After   26    202.346154   141.779531
  224  S1_Volume  Yes Monday  Evening               Sunny  Before  19    253.315789   113.553244
  225  S1_Volume  Yes Monday  Evening               cloudy After   20    280.650000   115.971991
  226  S1_Volume  Yes Monday  Evening Peak          Cloudy         16    651.000000   142.899498
  227  S1_Volume  Yes Monday  Evening Peak          Sunny          47    546.000000   221.113683
  228  S1_Volume  Yes Monday  Evening Peak          cloudy         16    721.375000   111.514947
  229  S1_Volume  Yes Monday  Evening Peak                 After   47    580.638298   239.534642
  230  S1_Volume  Yes Monday  Evening Peak                 Before  32    635.312500   121.729059
  231  S1_Volume  Yes Monday  Evening Peak          Cloudy Before  16    651.000000   142.899498
  232  S1_Volume  Yes Monday  Evening Peak          Sunny  After   31    508.000000   256.406318
  233  S1_Volume  Yes Monday  Evening Peak          Sunny  Before  16    619.625000    98.379452
  234  S1_Volume  Yes Monday  Evening Peak          cloudy After   16    721.375000   111.514947
  235  S1_Volume  Yes Monday  Mid-Day               Cloudy         16    441.062500    57.766736
  236  S1_Volume  Yes Monday  Mid-Day               Sunny          48    473.125000    79.920339
  237  S1_Volume  Yes Monday  Mid-Day               cloudy         16    450.250000    47.028360
  238  S1_Volume  Yes Monday  Mid-Day                      After   48    476.062500    70.772758
  239  S1_Volume  Yes Monday  Mid-Day                      Before  32    441.250000    67.181027
  240  S1_Volume  Yes Monday  Mid-Day               Cloudy Before  16    441.062500    57.766736
  241  S1_Volume  Yes Monday  Mid-Day               Sunny  After   32    488.968750    77.511075
  242  S1_Volume  Yes Monday  Mid-Day               Sunny  Before  16    441.437500    77.397647
  243  S1_Volume  Yes Monday  Mid-Day               cloudy After   16    450.250000    47.028360
  244  S1_Volume  Yes Monday  Morning               Cloudy         10    346.800000    40.575855
  245  S1_Volume  Yes Monday  Morning               Sunny          38    289.210526   112.421783
  246  S1_Volume  Yes Monday  Morning               cloudy         20    377.500000    61.677856
  247  S1_Volume  Yes Monday  Morning                      After   58    319.655172   106.132250
  248  S1_Volume  Yes Monday  Morning                      Before  10    346.800000    40.575855
  249  S1_Volume  Yes Monday  Morning               Cloudy Before  10    346.800000    40.575855
  250  S1_Volume  Yes Monday  Morning               Sunny  After   38    289.210526   112.421783
  251  S1_Volume  Yes Monday  Morning               cloudy After   20    377.500000    61.677856
  252  S1_Volume  Yes Weekend Early Morning Cloudy                 24     74.041667    47.484074
```

Figure 5-3 Sample means output from SAS (small part of actual output).

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5.2   Parameters Used to Evaluate VASS for Queue Mitigation

It is ideal to count the number of vehicles in the queue at a given location during the collection of the before and after data to evaluate the effectiveness of the VASS at mitigating queues in work zones. It was not practical for the BYU researchers to visit the site during slowdowns and count the number of vehicles in the queue for two reasons. First, occurrence of queues were random and the researchers would not be able to visit the site as queues begin to form (it takes about one hour from the BYU Transportation Lab to the study site). Second, even though a queue was viewable from the Transportation Lab using UDOT cameras in or near the study site, researchers did not have authority to move the cameras from the lab; hence, they were not able to see the extent of queues formed from the Lab.

Due to the limitations on volume data surrogate parameters were considered for evaluating the effectiveness of the VASS at queue mitigation. The surrogate parameters used were mean speed, 15th percentile speed, 85th percentile speed, standard deviation of speeds, and volume. These surrogate parameters were selected because of the following characteristics that these parameters can be associated with queue mitigation.

- If 15th percentile and 85th percentile speeds in the after period are closer to the mean, traffic flow during the after period was smoother than during the before period, thus contributing to a reduction of queue.

- If mean speed in the after data is closer to the work zone speed limit or a few miles per hour less, traffic flow was smoother than in the before period and contributed to the reduction of queue.

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- If 85th percentile speed in the after period is closer to the work zone speed limit compared to the before period, drivers were complying with the reduced speed limit for the work zone, in turn creating a safer driving condition in work zones.

- If standard deviation of speed of the after period is smaller than during the before period, traffic flow was smoother in the after period, thus implying less probability for queues to form.

