EMPIRICAL ASSESSMENT OF A CONGESTION AND WEATHER-RESPONSIVE
ADVISORY VARIABLE SPEED LIMIT SYSTEM

by

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To my beloved parents, for their endless love, support and encouragement
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Traffic congestion and safety along urban corridors have become major challenges for most highway agencies in the United States. Adverse weather conditions also present a considerable challenge, both in terms of safety and operations. All these problems along with the increasingly limited resources for infrastructure expansion have urged transportation agencies to investigate innovative traffic management approaches. One of these approaches is the use of Active Traffic Management (ATM) strategies. Within ATM, the practice of Variable Speed Limit (VSL) systems is well suited to improving safety and operations. These systems dynamically utilize real-time traffic and/or weather data to post appropriate speeds that are thought to improve safety and operations along a corridor.

The overall aim of this thesis is to investigate the benefits of a recently installed advisory VSL system along OR-217 freeway in Portland, Oregon. This corridor is characterized by high traffic levels, severe congestion and unreliable travel times. The congestion of the freeway contribute to crash rates exceeding the statewide averages for this type of facility. Pacific Northwest’s unpredictable climate presents another challenge that doubles the congestion and safety problems along the corridor. The effectiveness of this system was explored through an in-depth “before and after” and “on-and-off” analyses. The study was designed in a way that it encompasses both the safety and mobility benefits of the system. Besides, driver compliance with the system was also measured under different scenarios.

The results indicated that the system had significant impacts on both mobility and safety. In terms of mobility it was found that system had lowered the average speeds along the corridor. The advisory VSL activation also resulted in reduced capacities. Safety assessment of the system suggested that, VSL has decreased crash rates and temporal and lateral variations of speed. Under certain scenarios, the system also decreased the longitudinal variations of speed. Further, it was also found that due to the advisory nature of the system, the majority of drivers do not comply with the system. However, VSL has resulted in reducing the percentage of aggressive drivers and have increased the number of drivers complying the static speed limit.
CHAPTER 1

INTRODUCTION

1.1 Background

Congestion in transportation facilities happen when demand exceeds capacity. Travelers complain about traffic congestion due to added travel time that takes away from the time that they can dedicate to other activities. According to the Texas Transportation Institute (TTI), in 2014 alone, congestion caused Americans living in urban areas to travel an extra 6.9 billion hours and purchase an extra 3.1 billion gallons of fuel for a total cost of $160 billion (TTI, 2015). This has been translated to a cost of $960 per auto commuter. Besides affecting large urban areas, the growing delays has also hit the residents of smaller cities making congestion independent of size. These problems influence the need for investments to increase network capacity and accessibility, a demand that is difficult to meet for financial, ecological and physical reasons in most major urban regions.

Besides congestion, traffic and highway engineers are also concerned about the safety of transportation facilities. According to the National Highway Traffic Safety Administration (NHTSA), in 2014 alone, traffic crashes resulted in a total of 32,675 fatalities and over 2.3 million injuries (NHTSA, 2015). National Safety Council (NSC) has reported that the early estimates of traffic fatalities in 2015 saw an increase of 14% compared to 2014 making it the deadliest year for drivers since 2007.
Weather conditions have a significant impact on the safety and operations of the highway facilities. Adverse weather conditions increase crash risk and decrease throughput through visibility impairment, and reduced pavement friction. According to the Federal Highway Administration (FHWA), 22% of the yearly 5,760,000 crashes are weather-related. From 2004 to 2013, on average 6,000 people were killed and over 445,000 people were injured annually in weather-related crashes (FHWA, 2015). In addition to safety concerns, adverse weather conditions can reduce vehicular stability resulting in reduced traffic operational speed (Maze, Agarwal & Burchett, 2005) and highway capacity (Agarwal, Maze & Souleyrette, 2005).

Transportation also remains a major source of air pollutant emissions. According to the Air Emissions Inventory of the US Environmental Protection Agency (EPA), in 2014, on-road transportation was responsible for 31% of Volatile Organic Compound (VOC) emissions, 36% of NOx emissions and 33% of Carbon Monoxide (CO) emissions (EPA, 2015). Although a declining trend in total emission levels has been observed for the last two decades, transportation will continue to contribute to regional air pollution for years to come (ICF International, 2006).

Given the myriad of problems currently facing the transportation industry, there is a push towards exploring context-sensitive solutions. Conventional solutions like constructing additional highways, are typically ruled out due to high construction costs and constrained right-of-way. Using efficient, safe and reliable traffic management approaches to address these problems have become highly desirable due to its benefits to a wide constituency.
Various management strategies and methods that can address these problems have been researched. One such management approach is Active Transportation and Demand Management (ATDM). ATDM which is promoted by FHWA seeks to improve safety and increase efficiency throughout the entire trip chain as seen from the traveler’s perspective. ATDM is defined by the Glossary of Regional Transportation Systems Management and Operations Terms as the “collective approach for dynamically managing travel and traffic demand and available capacity of transportation facilities, based on prevailing traffic conditions, using one or a combination of operational strategies that are tailored to real-time and predicted conditions in an integrated fashion” (Neudorff, Mason, & Bauer, 2012).

Given this definition, under the ATDM approach, a transportation system is continuously monitored in real time to assess the system performance. To achieve performance objectives, many dynamic actions are evaluated and implemented in real time. Using this analogy, FHWA has defined four key steps in any ATDM approach cycle as depicted in Figure 1 (FHWA, 2013).

Many traffic and demand management approaches fall under the ATDM strategy toolbox. Table 1 provides a summary of the most commonly used approaches.
Table 1. Examples ATDM Approaches Strategies

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Source: (FHWA, 2013)
1.1.1 Active Traffic Management Systems

Of the most promising ATDM strategies that have gained attention in recent years are Active Traffic Management (ATM) systems. ATM is defined as a continuous process of dynamically managing recurrent and non-recurrent traffic congestion in real-time in order to maximize the efficiency and improve safety along highway facilities (Kurzhanskiy and Varaiya, 2010).

As shown in Table 1, ATM systems can come in many forms, including, dynamic lane use, variable speed limits, queue warning systems, and adaptive ramp metering systems. ATM strategies can either be deployed individually to address a specific need (e.g. deployment of adaptive ramp metering system to control traffic flow) or can be deployed in combination with other systems to meet the system-wide needs of traffic management (e.g. adaptive ramp metering combined with variable speed limits on the mainline).

Variable Speed Limit (VSL) Systems

VSL, which is of most interest to this research is one of the most cost-effective ATM approaches to manage congestion and improve safety along urban and rural corridors. VSL system is of great importance due to its ability to dynamically change the speed limits along a corridor based on prevailing traffic, roadway and weather conditions.

VSL systems can be enforceable or advisory in nature. These systems dynamically utilize real time traffic, weather and/or road surface condition data to post an appropriate speed that is thought to improve safety and operations along a corridor.
Traditionally, the implementation of a VSL system is considered in order to achieve the following objectives (Khondaker and Kattan, 2015):

1. *Improve Safety:* Depending on system objective, VSL is able to reduce vehicular speeds or speed variations. Lower speeds and speed variations are directly proportional to lower probability of crashes.

2. *Resolve traffic breakdown:* It is hypothesized that VSL can restore freeway capacity and hence prevent breakdown by reducing the speed of traffic reaching bottleneck locations (Hegyi et al., 2005).

3. *Environmental benefits:* Increased homogenization along the corridor can in turn reduce fuel consumption and traffic emissions (Zegeye et al., 2010).

Some VSL systems are only weather-responsive meaning that the system lowers speed limits during inclement weather conditions only. Other systems are only congestion-responsive and they can reduce speed limits when traffic on corridor reaches certain levels (e.g. peak periods, incidents, etc.) thereby smoothening the flow and reducing the risks of crashes. A few VSL corridors are equipped with both congestion and weather-responsive systems. Figure 2 depicts the advisory VSL system deployed along Oregon Route 217 (OR-217), in Portland, Oregon. The study of the effectiveness of this system is the main subject of this thesis.
1.2 Advisory VSL System along OR-217

A well-traveled urban freeway, OR-217 is located in the southwestern suburbs of Portland, Oregon. The corridor runs north-south through the cities of Beaverton and Tigard connecting Interstate 5 with US-26 (see Figure 3). For majority of its 7.5 miles length, the freeway has two lanes in each direction with auxiliary lanes added in the vicinity of the interchanges. The freeway operates at or above capacity especially during the morning and evening peak hours on weekdays. It also has crash rates higher than the statewide averages for this type of facility, with rear-end crashes being particularly frequent.