- As for the volume, throughput of the facility is evaluated. If throughput of the work zone was greater in the after period than in the before period, it is considered that the VASS is improving traffic flow, thus helping reduce the potential for queue formation.

The results of the analysis on these parameters are presented in the remainder of this chapter.

5.3   Results of the Statistical Analysis

Similar to the results of the previous analysis for no slow-down periods, there was generally no statistical significance between the before and after data when no slowdown was present during the peak period at the 95 percent confidence level. This outcome was expected; without the presence of a slow down the traffic flowed smoothly through the study area. In other words, without the presence of a stalled or slow vehicle or a crash the traffic rarely slowed down, even to the speed limit of 55 mph in the study site. The traffic in this area was often traveling at speeds greater than 60 mph through the work zone. Even when a slowdown was present during the peak hours, analysis results of the volume turned out to be inconclusive to say affirmatively whether the system was effective or ineffective at mitigating queues in work zones.

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The sample means of mean speeds, 15th percentile speed, 85th percentile speed, standard deviation of speeds, and volumes are presented in Table 5-1, Table 5-2, Table 5-3, Table 5-4, and Table 5-5 respectively. These tables are all similar in structure and are a representation of the means of the before and after data of the surrogate parameters evaluated. The tables present the statistical significance of the before and after data at the 95 percent confidence level as well as the means, given the factors presented below. The tables show the daygroup, significance, after mean, after sample size (n), before mean, before sample size (n), and the difference between the after and the before means for each sensor from top to bottom starting with Sensor 1 and progressing to sensor 5. The daygroup shows the particular day or group of days that were analyzed together. The meaning of the significance column is that if the difference in before and after data is considered statistically significant by the statistical analysis done using the SAS statistical software, then there is a "Yes" in the significance column. If the before and after data are not significant then a "No" is placed showing that the difference between before and after data is not statistically significant. The after and before means are direct outputs form the SAS software as well as the after and before sample sizes. The difference column shows the difference between the after data and the before data and is shown to help show how different the after and before data are.

The factors considered are the existence of a significant slowdown (speeds below 50 mph for about 30 min; see Figure 5-1), daygroup (Friday, Monday, Weekend, and Workday), and time of day (evening peak). Queues rarely formed in the study area during hours other than the evening peak throughout the data collection period, therefore off-peak times were not analyzed. A significant slowdown was identified by the reduction in speeds below 50 mph for about 30 minutes at one of the five sensors. Waiting 30 minutes allowed verification that the slowdown

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was not a minor delay where traffic only slowed for a short time and no queue formed. Although the slowdowns did not always stretch the entire length of the study zone, and all sensors did not show the evidence of a slowdown, as defined, they were still included in the analysis as a period containing a slowdown to maintain a sufficient number of data points for the means test. Daygroups considered for analyses were Monday, Workday (Tuesday, Wednesday, and Thursday), Friday, and Weekend (Saturday and Sunday). Due to the large amounts of traffic traveling northbound from Salt Lake City going toward the study area and approaching the work zone, the time of day that was of most interest was that of the evening peak. Although traffic was lighter in the early part of the 3:00 hour and traffic usually lightens up before the end of the 6:00 hour the evening peak was determined to be the time from 3:00 p.m. to 7:00 p.m.

5.3.1   Comparison of before and after mean speeds at evening peak

Table 5-1 shows the sensor number, the existence of a slowdown, the statistical results of the means test on before and after mean speeds, the before and after mean speeds, the number of data points associated with the before and after data, and the difference between the before and after data mean speeds. The difference was calculated by subtracting the before from the after. The difference showed the direction the particular item of interest went relative to the after data. If the number was positive then the after data mean was larger than the before mean. The instances that were statistically significant are shown in light grey and those that are not highlighted are not statistically significant. As an example, looking at sensor 4 when there was a slowdown on the weekend the mean speed in the after data was 49 mph and in the before data it was 44 mph. There was a large difference in the sample size of the before and after and the

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difference in speed was 5 mph. The SAS analysis showed this example to be significant at the 95 percent confidence level.

The only consistent statistical conclusion from the whole table is that at the 95 percent confidence level the before and after mean speeds were significantly different, during the weekend daygroup when there was a slowdown during the evening peak. This could possibly be due to the fact that on the weekends the northbound lanes only had two lanes whereas on weekdays three lanes were given to the northbound drivers. Additionally, looking at the difference of the speeds, Table 5-1 shows that the after speeds were consistently closer to the speed limit, except for at sensor 1. Sensor 1 was rarely affected by slowdowns because it was farthest from the active work area and mean speeds were often higher than the 55 mph speed limit during most of the data collection period.