Over the past decade OR-217 has been the subject of several extensive studies that recommended capacity and interchange improvements costing nearly $1 billion. To cut costs and to innovatively address the operational and safety issues, the Oregon Department of Transportation (ODOT) designed and built an Active Traffic Management (ATM) system along OR-217 and activated it on July 22, 2014. This system was an
addition to the previously built System-Wide Adaptive Ramp Metering (SWARM) system along the corridor which was deployed on May, 2005. The ATM system included Variable Message Signs (VMS) and Variable Advisory Speeds (VAS) signs. The VMS system provide real-time travel time and queue warning messages to the drivers. The VAS system, which is responsive to both congestion and weather conditions, provides the drivers with advisory speeds (DKS & Associates, 2013a). By posting advisory speeds upstream of areas of incidents or congestion, the congestion-responsive part of the system aims to minimize the spatial and temporal variations in speed that could lead to crashes and increased congestion. On the other hand, the weather-responsive part of the system notifies the drivers of the inclement weather and displays advisory speeds for possible hazardous roadway conditions such as water or ice on the roadway surface (DKS & Associates, 2013b).

Figure 3. Oregon Route 217 Location (Google Maps)
ODOT has predicted that system could result in 20 percent reduction in rear-end crashes (about one less crash every two weeks) and a 5 percent reduction in delay. It is also claimed that the system could lead to annual savings of about $6.6 million based on estimated reductions in crashes and vehicular delays (DKS & Associates, 2010).

1.3 Research Motivation and Significance

A plethora of literature on the effectiveness of VSL systems is available. Much of the existing literature associated with VSL has examined its impacts on either traffic safety or traffic operations. The safety benefits of using VSL have been well-documented both in Europe and the United States. Most of these studies have shown that VSL can be an effective tool in reducing speed variations and improving lane utilization and thereby improving safety. However, there are only a few studies in the literature that have used empirical data in assessing the safety effectiveness of VSL systems. Considering the safety effects of advisory VSL systems the number is even smaller.

Regarding the mobility benefits of VSL systems, studies are rather inconclusive. Recent empirical studies by Papageorgiou et al. (2008), Carlson et al. (2010), Soriguera et al. (2014) and Plana et al. (2016), have concluded that many aspects regarding the VSL effects on aggregate traffic behavior are lacking consensus in the scientific community. Therefore, there is an essential need to conduct more research using empirical data.

Among the other gaps in the current knowledge about the effects of VSL systems, driver compliance with the system, stands out. VSL impacts on safety and mobility are very sensitive to the level of speed compliance. However, there is very little that is
published on drivers’ compliance with VSL systems. Using simulation, most of these studies have assumed the percentage of drivers compliant with the system. These percentages are arbitrary and are not calibrated using real-time traffic data.

Using a comprehensive set of safety and mobility performance measures this study will try to address the gaps in the body of knowledge on VSL effectiveness. Compliance with the system would also be measured in real-time using appropriately designed experiment framework. Moreover, this study will be a valuable addition to the inadequate body of literature on the field evaluations of advisory VSL systems. These systems have been recently implemented in some locations in the United States and their effectiveness have been less-established.

1.4 Research Objectives

This study seeks to evaluate the effectiveness of the newly installed advisory VSL system along OR-217. The effort will include, developing, testing and comparing several safety and mobility performance measures using a “before” and “after” or “on” and “off” framework. The research will utilize the vast amount of freeway traffic data recorded using loop and radar detectors in order to improve the current knowledge regarding VSL effectiveness. The specific objectives of this research are as follows:

1. Examine the mobility impacts of the system by studying the changes in aggregate traffic flow parameters.
2. Investigate driver compliance with the system and characterize drivers’ behavior when facing different speed limits under different conditions.
3. Assess the safety impacts of the system using different safety performance measures.

1.5 Thesis Organization

This thesis is divided into eight chapters. Beyond the introduction, Chapters 2 and 3 summarize the literature findings regarding the state-of-the-art technologies used in VSL, its implementations in the United States and other countries, and its reported safety and mobility benefits. Chapter 4 presents an overview of the corridor and the main motivations for the installation of a VSL system along OR-217. Data collection and processing procedures are also discussed in this chapter. Chapter 5 provides an empirical evaluation of the VSL impacts on traffic flow parameters. Chapter 6 is devoted to the analysis of drivers’ compliance with the VSL advisory speeds along the study corridor. Chapter 7 presents a safety assessment of the system using carefully designed safety performance measures. Chapter 8 discusses the conclusions and identifies potential areas for future research.
2.1 Background and History

VSL is a widely-used ATM technique targeted towards improving safety and operations along highway facilities. The principle behind any VSL system is to post a speed limit that is appropriate for prevailing traffic, roadway and weather conditions. This can provide an opportunity to warn drivers of hazardous conditions and encourage more uniform flow (Fontaine and Miller, 2012).

VSL systems can be implemented as either advisory or regulatory (enforced). It is claimed that enforcement is vital to the success of any VSL system (Sisiopiku, 2001) and that VSL may lose its effectiveness without proper enforcement (CTC and Associates, 2003) (Ulfarsson et al., 2001) and (Steel et al., 2005). The systems can be manually or automatically activated. Usually, the manual system is controlled by operators in a Traffic Management Center (TMC) and speeds are posted by observing the conditions on the corridor or by reports from highway patrol. On the contrary, an automatic system does not involve the interference of traffic operators. It dynamically post speeds based on the control strategies designed for the system. There are some automatic systems that provide the ability for manual overrides. The general practice is to install speed limits over each travel lane. This appears to improve the visibility of the VSL signs over those installed along the roadside.
The concept of variable speeds in the United States dates back to as early as the 1950’s. To reduce the speed limits during adverse weather conditions, the New Jersey state police occasionally put up temporary wooden signs with reduced speed limits to decrease vehicle speeds and hence improve safety (Goodwin, 2003). Following New Jersey, the State of Michigan deployed its first VSL system in 1962 along the John C. Lodge freeway near Detroit. Like New Jersey, the VSL system in Michigan relied on traffic officials to manually post speed limits based on their observations of traffic conditions. The system in NJ is still in place but in Michigan the system was dismantled due to no significant impacts on traffic conditions (Robinson, 2000).

In Europe, automated VSL systems were first introduced in Germany more than three decades ago (Papageorgiou et al., 2006). It is now estimated that VSL systems have been installed on more than 500 miles of motorways in Germany. This system has a fully-automated enforcement system in place and is aimed to stabilize traffic flow during congestion. Following Germany, the Netherlands, built its first automated VSL system in the Early 1980’s (Han et al., 2009).

After the implementation of the first few VSL systems, the concept has been overwhelmingly supported by many other countries and states in the U.S. According to a report by FHWA, around 20 states (see Figure 4) had either implemented or planned to implement a VSL system (Katz, et al., 2012). Some of these systems are regulatory and others are advisory. In 2014, Oregon was added to this list by installing its first advisory VSL system along Oregon-217 in Portland. In addition to the United States, many other countries including Australia, France, Finland, Sweden, United Kingdom, Germany and
the Netherlands have built, updated or expanded their VSL systems. (Al-Kaisy et al., 2012). More details about the systems will be provided later.

Figure 4. VSL Installation Sites in the United States

This chapter firstly summarizes the literature findings regarding the state-of-the-art technologies used in VSL, followed by a summary of VSL implementations in the United States and other countries. Chapter 3 will provide a review of the evaluation studies on the effectiveness of VSL systems.

2.2 Components of VSL Systems

In order to operate properly, VSL systems require a synergy of real-time traffic and/or weather data collection, data processing, and dynamic speed limit display (Sisiopiku, 2001). The technologies and methods for data collection, and speed display are presented in the following sections.
2.2.1 Data Collection Technologies

VSL systems heavily rely on the continuous collection and processing of data. The type of data collected depends on whether the system is congestion-responsive, weather-responsive or both. The most important information needed to activate a congestion-responsive VSL system is real-time traffic data. A very common method to collect real-time traffic data is through the use of inductive loop detectors. These detectors are imbedded into the pavement and collect traffic counts, speed and occupancy data. In addition to inductive loop detectors many other traffic data collection technologies have been utilized in VSL systems. Examples include microwave traffic detectors, license plate recognizers, radar vehicle detectors, Closed Circuit Television (CCTV) and digital radio detectors. They have been used by many state Departments of Transportation (DOT) to collect traffic data that are required to be fed into a VSL algorithm (Goodwin and Pisano, 2003), (Pan et al., 2010). Oftentimes to increase the accuracy of traffic condition estimation, a combination of more than one data collection systems is used. An example include the data collection technology installed along OR-217 which is a combination of inductive loop detectors and Wavetronix radar sensors.

Weather responsive VSL systems rely on the collection of real-time weather data. Sensor technology intended to measure roadway weather conditions is divided into two general types, invasive and noninvasive (Ewan, 2013). Invasive sensors are installed in the pavement level and can use different sensing technologies to measure roadway conditions. By measuring the conductivity of liquid present on the sensors, these equipment can determine whether the road is dry, damp, wet or icy (Schedler, 2009).
Unlike invasive sensors, noninvasive sensors are typically installed somewhere along the roadside over the road surface and use non-contact means to monitor roadway weather conditions. These sensors typically use spectroscopic methods, thermal radiation, and infrared radar methods to determine surface weather conditions from a distance (Jonsson, 2010). In practice, weather sensors are typically used as part of Road Weather Information System (RWIS), which comprises the sensor stations, the communication system for data transfer and the central systems to collect the field data from the sensors (FHWA, 2013).

Some VSL systems are implemented to elicit safer driving behavior during fog. This requires a special visibility sensing technology to reduce the speed limits during foggy conditions when visibility drops below a certain limit.

2.2.2 Speed Display

As described previously, mainly there are two types of VSL displaying devices, overhead gantry and roadside signs. Overhead gantry signs (Figure 5a) have been installed along many highway facilities in Oregon, Minnesota, Washington and many European countries. They are generally preferred over roadside signs due to their clear visibility. Roadside signs (Figure 5b) have been implemented along some freeway facilities in the states of Wyoming, Maryland and Florida (ATKINS, 2011). A research on driver behavior and user acceptance was conducted by Stoelhorst et al. (2011) to see which of these displaying devices are well accepted by the drivers. The results indicated that VSL is best observed and understood when displayed on the matrix signs over each lane, instead of implementing them on the roadside as panels and signs.
There are two different display technologies used with VSL systems. Typical dynamic speed limit signs use fiber optic with Light Emitting Diode (LED) display technology (see Figure 5a). Using LED for variable speed display is very common in Europe. The second technology which is commonly used in rural areas is scrolling film technology. For this system, the speed limits are preprinted on a film that sits inside the speed limit sign. When the speed limit is changed, the film scrolls through to the selected posted speed (see Figure 5b).

In many cases, Variable Message Signs (VMS) are used in combination with VSL signs to provide more information to the drivers. The VMS typically inform drivers of downstream traffic conditions or provide them with travel time information. Bertini et al.
(2006) studied the combined effects of VSL and advanced traveler information systems provided by VMS on driver behavior on German freeways. It was found that providing information about downstream congestion reduced the average speeds along the corridor while maintaining the flow levels.

2.2.3 VSL Enforcement

Speeds displayed on VSL signs can be either regulatory or advisory. Many studies have indicated that enforcement is very crucial to the success of a VSL system. To enforce VSL, many technologies exist. Using automated enforcement through photo radar technologies is very common. This can be done by mounting cameras on overhead gantries above each lane. Using flashes while taking pictures provides enough lighting for the cameras during the dark hours. It is generally recommended that a small number of cameras should be rotated frequently so that motorists would not know if the flash coming from the camera box meant a picture was taken or not (Tignor et al., 1999).

2.3 Variable Speed Limit Implementation

2.3.1 Weather and Fog-Responsive VSL Systems

Although international experience in weather-responsive VSL systems is mature enough, the U.S. experience is still in its infancy. However, the number of these deployments is growing very fast. These systems have been installed to address rain, fog, wind, snow and icy conditions. Although mostly used to address safety challenges, some of these systems have been deployed for mobility reasons. Following is a synthesis of the
deployed systems in the United States and other countries. Information regarding many of these studies were obtained from Robinson (2000).

United States Experience

Arizona: The first experimental VSL system in Arizona was planned to be installed along Interstate 40 in 1998. The prototype algorithms incorporated a real-time fuzzy control system to identify speed limits appropriate for changing atmospheric and road surface conditions (Placer, 1998). However, after the prototype implementation of the system, none of the RWIS sites were providing enough data for a full utilization of the fuzzy control algorithm (Placer, 2001). For this reason, the RWIS sites along I-40 were upgraded so that they could be used as a test sites to monitor the complete data set of atmospheric and road surface conditions needed by the fuzzy control algorithm.

The system is currently suspended due to two main issues. The first issue involves liability problems. It is thought that enforcing such a system is subject to lawsuits. Currently there is no limit on the State’s liability with respect to the deployment and operation of VSL systems (Placer and Sagahyroon, 2007). The second issue is the general difficulty encountered in maintaining a reliable RWIS communication and sensor data flow for a proper fuzzy algorithm performance.

Nevada: A weather-responsive regulatory VSL system was installed along the rural Interstate 80 in Nevada in the late 90’s (Robinson, 2000). The system used four VSL signs (two in the eastbound and two in the westbound), visibility detectors, loop detectors, RWIS and static advanced warning signs. The system posted speeds using a
logic tree that was based on the 85th percentile speed, visibility (based on stopping sight distance), and pavement conditions (based on frost, ice, rain, or dry conditions). The system was later removed due to some technical issues (Katz, et al., 2012).

**New Jersey:** As previously mentioned, the VSL system installed in NJ is the first in the country and is still active. This system has been installed on New Jersey Turnpike over 148 miles in both rural and urban areas. The enforced posted speeds are based on average travel speed and are displayed automatically (manual override used for lane closures and construction zones) (Robinson, 2000). The posted speed limit can be reduced for six reasons including crashes, congestion, construction, ice, snow, and fog. Due to lost connections between environmental sensors and the dynamic speed logic, the weather-responsive part of this system is inactive (Katz, et al., 2012).

**Oregon:** Oregon Department of Transportation (ODOT) installed its first automatic weather-responsive advisory VSL system in July, 2014 along Oregon Route 217 as part of OR-217 Active Traffic Management project. The weather-responsive algorithms automatically determines the advisory speeds on the highway based on RWIS sensor data for corridor level roadway conditions. Speed reduction values are based on the grip factor which is calculated from the grip between the tires and the pavement. The evaluation of the safety and operational benefits of this system is the subject of this research.

**Tennessee:** On December 11, 1990, the Tennessee Department of Transportation (TDOT) installed a fog-responsive VSL system on a segment of Interstate 75 in
southeastern Tennessee (Goodwin, 2003). The system installed collected data from two Environmental Sensor Stations (ESS), eight forward-scatter visibility sensors, and 44 vehicle detectors. By continually monitoring the sensor data, the on-site computer predicted and detected conditions conducive to fog formation. The central computer then provided an audible alarm to the Highway Patrol office when established threshold criteria were met. When alerted dispatchers posted a reduced speed message and notified Highway Patrol troopers. The posted speeds are regulatory and the system is still active.

Utah: A fog-responsive VSL system was installed on a segment of Interstate 215 in Salt Lake City, Utah between 1995 and 2000. The visibility sensors near the road continuously evaluated the visibility conditions and during reduced visibility, the signs displayed the safe advisory speed. The system is also known as the Adverse Visibility Information System Evaluation (ADVISE) (Perrin et al., 2002).

Recently, Utah Department of Transportation (UDOT) installed a VSL system along I-80 in Parley’s Canyon (Figure 6). It was claimed that the new signs would help maintain consistent traffic flows and assist drivers in adjusting speeds when necessary due to weather conditions. The UDOT Traffic Operations Center (TOC) continuously monitored the speed limits on the freeway and in case of poor weather or low visibility, the engineers decided to reduce the speed limits that ranged from 35 to 65 miles per hour (UDOT, 2014). This system was temporarily installed and was torn-down shortly after installation.
Washington State: Washington State Department of Transportation (WSDOT) installed a regulatory weather-responsive VSL system on Snoqualmie Pass along the rural I-90 in 1997 (Ulfarsson et al., 2001). This system was deployed to improve safety and to increase the availability of road condition and weather information to motorists crossing Snoqualmie Pass. The static speed limits posted on the pass was 65 mph. When road conditions got poorer, the speed limits were reduced in 10-mph increments. The decision was taken by a computer logic and approved by the centrally located traffic operations personnel.

Wyoming: The Wyoming Department of Transportation (WYDOT) installed its first VSL system along Interstate 80 in the Elk Mountain Corridor in the spring of 2009 in an effort to improve safety and reduce road closures (Young et al., 2013). The VSL system was expanded in the 2009-2010 winter season to include 8 additional variable speed limit signs in four new locations (Buddemeyer et al., 2010). This VSL system was
implemented to address high wind, blowing snow and icy conditions on Interstate 80 in Wyoming. When warranted, the Wyoming Highway Patrol, maintenance personnel, and Traffic Management Operations Center (TMOC) operators determined an appropriate speed for the prevailing conditions.

**Other States:** The concepts of weather and fog-responsive VSL systems have been tried in many other states. In 1995, Alabama DOT (ALDOT) installed a VSL system on a 7-mile section of Interstate 10 in Mobile, Alabama. The section of roadway where the VSL system was implemented previously had a very high number of vehicle accidents due to visibility issues caused by fog. The system collects data from remote vehicle detectors, fog detection devices, and visibility sensors. Using some thresholds on visibility distance, an appropriate speed is determined and posted on VSL signs.

Delaware DOT (DelDOT) also operates a VSL system on Interstate 495 that changes speed limits based on weather conditions. The decisions on posted speeds are taken by the Chief Traffic Engineer of DelDOT TMC, or at the request of the Delaware State Police (DSP) for extreme weather conditions and poor roadway surface conditions (Werner, 2003). Other states that have installed weather or fog-responsive VSL systems include, Pennsylvania, South Carolina, Florida, Colorado, Idaho, Louisiana and New Mexico (Katz, et al., 2012). Chapter 3 will provide a synthesis of the evaluation of these systems.
International Experience

Australia: Weather-responsive VSL systems have been deployed on many Australian corridors. In 2005, Austroads designed and built a new weather-responsive VSL system on Highway F3 between Sydney and New England. The algorithms employed used the weather data from the weather stations on the roadside and posted speeds appropriate for the conditions.