Table 5-1. Results of the ANOVA on Mean Speed at Evening Peak

Sensor #	Slowdown ?	Daygroup	Significance	After	n	Before	n	Difference	Slowdown ?	Daygroup	Significance	After	n	Before	n	Difference
S1	No	Friday	-	-	-	68	32	-	Yes	Friday	Yes	59	112	70	16	-11
		Monday	No	68	37	66	32	2		Monday	No	67	47	66	32	1
		Weekend	Yes	69	32	71	16	-2		Weekend	Yes	65	144	59	38	6
		Workday	No	68	181	67	176	1		Workday	No	61	142	61	16	0
S2	No	Friday	-	-	-	66	32	-	Yes	Friday	Yes	55	112	67	16	-12
		Monday	No	65	37	64	32	1		Monday	No	61	47	63	32	-2
		Weekend	Yes	65	32	68	16	-3		Weekend	Yes	56	144	48	38	8
		Workday	Yes	64.7	181	65	176	-0.3		Workday	No	57	142	55	16	2
S3	No	Friday	-	-	-	67	32	-	Yes	Friday	No	57	96	63	16	-6
		Monday	No	66	37	66	32	0		Monday	No	60	47	63	32	-3
		Weekend	No	62	32	62	16	0		Weekend	Yes	49	112	43	38	6
		Workday	No	67	181	67	176	0		Workday	No	57	142	57	16	0
S4	No	Friday	-	-	-	63	32	-	Yes	Friday	No	53	112	60	16	-7
		Monday	No	64	37	62	32	2		Monday	No	56	47	58	32	-2
		Weekend	No	60	32	61	16	-1		Weekend	Yes	49	144	44	38	5
		Workday	No	63	181	63	176	0		Workday	No	54	142	53	16	1
S5	No	Friday	-	-	-	62	30	-	Yes	Friday	No	49	112	50	16	-1
		Monday	No	61	37	59	32	2		Monday	No	52	47	52	32	0
		Weekend	No	60	32	60	16	0		Weekend	Yes	48	144	42	38	6
		Workday	No	61	181	61	176	0		Workday	No	49	142	51	16	-2

5.3.2 Comparison of before and after 15th percentile speeds at evening peak

The results of the means test on the 15th percentile speeds are presented in Table 5-2. The conclusion was similar to that of the mean speeds. At the 95 percent confidence level the before and after 15th percentile speeds were significantly different, with respect to the weekend daygroup when there was a slowdown during the evening peak. However, at sensors 2 and 3, even though the difference in 15th percentile speeds was not statistically significant, the 15th percentile speeds were still closer to the mean speeds indicating that the VASS system helped make the traffic flow smoother and reduce variation in traffic speeds. The instances that were statistically significant are shown in light gray and those that were not statistically significant are not highlighted.

Table 5-2. Results of the ANOVA on 15th Percentile Speed at Evening Peak

Sensor #	Slowdown ?	Daygroup	Significance	After	n	Before	n	Difference	Slowdown ?	Daygroup	Significance	After	n	Before	n	Difference
S1	No	Friday	-	-	-	64	32	-	Yes	Friday	Yes	54	112	66	16	-12
		Monday	No	64	37	62	32	2		Monday	No	62	47	62	32	0
		Weekend	Yes	66	32	68	16	-2		Weekend	Yes	61	144	54	38	7
		Workday	No	64	181	63	176	1		Workday	No	55	142	54	16	1
S2	No	Friday	-	-	-	62	32	-	Yes	Friday	Yes	50	112	64	16	-14
		Monday	No	62	37	61	32	1		Monday	No	57	47	59	32	-2
		Weekend	No	62	32	64	16	-2		Weekend	Yes	50	144	41	38	9
		Workday	Yes	61.5	181	61.8	176	-0.3		Workday	No	52	142	51	16	1
S3	No	Friday	-	-	-	61	32	-	Yes	Friday	No	52	96	58	16	-6
		Monday	No	63	37	62	32	1		Monday	No	55	47	58	32	-3
		Weekend	No	59	32	56	16	3		Weekend	Yes	42	112	35	38	7
		Workday	No	64	181	63	176	1		Workday	No	52	142	52	16	0
S4	No	Friday	-	-	-	60	32	-	Yes	Friday	No	48	112	55	16	-7
		Monday	No	61	37	60	32	1		Monday	No	51	47	53	32	-2
		Weekend	No	57	32	57	16	0		Weekend	Yes	43	144	36	38	7
		Workday	No	60	181	60	176	0		Workday	No	48	142	48	16	0
S5	No	Friday	-	-	-	60	30	-	Yes	Friday	No	45	112	44	16	1
		Monday	No	59	37	56	32	3		Monday	No	47	47	47	32	0
		Weekend	No	57	32	57	16	0		Weekend	Yes	41	144	35	38	6
		Workday	No	59	181	58	176	1		Workday	No	44	142	48	16	-4

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As an example, looking at sensor 4 when there was a slowdown on the weekend the 15th percentile speed in the after data is 43 mph and in the before data it was 36 mph. There was a large difference in the sample size of the before and after data, the sample size stayed the same for all analyses. The difference in the 15th percentile speed was 7 mph as shown in the difference column. The SAS analysis showed this example to be significant at the 95 percent confidence level.