To address traffic crashes, and weather-related challenges on the Adelaide-Crafers Highway, South Australia deployed a VSL system in 2005. The speeds posted were controlled by TMC personnel based on their observance of inclement weather or accidents.

Finland: Many weather-responsive VSL deployments have occurred in Finland. In 1994, the Finnish government, installed an experimental weather-responsive VSL system on the rural sections of E18 highway in Southern Finland between Kotka and Hamina (Robinson, 2000). Two weather stations were employed to monitor local weather (wind velocity and direction, air temperature, relative humidity, rain intensity and cumulative precipitation) and road surface conditions (dry, wet, salted, snowy). The weather data were analyzed and then used to establish the appropriate speed limit.

France: France implemented its first weather-responsive VSL system in urban Marseille area (Robinson, 2000). The information about the system was very limited and no description of system algorithms was provided. However, it was mentioned that the system provided speed limits based on the prevailing speeds and weather conditions.
The Netherlands: The Netherlands, has suffered from many fog-related crashes over the last few decades. In November 1990, a serious crash was reported on A16 Motorway which involved 100 vehicles and eight fatalities. For this reason, Dutch Ministry of Transport implemented a fog advisory system in a high fog area of this corridor. The VSL system is interconnected with 20 visibility sensors that provide measurements in a minute basis. Based on some thresholds on visibility, advisory speeds are triggered and posted on the VSL signs (Zarean et al., 2000).

Germany: As the birthplace of VSL systems, Germany has many VSL deployments along its Autobahns. The corridors are very well-fitted for any ATM deployment since they are equipped with inductive loop detectors for each travel lane. The loops provide count and speed measurement for cars and trucks separately. Environmental conditions are monitored through ice, wind and fog detectors installed along the corridors. The traffic and environmental data are transmitted to a TMC which in turn provides appropriate speeds and dynamic messages based on it computer algorithms. The systems have been extensively evaluated. A description of these evaluations is provided in Chapter 3.

2.3.2 Congestion-Responsive VSL Systems

Congestion-responsive VSL systems are deployed with an intent to resolve or at least delay the start of traffic breakdown by slowing down the vehicles that would otherwise enter a bottleneck region (Hegyi, 2005). This can improve the corridor’s throughput and can provide environmental benefits. The original congestion-responsive
VSL systems depended on manual observations of traffic conditions and the subsequent triggering of VSL. In more recent decades, using automatic traffic recorders like inductive loop detectors and electronic processing technologies have revolutionized congestion-responsive VSL systems. Although very few deployments have occurred in the U.S. as compared to Europe, the numbers are consistently increasing. Following is a synthesis of congestion-responsive VSL deployments in the United States and other countries. Chapter 3 will provide a synthesis of the evaluation of these systems.

United States Experience

**Florida:** On September 15, 2008, a VSL system was deployed on Interstate 4 from Rio Grande Avenue to Maitland Boulevard in Orlando, Florida. The system was intended to reduce driver speeds before reaching a downstream congestion (ATKINS, 2009). A total of 20 VSL signs were installed at 16 locations, and inductive loops were used to measure speed, volume, and occupancy at 30 second intervals. The traffic data collected are entered into a software called SunGuide, which in turn provides recommended reduced speed limits. The speed limit is then displayed on the VSL LED panels.

**Minnesota:** The Minnesota Department of Transportation (MnDOT) installed its first advisory VSL system in July 2010 at Interstate 35W in Twin Cities, Minnesota (see Figure 7). This system was designed to prevent the rapid propagation of shockwaves that are caused by fixed or moving bottlenecks by reducing the average speeds of incoming flows to downstream congestion (Kwon et al., 2011). The locations of bottlenecks are
determined every 30 seconds in real-time by examining the speed deceleration patterns of traffic flows on the corridor.

A new advisory VSL system was installed along an eight-mile section of Interstate 94 between downtown Minneapolis and downtown St. Paul on September 27, 2012. This section of I-94 experiences more crashes than any other freeway location in the state of Minnesota. Moreover, this section includes a significant shockwave-generating bottleneck located at the merge point of I-94 and traffic entering from I-35W northbound. This system is designed to prevent the rapid propagation of shockwaves by reducing speeds upstream of a bottleneck location. As congestion level increases, two or three sets of signs upstream to the congestion display an advisory speed limit which is a function of the speed differential between upstream and downstream traffic (Hourdos and Zitzow, 2014).

Figure 7. I-35W Variable Speed Limit System (Kwon et al., 2011)
Missouri: A congestion-responsive VSL system was initiated on May 22, 2008 along 38 miles of Interstate 270 and Interstate 255 in St. Louis County to change speed limits during recurring and nonrecurring congestion periods. This was the first of its kind of VSL implementation in the state of Missouri (Bham et al., 2010). The system uses a rule-based algorithm that depends on certain volume, occupancy and speed thresholds in posting new speeds. The system was initially implemented as regulatory but due to low driver compliance, it was changed to advisory in 2011 (MoDOT, 2013).

Oregon: As part of OR-217 ATM project, the ODOT also installed a congestion-responsive VSL system along OR-217 in Portland. This system automatically adjusts the advisory speeds on the highway based on downstream traffic conditions. The primary purpose of the congestion-responsive VSL system is to minimize the spatial and temporal variations in speed that can lead to crashes and increased congestion. The evaluation of the safety and operational benefits of this system is the subject of this research.

Washington State: Washington State implemented its first congestion-responsive VSL system on a 7 mile section of Interstate-5 near downtown Seattle. Similar systems were later installed on an eight mile section of State Route 520 EB and WB and on I-90 EB and WB in November 2010 and June 2011 respectively. The VSL system is used in conjunction with lane control signals to provide timely warning of downstream queues for the drivers. The algorithms developed tried to smooth traffic flow, manage demand and reduce congestion-related crashes (Balogh, 2012).
International Experience

**Australia:** A congestion-responsive VSL system was installed for queue management on M4 Motorway in New South Wales. The system is controlled by a field device requiring no input from TMC operators or highway patrol. The system uses processed occupancy and incident detection data in order to post appropriate speed limits (Han et al., 2009). In 2002, another VSL system was installed on West Ring Road in Victoria to address traffic congestion and incidents along the corridor. The VSL system processed input data to calculate recommended speed limits and checked their feasibility and logic before posting.

**Germany:** VSL policies have been acknowledged since the early 1970s in Germany (Zackor, 1979). The congestion-responsive VSL systems have been installed at A8 between Salzburg and Munich, A3 between Sieburg and Cologne, and A5 near Karlsruhe (Mirshahi et al., 2007). These systems are aimed at stabilizing traffic flow under heavy flow conditions, reducing crash probability, improving drivers’ comfort and reducing environmental impacts.

**The Netherlands:** The Netherlands installed a VSL system along a 12.4 mile stretch of A2 Motorway between Amsterdam and Utrecht in 1992. This VSL system was aimed to create speed and flow uniformity within and between lanes and thereby reduce the risk of shockwaves, crashes and congestion (Robinson, 2000). The posted speeds on the VSL signs were determined by a system control algorithm that was based on one-
minute averages of speeds and volumes across all lanes. If an incident was detected, the system always showed a static speed limit of 50 km/h (31 mph).

**Sweden:** A congestion-responsive VSL system was built along the E4 Motorway in 1996. This motorway passes from the west side of the city of Stockholm and is highly congested. This VSL system was implemented as part of a larger system called Motorway Control Systems (MCS). In addition to VSL, the system included Automatic Incident Detection (AID) algorithms that detected slow traffic as a basis for the activation of speed signs, showing gradually decreasing velocity legends on VSL signs mounted on the MCS gantries (Nissan, 2010).

**United Kingdom:** A VSL system was deployed along a 14 mile stretch of M25 Motorway in London area to smooth traffic flows along the corridor (Robinson, 2000). VSL signs were placed every 0.6 miles. Volume data from inductive loop detectors were used to change speed limits according to real-time measurements. Speeds were reduced from 70 to 60 mph when volumes exceeded 1,650 vehicles per hour per lane and from 60 to 50 mph when volumes exceeded 2,050 vehicles per hour per lane. The posted speed limits were regulatory and enforced by some enforcement measures (Highways Agency, 2004). This system has been the subject of many extensive studies. The results of these studies are mentioned in the following chapter.

Another congestion-responsive VSL system was built along M42 Motorway in September 2006. M42 is one of the busiest motorways in the UK with an Annual Average Daily Traffic (AADT) of approximately 134,000 vehicles. The system deployed
uses regulatory variable speed limits together with a dynamic use of hard shoulder during periods of congestion or incidents. The activation and deactivation of the system are reliant on pre-identified flow and speed thresholds (Highways Agency, 2008).
CHAPTER 3

STATE-OF-THE-ART REVIEW:
EVALUATION STUDIES

3.1 Background

System evaluation is an integral part of any objective-driven planning study. For assessing any system, performance measures should be selected in a manner that will provide adequate information to planners, operators, and decision-makers (FHWA, 2010). In an ATM context, these measures are extremely critical. They can provide the planners with the information needed to expand the coverage of ATM techniques in a way that will eventually meet the regional transportation goals. Moreover, these measures are of great importance to the operators of the already implemented ATM systems. By carefully monitoring the performance of the systems, operators can make tweaks to maximize the benefits the system offers.

Defining appropriate performance measures to evaluate VSL or VAS systems is difficult due to their unique characteristics. Typically many metrics are involved in any VSL/VAS evaluation study. They can be associated with either the safety or the mobility effects of the system. Fortunately, many guides exist in the literature that have identified potential measures of effectiveness (MOE) for a system evaluation. The Active Traffic Management Feasibility and Screening Guide (Neudorff and McCabe, 2015) has identified the following performance measures to assess the mobility effects of VSL systems:
• Speed differential between lanes.
• Duration of speed less than $x$ mph.
• Frequency of speed less than $x$ mph.
• Flow and/or speed plots.
• Lane utilization.
• Headway distribution.
• Vehicle speed distribution.
• Vehicle hour delay.

In addition, the following MOEs have been identified to assess the safety effects of a VSL system:

• Crash rates (by crash type).
• Number of crashes per segment.
• Number of secondary crashes and rates.
• Number of property-damage only crashes and rates.
• Number of injury crashes and rates.
• Percent vehicles exceeding speed limit by $x$ percent.

Compliance with VSL or VAS systems is an MOE that has not received much attention in these summary documents. However, their importance is undisputed. Compliance with the speed limits can affect both safety and operations along a corridor.

VSL control strategies have been evaluated through both field tests and simulation experiments. Simulation, although a valuable tool for assessing the impacts of a system, should be used with caution as they may not replicate the real-world driver
behavior. This section provides an overview of VSL/VAS evaluation studies together with their findings. The first part of this chapter will summarize the studies conducted on the impacts of VSL/VAS systems on traffic operations. The second section will provide a synthesis of the studies conducted on the safety impacts of VSL/VAS systems. In the last part of this chapter, studies on compliance with VSL/VAS will be reviewed.

3.2 Mobility Effects of Variable Speeds Limit Systems

From the operations perspective, two views on the use of VSL/VAS systems can be found in the literature. The first is based on the so called “homogenization effect”, whereas the second tries to prevent traffic breakdown by restricting the traffic flow levels on the mainline (Hegyi et al., 2005). The idea behind the homogenization effects is that, VSL promotes the reduction in speed, flow and occupancy differences within and between lanes and hence will result in higher capacity values. The procedure is to post speed limits above but close to the critical speed (speed at capacity) to maximize the flow levels on the facility. The breakdown prevention approach tries to prevent traffic breakdown and resolve traffic jams by posting speeds lower than the critical speed. Very few studies in the literature have examined the homogenization effects of VSL systems. With exception of one study by Soriguera et al. (2015), no other empirical study has experimented the effects of sub-critical speed limits on traffic flow. The following sections provide a detailed review of literature on the mobility effects of VSL/VAS systems.
3.2.1 Impacts of VSL/VAS Systems on Fundamental Flow Diagrams

A fundamental diagram (see Figure 8) simply shows the relationships between the fundamental traffic flow parameters including traffic flow, speed and density. In a freeway context, flow is the average number of vehicles passing a point or a short section of a freeway over a specified time period generally less than an hour. The speed used to establish a fundamental diagram is the space-mean speed which is defined as the average speed of all the vehicles occupying a given section of a freeway over some specified time period. Average speed is proportional to the slope of flow-occupancy curves (May, 1990). Density is defined as the average number of vehicles occupying a section of a freeway at a particular instant (Plana et al., 2016). Since the introduction of inductive loop detectors, occupancy has been introduced as a surrogate to density. Occupancy is defined as the percent of time the detection zone of a detector is occupied by some vehicle (FHWA, 1996). Figures 8a and 8b show the single-regime flow-occupancy and speed-flow diagrams as proposed by Greenshields in 1934 (Greenshields, 1935). \( o_{cr} \) and \( v_{cr} \) represent the occupancy and speed at capacity, \( q_{cap} \) respectively. These diagrams can represent all possible traffic states, from free-flow to a complete breakdown.

![Figure 8. (a) Flow-occupancy and (b) speed-flow diagrams](image)
According to Papageorgiou et al. (2006), a fundamental diagram does not capture the full spatio-temporal traffic dynamics. The congested segment of the fundamental diagram represents a stationary-stable state. Traffic instabilities occurring in a non-stationary and non-homogeneous traffic condition are not shown. Nevertheless, it is a very useful tool in visualizing the critical parameters of a freeway section (capacity, critical occupancy, and critical speed).

Empirical studies have also shown that discontinuities are always present in fundamental diagrams. The first discontinuous fundamental diagram was proposed by Edie in 1961 (Edie, 1961). Based on his observations of the poor performance of Greenshields model under free-flow conditions, Edie proposed the idea of a two-regime model. He demonstrated that the discharge flow rate at a bottleneck is reduced following the onset of congestion (Figure 9). This reduction in flow, which is also known as the capacity drop, can be measured by comparing the queue discharge flow rate ($q_{out}$) to the maximum pre-queue discharge flow rate ($q_{cap}$) (Chamberlayne et al., 2012). It is generally observed that the values for $q_{out}$ are 5 to 10% less than $q_{cap}$.

![Figure 9. Capacity Drop Phenomenon](image)
Many studies have indicated that the values of the critical parameters ($q_{cap}$, $o_{cr}$ and $v_{cr}$) are not constant and may vary from day to day without any obvious reason (Papageorgiou, 2008). The variations in $q_{cap}$ are found to be more pronounced under different weather and light conditions. Critical occupancy is generally found to be less sensitive to different conditions. No research has been directed towards critical speed and its variations with respect to different weather and light conditions.

Traffic management systems like VSL or VAS systems are also thought to have impacts on these critical parameters. However, very few studies in the literature have examined the effects of these systems on fundamental flow relationships.

Cremer in 1979 proposed the first quantitative model to study the VSL-induced fundamental diagram changes. The fundamental diagrams presented by Cremer is shown in Figure 10a. His results suggested that VSL has increased the capacity by 21% and has shifted the diagrams towards higher densities (Cremer, 1979). Later, in 1990, using data from Dutch freeways, Smulders indicated that VSL impacts on capacity is far less dramatic than what was assumed. His conclusion suggested that VSL increased capacity in the orders of 1 to 2%. However in his study, he has acknowledged the traffic homogenization effects of VSL systems (Smulders, 1990).

Zackor investigated the VSL effects on traffic flow attributes using traffic data from a German Motorway in 1991. He showed that at lower traffic volumes, VSL was effective in lowering speeds, while at higher volumes, higher speeds were observed due to VSL stabilizing effect on speeds. A capacity and speed increase of about 5 to 10% due
to VSL was also observed by comparing the changes in fundamental diagrams due to speed limits (Zackor, 1991) (Figure 10b).

In 2004, Hegyi proposed a model for the flow-occupancy diagram under variable speeds. He claimed that VSL can significantly affect the uncongested part of the diagram which is shown as straight line in Figure 10c with the slope corresponding to the speed enforced by the VSL gantry. He also claimed that VSL does not affect the congested branch of the diagram and has no significant impact on the capacity (Hegyi, 2004).

In 2008, (Papageorgiou et al., 2008) examined the effects of a regulatory VSL system on traffic flow parameters using data from M42 motorway in U.K. Using the theory that mean speed during a specific traffic state is fundamentally proportional to the slope of flow-occupancy curves, the slopes of the curves for before and after periods were compared (Figure 10d). It was found that VSL reduced slopes at under-critical occupancies and shifted the critical occupancy to higher values, thus allowing higher flows at over-critical occupancies. However this increase was rather inconclusive as the results were not consistent for all locations.

Carlson et al. presented a model for the flow-occupancy diagram based on data from (Papageorgiou et al., 2008) in 2010. Their conclusions suggested that, the lower the posted speed limit, the lower the capacity and the more the shift towards higher occupancies (Figure 10e). It was also found that VSL significantly affects the congested branch of the diagram. The results of this study was the total opposite of what was found by (Cremer, 1979).
Nissan and Koutsopoulos also studied the impacts of an advisory VSL system on flow parameters along E4 Motorway in Stockholm, Sweden (Nissan and Koutsopoulos, 2011). A traffic stream model was specified and its parameters were estimated using regression analysis for periods before and after VSL implementation. Statistical tests were conducted to test the equality of the coefficients across two models. The results indicated that VSL did not have any significant impact on traffic flow both immediately and several months after its implementation. This result was linked to the advisory nature of the VSL system.

In another study by Kianfar et al. on the effects of VSL on traffic flow parameters along I-270 in Missouri, it was found that VSL slightly increased the critical occupancies at 4 locations and decreased at other four locations. The maximum flow before breakdown decreased at four locations and increased at other four locations. The flow after breakdown decreased at three locations and increased at other five locations. This inconsistency in results was thought to be related to the fact that the algorithm used to calculate speeds did not consider the individual lane speeds but rather calculated averages speeds over all lanes (Kianfar et al., 2013).