5.3.3 Comparison of before and after 85th percentile speeds at evening peak

Table 5-3 shows the comparison of the before and after 85th percentile speeds. The 85th percentile speeds resulted in conclusions similar to the other speed comparisons. The conclusion is that at the 95 percent confidence level the before and after 85th percentile speeds were significantly different, only with respect to the weekend daygroup when there was a slowdown during the evening peak. This comparison also shows some reduction in 85th percentile speeds when no statistical significance was present. The instances that were statistically significant are shown in light gray and those that were not statistically significant are not highlighted. The 85th percentile speed is the speed at which it is expected to be close to the speed limit. The after 85th percentile speeds were closer to the speed limit as seen in Table 5-3, particularly at sensors 3, 4, and 5 when significance was seen, and during the weekend daygroup.

This result indicates that the VASS was effective at smoothing the flow of traffic in the study area. Looking at sensor 4 when there was a slowdown on the weekend the 85th percentile speed in the after data is 56 mph and in the before data it is 52 mph. Again the sample size was unchanged and the difference in the 85th percentile speed was 4 mph.

Table 5-3. Results of the ANOVA on 85th Percentile Speed at Evening Peak

Sensor #	Slowdown ?	Daygroup	Significance	After	n	Before	n	Difference	Slowdown ?	Daygroup	Significance	After	n	Before	n	Difference
S1	No	Friday	-	-	-	72	32	-	Yes	Friday	Yes	64	112	73	16	-9
		Monday	No	72	37	70	32	2		Monday	No	71	47	70	32	1
		Weekend	Yes	72	32	74	16	-2		Weekend	Yes	69	144	64	38	5
		Workday	No	71	181	71	176	0		Workday	No	67	142	68	16	-1
S2	No	Friday	-	-	-	69	32	-	Yes	Friday	Yes	60	112	70	16	-10
		Monday	No	69	37	67	32	2		Monday	No	65	47	67	32	-2
		Weekend	Yes	68	32	71	16	-3		Weekend	Yes	62	144	54	38	8
		Workday	Yes	68	181	68.3	176	-0.3		Workday	No	62	142	60	16	2
S3	No	Friday	-	-	-	71	32	-	Yes	Friday	No	62	96	68	16	-6
		Monday	No	70	37	70	32	0		Monday	No	65	47	69	32	-4
		Weekend	No	66	32	68	16	-2		Weekend	Yes	56	112	51	38	5
		Workday	No	71	181	70	176	1		Workday	No	63	142	62	16	1
S4	No	Friday	-	-	-	66	32	-	Yes	Friday	No	57	112	64	16	-7
		Monday	No	67	37	65	32	2		Monday	No	60	47	63	32	-3
		Weekend	No	63	32	65	16	-2		Weekend	Yes	56	144	52	38	4
		Workday	No	66	181	66	176	0		Workday	No	59	142	58	16	1
S5	No	Friday	-	-	-	64	30	-	Yes	Friday	No	54	112	55	16	-1
		Monday	No	64	37	62	32	2		Monday	No	56	47	57	32	-1
		Weekend	No	62	32	64	16	-2		Weekend	Yes	55	144	48	38	7
		Workday	No	64	181	64	176	0		Workday	No	64	142	66	16	-2

5.3.4 Comparison of before and after standard deviations at evening peak

Table 5-4 shows the statistical results of the means test on before and after standard deviation of speeds, the before and after standard deviation of speeds, the number of data points associated with the before and after data, and the difference between the before data and after data. The difference was calculated by subtracting the before from the after. The difference showed the direction the particular item of interest went relative to the after data. If the number was positive then the after data mean was larger than the before mean. The instances that were statistically significant are shown in light gray and those that were not statistically significant are not highlighted. Table 5-4 shows comparisons of the before and after standard deviation of the speeds. Similar to the previous comparisons, the before and after standard deviations were significantly different at the 95 percent confidence level on the weekends when there was a slow down during the evening peak. A consistent trend can be seen in the difference at sensors 3, 4,

and 5 which indicates that the after mean standard deviations were less than the before standard deviations. The fact that the average standard deviation of speeds in the after data was less than the before data average standard deviation of speeds indicates that there was less variation in the speeds in the after data during the evening peak. Less variation in the after speed distribution implies that the VASS system was helpful in improving traffic flow, and may be a sign that queue can be reduced by the VASS. As an example, the sample size was unchanged from the sample size in the mean speed example. Looking at sensor 4, when there was a slowdown on the weekend, the standard deviation of speeds in the after data was 6.63 mph and in the before data it is 8.06 mph. The difference in the standard deviations was -1.43 mph indicating that the speed variation was decreased by the VASS system. The SAS analysis showed this example to be significant at the 95 percent confidence level.