In 2014, Soriguera et al., experimented on a VSL freeway in Barcelona. Different speed limits ranging from 100 km/h to 40 km/h were used to determine the impacts of different speeds on the fundamental flow parameters (Soriguera et al., 2015). The results suggested that for 80 km/h speed limit, flows near capacity can be achieved for a wide range of occupancies (18 to 26%) and speeds (70 to 50 km/h). They also found that speeds above 50 km/h reduced the free flow speed in accordance with the speed limit in
force. The 40 km/h speed corresponded to a significant increase in the critical occupancy.

Figure 10. (a) (Cremer, 1979), where: $b=1, 0.8, 0.6$ correspond to no speed limit, $VSL=0.8v_f, VSL=0.6v_f$ respectively (b) (Zackor, 1991) (c) (Hegyi, 2004) (d) (Papageorgiou et al., 2008) (e) (Carlson et al., 2010) where $b = 1.0$ means no VSL applied, decreasing $b$-values correspond to decreasing VSL (f) (Soriguera et al., 2015) where $b = 0.8, 0.6$ and 0.4 correspond to 80, 60 and 40 km/h speeds respectively.
This suggested that lower speed limit provided very high and stable occupancies and thus prevented traffic breakdown (Figure 10f).

In a recent study, Plana et al. (2016), evaluated the VSL effects on the flow-density diagrams on a stretch of A13 freeway in Rotterdam. To perform the analysis, a new methodology for the definition of stationary periods were developed. Contrary to the study by Soriguera et al. (2015), this study found a 15% reduction in flow due to low speed limits. This study also concluded that flows around 1850 vehicles per hour per lane can be sustained when speed limits of 50 km/h are in force.

The results from these studies indicate that there is no consensus among researchers about the actual effects of VSL/VAS systems on the fundamental relationships of traffic flow parameters. This brings the need to further research the topic using empirical data. Among the most important gaps in the current knowledge about VSL is the actual effects of sub-critical speed limits on traffic flow parameters. The answer to this question has therefore driven this research to determine the actual effects of VSL on the fundamental diagrams using empirical data.

3.2.2 Other Mobility Effects

Many researchers including (Zackor, 1979), (Van den Hoogen and Smulders, 1994) and (Pirkko, 2001) have studied the effects of VSL on flow and speed homogenization in Germany, Netherlands and Finland respectively. Their conclusions suggest that VSL has reduced speeds in all lanes, speed differential between lanes, severity of shockwaves and headways between vehicles. Using a per lane analysis,
(Knoop et al., 2010) and (Duret et al., 2012) have also found an increase in the utilization of the shoulder lane as a result of VSL homogenization.

Travel time reliability improvement as a result of VSL has been studied by researchers including (DeGaspari et al., 2013) and (Downey and Bertini, 2014) using several reliability measures including travel time buffer index, planning time index and the difference between mean and 95th percentile travel time. Researchers have found significant improvement in reliability for the periods when VSL was running. A study of M25 Controlled Motorway in UK (Highways Agency, 2004) indicated the same results but it was reported that the system had a small impact on travel time itself.

In a study by (Weikl et al., 2013) in Germany, it was found that, flow drop caused by congestion on Autobahn 99 became more homogeneous after the introduction of a VSL system. It was also found that median and center lane flows were harmonized with VSL system. (Hourdos et al., 2013) studied the effects of an advisory VSL system installed along I-35W in Minnesota. Their conclusions suggested that VSL have resulted in slower shockwave velocities, and increased gaps during congestion.

### 3.3 Safety Effects of Variable Speeds Limit Systems

Given the historical roots of VSL systems in primarily safety and weather-related applications, many evaluations of their safety impacts have been performed. The general literature on the safety effects of VSL system can be divided into two parts; empirical and simulation studies.
3.3.1 Empirical Studies

Several studies have confirmed safety improvements through VSL systems. Robinson, (2000) has provided a synthesis of VSL systems that have been implemented in the United States and other countries together with their reported benefits. The evaluation studies reported in (Robinson, 2000) have used crash data to assess the safety effects of VSL systems. In Germany, it was found that the crash rates were reduced by 20 to 30% after VSL implementation. It is also reported that the regulatory VSL system implemented along M-25 corridor in the U.K., decreased the amount of crashes by 10 to 15%. In Finland, it was found that the weather-responsive VSL system along E18 Motorway has reduced crashes by 13% during the winter and 2% during the summer and reduced the overall injury risk by 10% (Rama and Schirokoff, 2004). In another evaluation of a VSL system near Antwerp, Belgium, lower crash rates were found after system deployment. However it was argued that the reduction in crash rates were mostly due to accompanying warning signs that heightened driver awareness. The conclusions suggest that, although safety benefits of VSL systems have been studied more than its operational benefits, there is still a lack of overarching consensus in the literature about their actual safety benefits (Corthout et al., 2010).

Relying on crash statistics to assess the safety benefits of VSL systems require multiple years of data. Small sample sizes of crash data may lead to inconclusive or statistically insignificant results. Moreover, the use of crash data for safety analysis is a reactive approach. This means that a significant number of crashes need to be recorded before an action can be taken which reduces the ability to assess the safety effects of a
recently implemented safety countermeasure (Tarko, 2009). Therefore, many studies have used non-crash traffic events (also known as surrogate safety measures) that are physically and predictably related to vehicle crashes as a replacement to crash data. Studies have related the safety benefits of VSL systems to some surrogate safety measures like speed, speed variance and number of short headways. In general, most of the studies including (Highways Agency, 2004), (Van den Hoogen and Smulders, 1994), (Rama, 1999), (Brandenburg and Twisk, 2008), (Yadlapati, 2004), conclude that VSL can be an effective tool in harmonizing traffic flows, reducing mean speed and speed variance, and homogenizing headways therefore leading to fewer crashes, stable traffic flow, reliable travel times, and reduced traffic emissions (Lee et al., 2006), (Waller et al., 2010).

VSL impacts on safety and mobility are very sensitive to the level of speed compliance. In a study by (Hellinga and Mandelzys, 2011), it was found that the safety benefits of VSL under the very high compliance scenario are more than four times the benefits obtained under the low compliance scenario. (Hadiuzzaman et al., 2015) also found that safety along the corridor is improved when the level of compliance with VSL is between 50 to 60%. Some studies found that advisory VSL systems have little to no significant impacts on traffic safety and operations because of low driver compliance (CTC and Associates LLC, 2003), (Ulfarsson et al., 2001), (Steel et al., 2005), (Edara et al., 2013), (Nissan and Koutsopoulos, 2011).
3.3.2 Simulation Studies

Many studies in the literature have used simulation models to assess the safety effects of VSL systems. It is argued that field evaluations are time-consuming and are easily affected by the presence of confounding effects (e.g. speed enforcement policies and changes in traffic volume) (Lee et al., 2004). Using a macroscopic simulation model, (Sailer et al., 1997), formulated a mathematical expression of speed-density relationship as a function of speed limit. It was found that free-flow speeds decrease with speed limits. Using a Model Predictive Control (MPC) approach to coordinate VSL for highway traffic, (Breton et al., 2005), found that the reduction of speed limits suppressed the upstream traveling shockwaves by creating a low-density wave traveling upstream.

Some researchers have integrated simulation models with real-time crash prediction models to assess the potential safety benefits of variable speed limits. To formulate the crash-prediction models, Crash Potential (CP) is expressed as function of many surrogate safety measures (also termed crash precursors) and some external control factors. Lee et al. (2004) and Lee et al. (2006) developed a real-time crash-prediction model to estimate crash potential based on short-term variation of traffic flow characteristics (mainly variations of speed, flow and density) and integrated it with a microscopic traffic simulation model for calibration purposes. It was determined that VSL can reduce crash potential by 5 to 17% by reducing the speed limits during risky traffic conditions. Using PARAMICS microsimulation package, Abdel-Aty et al. (2006) found that reducing speeds upstream and increasing speeds downstream has the greatest safety potential. It was also observed that VSL improves safety only during uncongested
traffic conditions (Abdel-Aty et al., 2008). In another study, Abdel-Aty et al. (2006) noted that VSL migrates crash risks from one location to another. Despite this, it was found that the overall safety of the freeway can be improved due to VSL application.

### 3.4 Compliance with Variable Speed Limit Systems

Although many studies acknowledge the fact that driver compliance is vital to the success of any VSL system, particularly in terms of safety benefits, only a few of those studies have measured compliance in real time. The general literature on drivers’ compliance with VSL systems can be divided into two broad categories: empirical and simulation studies.

#### 3.4.1 Empirical Studies

In a study of VSL systems in England, it was found that improvements in compliance can improve facility’s operational performance and decrease the number of rear-end collisions by 25 to 30% (Tignor et al., 1999). In order to improve compliance levels, automated enforcement systems were implemented along the corridors. No quantitative results of compliance improvement due to these enforcement systems were stated in the report.

The Motorway Incident Detection and Automated Signaling (MIDAS) speed control system along M25 Motorway in England has been particularly effective in increasing driver compliance (Harbord, 1998). Due to the enforced nature of this VSL system, it was found that the majority of M25 drivers comply with dynamic speeds. There are indications that lane utilization has improved both laterally (distribution across
lanes) and longitudinally (more even headway spacing). However, the findings in compliance improvements did not involve quantitative results.