Table 5-4. Results of the ANOVA on Standard Deviation of Speeds at Evening Peak

Sensor #	Slowdown ?	Daygroup	Significance	After	n	Before	n	Difference	Slowdown ?	Daygroup	Significance	After	n	Before	n	Difference
S1	No	Friday	-	-	-	3.75	32	-	Yes	Friday	No	5.38	112	3.75	16	1.63
		Monday	No	4.1	37	4.34	32	-0.24		Monday	No	4.22	47	3.96	32	0.27
		Weekend	No	3.35	32	3.02	16	0.33		Weekend	Yes	4.2	144	5.18	38	-0.98
		Workday	No	4.01	181	3.97	176	0.04		Workday	No	5.93	142	6.71	16	-0.78
S2	No	Friday	-	-	-	3.21	32	-	Yes	Friday	No	4.43	112	3.01	16	1.42
		Monday	No	3.26	37	3.14	32	0.12		Monday	No	3.99	47	3.89	32	0.10
		Weekend	No	2.98	32	3.20	16	-0.22		Weekend	Yes	5.96	144	6.23	38	-0.27
		Workday	No	3.21	181	3.14	176	0.08		Workday	No	4.67	142	4.24	16	0.43
S3	No	Friday	-	-	-	4.15	32	-	Yes	Friday	No	5.1	96	5.15	16	-0.04
		Monday	No	3.31	37	3.75	32	-0.44		Monday	No	5.01	47	5.32	32	-0.31
		Weekend	Yes	3.51	32	6.80	16	-3.29		Weekend	Yes	7.43	112	8.79	38	-1.36
		Workday	No	3.5	181	3.48	176	0.02		Workday	No	5.33	142	4.68	16	0.65
S4	No	Friday	-	-	-	3.05	32	-	Yes	Friday	No	4.72	112	5.04	16	-0.31
		Monday	Yes	2.94	37	2.96	32	-0.03		Monday	No	4.66	47	4.92	32	-0.26
		Weekend	No	2.8	32	3.94	16	-1.11		Weekend	Yes	6.63	144	8.06	38	-1.43
		Workday	No	2.89	181	2.90	176	0.00		Workday	No	5.17	142	4.82	16	0.35
S5	No	Friday	-	-	-	2.49	30	-	Yes	Friday	No	4.5	112	5.41	16	-0.91
		Monday	No	2.67	37	3.07	32	-0.40		Monday	No	4.13	47	4.85	32	-0.73
		Weekend	No	2.72	32	3.46	16	-0.74		Weekend	No	7.07	144	7.46	38	-0.39
		Workday	No	2.46	181	2.71	176	-0.25		Workday	No	4.63	142	3.62	16	1.01

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5.3.5 Comparison of before and after 15-minute volumes at evening peak

Table 5-5 shows the sensor number, the existence of a slowdown, the statistical results of the means test on before and after volumes, the before and after volumes, the number of data points associated with the before and after volumes, and the difference between the before and after data volumes. The difference was calculated by subtracting the before from the after. If the difference was positive then the after data volume was larger than the before data volume. The instances that were statistically significant are shown in light gray and those that were not statistically significant are not highlighted. The comparison of before and after 15-minute volume data was difficult to accurately gather due to the fact that an additional queue mitigation technique was used in the work zone. The number of lanes was changed from two to three and then from three back to two by using a moveable barrier system in the work zone. The movable barrier changed the northbound lane configuration from two lanes to three lanes in the evening peak hours on weekdays. The barrier was moved between 11:00 am and 1:00 pm, then back to two lanes between 8:00 pm and 10:00 pm daily. The difficulty was that the sensors would need to be calibrated every time the barrier was moved in order to gather accurate data, for each lane, from the sensors. It was determined that recalibrating the system twice a day in order to gather all of the volume data would not be feasible. Therefore, only volume data from the outer two lanes that were consistently used by traffic in the work zone were collected at sensor 5. At sensor 1 there were no lane closures associated with the construction; therefore, sensor 1 was set up to monitor all five lanes of traffic. Sensors 2 and 3 were set up to gather data from all lanes except those that would be closed with barrels during the morning peak. Sensor 4 was calibrated to gather data from all three lanes even though it was known that the inside lane at sensor 4 would be closed off with barrels at times. Sensor 4 was not affected by the movable concrete

barrier but the inside lane was closed with barrels. The purpose in gathering data from all three lanes at sensor 4 was to gather the most accurate information possible regarding the traffic volume entering the work zone. Since only sensors 1 and 4 collected data from all lanes of traffic, only the data from sensors 1 and 4 are appropriate for the analyses. As an example, looking at sensor 4 when there was a slowdown on the weekend the mean volume for all lanes in the after data was 440 vehicles in a 15 minute period and the before volume was 418 vehicles in a 15 minute period. The sample size was unchanged from the previous examples and the difference in volume of vehicles is -47 vehicles for the average 15-minute period. The SAS analysis showed this example to be significant at the 95 percent confidence level.