Van Den Hoogen and Smulder’s study of A2 controlled Motorway in Amsterdam reported that the VSL system had been effective in reducing speeds and speed variations. Although it was reported that drivers complied with the speed limits, no definite conclusion could be drawn from this study (Van den Hoogen and Smulders, 1994).

Ulfarsson et al. (2005) studied the impacts of variable speeds on mean speed and speed variations for a VSL system installed in the vicinity of Snoqualmie Pass on I-90 in the state of Washington. Although it was found that VSL had significantly reduced mean speeds and speed variations for a downhill direction, it had increased it during the favorable driving conditions leading to unsafe situations. It was also found that drivers compensate for reduced speeds in a VSL section by driving faster as they are out of the reduced zone creating shorter headways and dangerous conditions.

ATKINS, (2009) assessed the effectiveness of a VSL system implemented on a stretch of Interstate 4 in Orlando, Florida. It was found that although driver speeds were reduced, this reduction was more dependent on occupancy levels than VSL posted speeds. It was also shown that traffic exceeded the speed limit by more miles per hour when the VSL was reduced compared to the baseline speed limit. The findings from this study suggest that the full benefits of the VSL system cannot be accurately evaluated since the drivers are simply not complying with the reduced speeds.

Mott MacDonald, (2008) studied the effects of time on driver compliance with a VSL system deployed on M42 Motorway in England. It was found that driver compliance
increased with time and it was higher after the VSL system was deployed. The results of
the study confirms a previous study by (Van Den Hoogen and Smulder, 1994).

Rämä, (1999) investigated the effects of weather-controlled VSL system and
warning signs on driver behavior on E18 Highway in Finland. It was found that changing
the speed limit from 100 km/h to 80 km/h reduced the mean speed during free-flow
traffic conditions by 3.4 km/h. Further, VSL also decreased the speed variance but had no
tangible effects on headways. Compliance levels were not quantified in this research.

3.4.2 Simulation Studies

Using various microsimulation packages, researchers including (Hellinga and
Mandelzys, 2011), (Hadiuzzaman et al. 2015), (Bhowmick, 2011) and (Park and
Yadlapati, 2003) have found that high levels of compliance with VSL systems could
result in improvements in safety. However, in regards to mobility benefits, the results are
inconsistent as some studies including (Hellinga and Mandelzys, 2011) and (Park and
Yadlapati, 2003) have reported an increase in travel time with increase in compliance and
others have reported otherwise (Hadiuzzaman et al. 2015).

Habtemichael and De Santos, (2013) provided a quantitative evaluation of safety
and operational benefits of VSL systems under different compliance and traffic levels
using VISSIM. It was found that the system had the highest safety benefits during highly
congested traffic conditions followed by lightly congested and uncongested traffic
conditions. Moreover the system had the highest operational benefits during the lightly
congested traffic conditions. In general it was noted that the success of VSL is highly
dependent on the level of driver compliance. However, many assumptions were made in
the simulation model while defining these levels of compliance. Furthermore, other factors that may affect operating speeds like ramp metering and shoulder running were not considered in the analysis.

Using a driving simulator, (Lee and Abdel-Aty, 2008) examined the effects of warning messages and VSL system on driver speeds. It was found that the drivers who were shown a warning message or a variable speed sign drove at uniform speeds with a reduced variation. It was also found that an abrupt reduction in speed created greater speed variations and shorter headways. The study recommended that VSL signs be placed upstream of the congestion so that speed limit can be reduced gradually and hence make the transition smoother. Although a good compliance with the variable speeds was found, it was noted that using simulator may not necessarily depict the real world driving situation since in a simulator driver is aware that someone is monitoring the speed.

In summary, most of the researches confirm that drivers tend to travel at their desired speed whenever there is no enforcement. Advisory speeds have been found to have little to no significant impacts in traffic operations because of low driver compliance (Nissan and Koutsopoulos, 2011). Increased compliance can be accomplished through some method of enforcement, or by making drivers aware to the specific strategies of VSL implementation.
This section provided a comprehensive review of literature on the safety and mobility effects of VSL systems. In addition, many studies on the compliance behavior of drivers on VSL corridors were reviewed. The main conclusion is that in spite of VSL popularity as an efficient ATM strategy, their actual effects on safety and operations remains controversial. Table 2 and Table 3 provide a summary of the VSL/VAS deployment examples as detailed in Chapter 2 together with their reported benefits.

The conclusion of this chapter provide evidence that, there is a need for further research that evaluates the actual safety and traffic performance impacts of a VSL system for practical application. The current study on the effectiveness of the OR-217 VAS system will build upon the previous studies and will further the literature on this topic.
### Table 2. Weather and Fog-Responsive Variable Speed Limit Systems

<table>
<thead>
<tr>
<th>State</th>
<th>Type</th>
<th>Type of Activation</th>
<th>Status</th>
<th>Location</th>
<th>Results</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alabama</td>
<td>Regulatory</td>
<td>Manual</td>
<td>Active</td>
<td>Interstate 10</td>
<td>The public perception has been positive. Reduced mean speeds during fog conditions.</td>
<td>(Katz, et al., 2012), (Goodwin, 2003)</td>
</tr>
<tr>
<td>Arizona</td>
<td>Experimental</td>
<td>Experimental</td>
<td>System Suspended</td>
<td>Interstate 40</td>
<td>None Reported</td>
<td>(Placer, 1998), (Placer, 2001), (Placer and Sagahyroon, 2007)</td>
</tr>
<tr>
<td>Colorado</td>
<td>Advisory</td>
<td>Manual</td>
<td>Active</td>
<td>Rural Interstate 70</td>
<td>Reduced truck-related accidents. Mean speeds 8 mph lower during sign activation.</td>
<td>(Janson, 1999), (Robinson, 2000), (Katz, et al., 2012)</td>
</tr>
<tr>
<td>Delaware</td>
<td>Regulatory</td>
<td>Manual</td>
<td>Active</td>
<td>Urban Interstate 495</td>
<td>Favorably received by police, emergency services, and DelDOT personnel.</td>
<td>(Werner, 2003), (Katz, et al., 2012)</td>
</tr>
<tr>
<td>Florida</td>
<td>Regulatory</td>
<td>Hybrid</td>
<td>Active</td>
<td>Interstate 4</td>
<td>Motorist compliance with posted speed limits hasn’t changed. No significant impact on drive speed reduction. Rear-end crashes have shown no significant change</td>
<td>(ATKINS, 2009), (Katz, et al., 2012)</td>
</tr>
<tr>
<td>Idaho</td>
<td>Advisory</td>
<td>Manual</td>
<td>Experimental</td>
<td>Interstate 84</td>
<td>None Reported</td>
<td>(Katz, et al., 2012)</td>
</tr>
<tr>
<td>Louisiana</td>
<td>Advisory</td>
<td>Manual</td>
<td>System Suspended</td>
<td>Interstate 10 / Interstate 310</td>
<td>None Reported</td>
<td>(Katz, et al., 2012)</td>
</tr>
<tr>
<td>Nevada</td>
<td>Regulatory</td>
<td>Manual</td>
<td>System Suspended</td>
<td>Rural Interstate 80</td>
<td>None Reported</td>
<td>(Katz, et al., 2012)</td>
</tr>
<tr>
<td>New Jersey</td>
<td>Regulatory</td>
<td>Manual</td>
<td>Active</td>
<td>Interstate 95</td>
<td>Decreased vehicle speeds and reduced frequency and severity of weather-related crashes.</td>
<td>(Goodwin, 2003), (Robinson, 2000), (Katz, et al., 2012)</td>
</tr>
<tr>
<td>New Mexico</td>
<td>Regulatory</td>
<td>Automated</td>
<td>System Suspended</td>
<td>Interstate 40</td>
<td>Slight reduction in crashes.</td>
<td>(Robinson, 2000)</td>
</tr>
<tr>
<td>State/Country</td>
<td>Regulatory Manual</td>
<td>Active System</td>
<td>OR-217</td>
<td>Currently studied</td>
<td>(Katz, et al., 2012)</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Oregon</td>
<td>Advisory</td>
<td>Automated</td>
<td>Active</td>
<td>OR-217</td>
<td>Currently studied</td>
<td></td>
</tr>
<tr>
<td>Pennsylvania</td>
<td>Regulatory</td>
<td>Manual</td>
<td>Active</td>
<td>Turnpike</td>
<td>None Reported</td>
<td></td>
</tr>
<tr>
<td>South Carolina</td>
<td>No speed change</td>
<td>Manual</td>
<td>System</td>
<td>Urban Interstate 526</td>
<td>None Reported</td>
<td></td>
</tr>
<tr>
<td>Tennessee</td>
<td>Regulatory</td>
<td>Manual</td>
<td>Active</td>
<td>Rural Interstate 75</td>
<td>Significantly improved safety.</td>
<td></td>
</tr>
<tr>
<td>Utah</td>
<td>Regulatory</td>
<td>Manual</td>
<td>Systems</td>
<td>Interstate 80 / Interstate 215</td>
<td>Reduced speed variability during foggy conditions by 22% to 35%.</td>
<td></td>
</tr>
<tr>
<td>Washington State</td>
<td>Regulatory</td>
<td>Manual</td>
<td>Active</td>
<td>Rural Interstate 90</td>
<td>System reduced the average vehicle speed by up to 13 percent. Speed variance increased slightly, but the overall roadway safety has improved.</td>
<td></td>
</tr>
<tr>
<td>Wyoming</td>
<td>Regulatory</td>
<td>Manual</td>
<td>Active</td>
<td>Interstate 90</td>
<td>Speed reduction observed to be 0.47 – 0.75 mph per each 1 mph lower on VSL.</td>
<td></td>
</tr>
</tbody>
</table>