Looking at the volumes of sensors 1 and 4 in Table 5-5, the observed volume difference was conflicting on the weekend where consistent significance was seen in the speed data. Sensor 1 shows that there was an increase in traffic volume on the weekend, and sensor 4 shows a decrease in volume on the weekend. The interesting part about this is that both sensors 1 and 4 saw speeds consistent with a conclusion of supporting the VASS, whereas, when looking at the 15-minute traffic volume the sensors show different results. The dynamic changes in traffic flows from I-80 eastbound to I-15 northbound and the traffic exiting the highway at the 600 north exit might have affected the volume data. This made statistical conclusions difficult to infer from the 15-minute traffic volumes. Due to the limitations on the collected data, no further analyses on 15-minute traffic volumes were preformed.

Table 5-5. Results of the ANOVA on Before and After 15 Minute Volumes at Evening Peak

Sensor #	Slowdown ?	Daygroup	Significance	After	n	Before	n	Difference	Slowdown ?	Daygroup	Significance	After	n	Before	n	Difference
S1	No	Friday	-	-	-	707	32	-	Yes	Friday	Yes	682	112	791	16	-109
		Monday	No	668	37	680	32	-12		Monday	Yes	581	47	635	32	-54
		Weekend	No	445	32	484	16	-39		Weekend	Yes	543	144	442	38	101
		Workday	No	683	181	696	176	-13		Workday	No	675	142	667	16	8
S2	No	Friday	-	-	-	721	32	-	Yes	Friday	Yes	674	112	771	16	-97
		Monday	No	688	37	686	32	2		Monday	Yes	585	47	658	32	-73
		Weekend	No	464	32	493	16	-29		Weekend	Yes	544	144	429	38	115
		Workday	No	708	181	696	176	12		Workday	No	676	142	663	16	13
S3	No	Friday	-	-	-	566	32	-	Yes	Friday	Yes	540	96	616	16	-76
		Monday	No	526	37	520	32	6		Monday	Yes	433	47	499	32	-66
		Weekend	No	357	32	403	16	-46		Weekend	Yes	388	112	324	38	64
		Workday	No	550	181	542	176	8		Workday	No	527	142	532	16	-5
S4	No	Friday	-	-	-	582	32	-	Yes	Friday	Yes	410	112	327	16	83
		Monday	No	524	37	522.7	32	0.8		Monday	Yes	528	47	633	32	-105
		Weekend	No	357	32	371	16	-14		Weekend	Yes	440	144	487	38	-47
		Workday	No	547	181	542	176	5		Workday	No	529	142	486	16	43
S5	No	Friday	-	-	-	317	30	-	Yes	Friday	Yes	323	112	367	16	-44
		Monday	No	325	37	331	32	-6		Monday	Yes	278	47	293	32	-15
		Weekend	No	430	32	446	16	-16		Weekend	Yes	452	144	418	38	34
		Workday	No	333	181	334	176	-1		Workday	No	323	142	318	16	5

5.4   Chapter Summary

The data were analyzed using SAS statistical software (SAS Institute Inc. 2008) to investigate the possibility of statistical differences between the before and after speed and volume data. Factors that were considered are the weather, daygoup, time of day, and existence of a significant slowdown. After the initial statistical analysis was done it was discovered that the weather was not a factor that could be compared using the before and after data due to limited types of weather during the study period. It was also found that there was not enough consistency in the volume data to come to any statistical conclusions. Volume data were not gathered from all lanes at sensors 2, 3, and 5, that is, volume data were not complete at these sensors. No statistical conclusions can be made regarding the effectiveness of the VASS at mitigating queues, in terms of volume data, due to the constraints of the data collection. Therefore, surrogate parameters were investigated to evaluate the effectiveness of the system.

These parameters included mean speed, 15th percentile seed, 85th percentile speed, and standard deviation of speeds.

Significance was measured at the 95 percent confidence level. Two separate situations were investigated to see the effects of the system on mitigating queues. The first situation was when no significant slowdown was present during the evening peak period. The results of this analysis on the mean speed, 15th percentile seed, 85th percentile speed, and standard deviation did not show any statistical significance at the 95 percent confidence level. It was expected that when there was not a slow down the system would not make a difference since the message displayed was simply a reminder to drivers that they should be traveling at the speed limit of 55 mph.

The second situation was when there was a significant slow down during the evening peak period. The results of the statistical analysis, when there was a slow down during the evening peak, showed that, at the 95 percent confidence level, there was a statistical difference in all (mean, 15th percentile, and 85th percentile) speeds of traffic at all sensors on the weekends. Standard deviation of speeds was also looked at when there was a significant slowdown during the evening peak. Similarly at the 95 percent confidence level it was found that the standard deviation of the speeds was reduced with the advisory speed presented on the VMS boards. This implies that the traffic flow in the work zone entrance was better with the VMS turned on and the VASS active. It may be speculated that drivers on weekends were unfamiliar drivers instead of weekday commuters. Not being familiar with work zone conditions, drivers might have been more likely to heed the speed message presented on VMS boards. Another purely speculative idea is that because the number of lanes was reduced for the northbound traffic on weekends that

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the slowdowns were more significant. Though these ideas are stated here, they are purely speculative and the results of this study neither confirm nor disprove them.

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6 CONCLUSIONS AND RECOMMENDATIONS

UDOT is continuously trying to upgrade its transportation network facilitating a need for managing construction across the state. With increased construction comes the need to temporarily reduce the number of traffic lanes. One of the results of decreasing traffic lanes is increased queue at the work zone entrance, therefore, transferring delays on to drivers in the form of time delay. The purpose of this study was to evaluate the effectiveness of a VASS at mitigating these queues that inevitably form in work zone entrances when demand exceeds capacity. It was anticipated that by implementing a VASS in work zone areas, the queues would be reduced and vehicle flow would be improved.

This study had three objectives:

- Research VASS systems that are available for use by UDOT,

- Select and implement a VASS at a work zone in Utah, and

- Perform a statistical analysis to evaluate the effectiveness of the VASS at mitigating queues in the work zone.

The results of each task are summarized in the remaining sections, including a section outlining recommendations for future implementation of a VASS.

6.1 Literature Review

The first step in evaluating the VASS was to perform a literature review to investigate what options were available for implementation. First a review of the research done to help

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mitigate queues was conducted. Many different methods were outlined that may help mitigate queues in work zone areas. Research was then conducted to investigate the types of systems that were available to implement at the project level. Only one study was found that dealt specifically with an advisory speed system in work zones (see Kwon et al. 2007). Most of the research, which used similar technologies as VASS, dealt specifically with controlling speeds at specific times in the year, during adverse weather conditions, or periods of congestion (Rama 1999).

6.2   System Implementation

After the particular VASS was chosen and details were worked out for renting the equipment from ASTI, a long-term work zone was selected to deploy the system. BYU researchers worked with UDOT to identify an appropriate work zone for a period of about one year. The selected work zone was that of the Beck Street Widening project in north Salt Lake City. After the appropriate work zone was identified, ASTI was contacted and the delivery of the equipment was scheduled for early March 2010. The VASS was deployed to the work zone in early March 2010 and the system began gathering before data, with the VMSs set to blank screens. Questions were raised with turning on the VMSs; however; they were eventually resolved and about one month of before data was collected before the VMSs were activated and the after data collection began. While after data were collected, before data were converted from .xml files to Excel spreadsheets. VBA programs were then used to convert the raw data to a format that would allow for statistical analysis. The system was removed from the study area on June 14, 2010 and after data collection ended that morning. After the system was removed from

the field the remaining data were converted to the same format as the before data using the same VBA programs in Excel. The data were then ready for the statistical analysis.

6.3   Statistical Analysis

For the statistical analysis, the data were considered independent because the observations were not always taken on the same vehicles. An initial statistical analysis was performed on the data when there was no slowdown present. This analysis showed no statistical significance as would be expected since the traffic was not impacted by slowdowns. It was discovered the intervals of data reporting were not consistent (data reporting intervals were sometimes one minute and sometimes two minutes). These data points were then grouped into 15-minute intervals in order to better analyze the data. VBA programs were used to group the data into the 15-minute intervals, summarize the data, and create one file for statistical analysis with the addition of weather information. Before the final analysis in SAS (SAS Institute Inc. 2008) a column was added that specified whether or not there was a slowdown during the peak period of a given 15-minute interval. The null hypothesis was that there was no difference in the before and after implementation of a VASS. A statistical analysis was performed on the entire data set using SAS (SAS Institute Inc. 2008). The independent variables that were considered to evaluate the effectiveness of VASS on queue mitigation were: mean speed, 15th percentile speed, 85th percentile speed, standard deviation of speeds, and volume. The results of the analysis were compiled and put into tables as shown in Chapter 5. Statistical conclusions about the effectiveness of the VASS can be made by looking at the significance in these tables, taken from *p*-values in the SAS output.

6.4   Analysis Results

The volume data were determined to be the best factor to evaluate the effectiveness of the VASS on queue mitigation; however, due to the fact that data from all lanes could only be collected from some of the sensors, particularly in the active work zone, the volume data were determined to be inappropriate to evaluate the effectiveness of the system. Attempts were made to fully investigate the volume data; however, the volumes obtained at sensors 2, 3, and 5 were not the entire volume at the location of the sensors. The number of lanes at sensors 2 and 3 were reduced by one lane during the off-peak time and sensor 5 had a movable concrete barrier that reduced the lanes to two lanes during the off-peak hours and back to three lanes during peak hours. Trends found in the volumes at sensors 1 and 4 were not consistent. Therefore, the only reliable way to investigate the effectiveness of the system at mitigating queues was to look at the speed data. As a result, the only statistical conclusion that could be made from the speed data was that on the weekends when there was a slow down during the evening peak there was a statistical difference, at the 95 percent confidence level, between the before and after data among the four speed parameters chosen, indicating the VASS was helpful in improving traffic flow at this study site during evening peak hours when there was slow down in traffic on weekends. One speculative reason for the significance only on weekends (not verified by this study) could be that the lane configuration did not change on the weekends and there remained only two lanes open to northbound traffic on weekends.

6.5   Conclusions

Due to the limitations and inconsistencies with the volume data, the speed data were used as surrogate parameters for evaluating the effectiveness of the VASS used in this study. The

following were major conclusions drawn from the deployment work and from the in-depth statistical analysis performed in the study:

- This study was instrumental in understanding driver behavior at work zones when a large VMS instead of a small sign was investigated; it also utilized ITS technology and used an advisory speed instead of the more common VSL application.

- The VASS system consisting of microwave sensors and VMSs was relatively problem free once the system was calibrated and operational. The feature to remotely monitor the operation of the sensors was very helpful to the researchers to identify which sensors might be malfunctioning.

- The placement of microwave sensors and VMSs required careful considerations, and potential safety issues and interpretation or misinterpretation of VMS messages needed to be thoroughly discussed among the stakeholders and problems be resolved before turning on VMSs.

- The statistical analysis indicated that when there was not a slow down present in the work zone during the evening peak, the VASS was not effective at mitigating queues any more than without the VASS deployed in the work zone. This result was expected since there was no queue to reduce when there was no slowdown.

- The statistical analysis showed that when there was a slow down during the evening peak, the VASS was effective at increasing speeds and decreasing variation in speeds during the weekends, thus providing smooth traffic flow to drivers.

- During the evening peak when there was a slowdown, weekdays showed no statistical significance when comparing the before and after data.

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- The VASS used in the study produced a large data set of traffic flow characteristics at work zone entrances. This by-product of the study can be used for studying traffic flow characteristics and capacities at work zone entrances.

6.6 Recommendations

Based on the findings and conclusions of this study a set of recommendations are presented in this section:

- Renting a VASS costs money, and UDOT is tied to the specific system rented. Therefore, it is recommended that engineers investigate the cost of the implementation at a proposed work zone, and the type of VASS, in order to decide if a VASS will be feasible at the desired location.

- It is recommended that VASSs not be used in short term work zones due to the costs associated with renting a VASS and the time required to set up the system in the work zone.

- Engineers should conduct preliminary studies of work zones to evaluate if queues are expected to form regularly as a result of work zone restrictions.

- The VASS investigated in this study shows some level of effectiveness, on weekends, when implemented in the long term work zone. Hence, it is recommended that UDOT analyze more cases to reach more definitive results on the effectiveness of VASSs.

- As a way to lower costs, it is recommended that UDOT engineers consider using UDOTs existing sensors and/or VMS boards to give drivers more information. One issue to be considered with using existing VMSs and sensor systems is the cost

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associated with trying to establish an algorithm in order to provide real-time information to drivers.

- It is recommended that UDOT perform additional studies on the effectiveness of VASSs in long term work zones, where movable median barriers are not used and where queues are expected to form regularly during the construction process, as these situations were not fully experienced in this study.

- A VASS creates a large amount of traffic flow data. This data can be used to better predict traffic flow characteristics at work zone entrances. Implementation of a VASS is recommended to generate traffic flow data that can be used to better predict future traffic flow characteristics and capacities in work zones.

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