### Other Countries

<table>
<thead>
<tr>
<th>Country</th>
<th>Regulatory Manual</th>
<th>Active System</th>
<th>OR-217</th>
<th>Currently studied</th>
<th>(Katz, et al., 2012)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>Advisory</td>
<td>Not Specified</td>
<td>Active</td>
<td>Highway F3</td>
<td>No formal safety or operational evaluation was completed. Results of a resident survey indicated that the system was viewed positively.</td>
</tr>
<tr>
<td>Finland</td>
<td>Regulatory</td>
<td>Manual</td>
<td>Active</td>
<td>Rural E18 Motorway</td>
<td>95% of drivers interviewed endorsed the use of speed limits set according to the prevailing road conditions.</td>
</tr>
<tr>
<td>France</td>
<td>Not Specified</td>
<td>Hybrid</td>
<td>Not Specified</td>
<td>Urban - Marseille</td>
<td>None Reported</td>
</tr>
<tr>
<td>The Netherlands</td>
<td>Advisory</td>
<td>Automatic</td>
<td>Not Specified</td>
<td>Urban A16 Motorway</td>
<td>Drivers reduce their mean speeds by approximately 8 to 10 km/h during fog conditions after the system was installed</td>
</tr>
</tbody>
</table>

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Table 3. Congestion-Responsive Variable Speed Limit Systems

<table>
<thead>
<tr>
<th>United States</th>
<th>State</th>
<th>Type</th>
<th>Type of Activation</th>
<th>Status</th>
<th>Location</th>
<th>Results</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Florida</td>
<td>Regulatory</td>
<td>Hybrid</td>
<td>Active</td>
<td>Interstate 4</td>
<td>Motorist compliance with posted speed limits hasn’t changed. No significant impact on drive speed reduction. Rear-end crashes have shown no significant change</td>
<td>(ATKINS, 2009)</td>
</tr>
<tr>
<td></td>
<td>Minnesota</td>
<td>Advisory</td>
<td>Automatic</td>
<td>Active</td>
<td>Interstate 35W</td>
<td>A very small compliance to the speed limits was observed. However, VSL system has positively affected the most severe congestion.</td>
<td>(Kwon et al., 2011)</td>
</tr>
<tr>
<td></td>
<td>Minnesota</td>
<td>Advisory</td>
<td>Automatic</td>
<td>Active</td>
<td>Interstate 94</td>
<td>No significant change in safety was observed due to the system. Crash and near crash rates remained similar, and shockwave generation patterns were consistent.</td>
<td>(Hourdos and Zitzow, 2014)</td>
</tr>
<tr>
<td></td>
<td>Missouri</td>
<td>Advisory</td>
<td>Automatic</td>
<td>Active</td>
<td>Interstate 270 / Interstate 255</td>
<td>Benefits have been seen with respect to reduction in the number of crashes. The driving public and law enforcement were widely dissatisfied with the VSL system. Shockwaves were also reduced.</td>
<td>(Bham et al., 2010), (MoDOT, 2013)</td>
</tr>
<tr>
<td></td>
<td>Oregon</td>
<td>Advisory</td>
<td>Automatic</td>
<td>Active</td>
<td>OR-217</td>
<td>Currently studied.</td>
<td>Currently studied.</td>
</tr>
<tr>
<td></td>
<td>Washington</td>
<td>Regulatory</td>
<td>Automatic</td>
<td>Active</td>
<td>Interstate 5, Interstate 90, SR 520</td>
<td>Positive public perception. No formal evaluation.</td>
<td>(Balogh, 2012)</td>
</tr>
<tr>
<td></td>
<td>Other Countries</td>
<td>Regulatory</td>
<td>Automatic</td>
<td>Active</td>
<td>M4 Motorway</td>
<td>None Reported</td>
<td>(Han et al., 2009)</td>
</tr>
<tr>
<td>Country</td>
<td>Control Type</td>
<td>Automatic/Active</td>
<td>Motorway</td>
<td>Outcomes</td>
<td>Reference</td>
<td></td>
<td></td>
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<td>-------------</td>
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<td>--------------------------------------------------------------------------</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Germany</td>
<td>Regulatory</td>
<td>Automatic/Active</td>
<td>A8, A3, A5</td>
<td>On the A5 crash rates fell by 20%. There was also a 67% decline in secondary crashes. Reduced travel times, decreased fuel consumption, and lower emissions were also found. For A9 the system responded well to traffic but congestion and shockwaves were still present.</td>
<td>(Mirshahi et al., 2007)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>The Netherlands</td>
<td>Regulatory</td>
<td>Automatic/Active</td>
<td>A2 Motorway</td>
<td>Drivers adjusted their speed due to the VSL, and in general, the drivers complied with the speed signs. The severity of shockwaves and speed in all lanes were reduced by speed control measures.</td>
<td>(Robinson, 2000)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sweden</td>
<td>Advisory</td>
<td>Automatic/Active</td>
<td>E4 Motorway</td>
<td>System had no significant impact. Although the drivers did not adapt their speeds to the displayed VSL, but the signs made them more cautious with regard to the possibility that there would be a queue ahead.</td>
<td>(Nissan, 2010)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>United Kingdom</td>
<td>Regulatory</td>
<td>Automatic/Active</td>
<td>M42 Motorway</td>
<td>The observed capacity increased by an average of 7 to 9%. Reduced the average journey times during periods of recurrent severe congestion by up to 24%. Fuel consumption has been reduced by 4%. Vehicle emissions have been reduced by 4 to 10%.</td>
<td>(Highways Agency, 2008)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
CHAPTER 4

STUDY CORRIDOR AND FIELD DATA

The first section of this chapter provides an introduction to the study corridor and the operational and safety challenges along the corridor that ultimately prompted the use of an active traffic management system. The second part of this chapter will provide details about the ATM system, and other instruments installed along the freeway. In the third section, the data collection and processing procedures will be detailed. The fourth section describes the analysis framework for this research.

4.1 Study Corridor

Oregon Route 217 is a freeway (limited access facility) connecting the southwestern suburbs of Beaverton and Tigard. This freeway has a total length of 7.52 miles and has two travel lanes in each direction for most of its length, with a third auxiliary lane for exiting and merging. The northern terminus of OR-217 connects with US-26 through a partial-cloverleaf interchange. The southern terminus of OR 217 is attached to Interstate 5 (see Figure 11). This freeway is characterized by its many closely-spaced interchanges (sometimes less than ¼ mile). In total there are eleven sets of on- and off-ramps in each direction connecting with intersecting local streets. The freeway’s posted speed limit is 55 miles per hour.

Due to its location, OR-217 is a popular commuter route. With over 122,000 vehicles per day, the freeway often operates at or above capacity during peak hours and
sometimes even during off-peak hours. The total traffic volumes on this highway doubled between 1985 and 2005 and by 2025, traffic volumes are expected to increase by another 30% (Metro, 2005). It has been estimated that if no improvements were made to OR-217 freeway, the daily congestion would have increased from three hours to eight hours in 2025 (Metro, 2006).

Figure 11. Oregon 217 Corridor (DKS & Associates, 2010)
In addition to congestion, OR-217 is also one of the least reliable freeways in Portland area. As shown in Figure 12, the southbound (SB) direction of OR-217 has the second highest buffer index (which is the extra time over driver’s expected average travel time to a destination) of all freeways in Portland area during the afternoon peak period (Lyman and Bertini, 2008).

![Figure 12. Portland freeways afternoon peak buffer index (Lyman and Bertini, 2008)](image)

This corridor also has crash rates higher than the statewide averages for this type of facility, with rear-end crashes being particularly frequent. The following sections provide a summary of the congestion and crash patterns along the freeway that sparked the need to ultimately install an advisory VSL system along the corridor.
4.1.1 Typical Traffic Patterns

Travel Times: Due to its location, congestion is always present on OR-217 during normal commuting periods (morning and late afternoon). A typical midweek day and weekend average travel times along the NB direction of OR-217 is shown in Figure 13a and 13b respectively. These plots were created from using one month of freeway loop detector data aggregated into 10-minute averages.

![Figure 13. Average travel times during (a) Midweek Days (b) Weekends](image)

As can be seen in Figure 13a, the average travel time distribution during midweek days is bimodal with a remarkable deviation from free-flow travel time (of approximately 7 minutes) during the peak hours. The significant gaps between average travel times during clear and adverse weather conditions are also noticeable. For a typical midweek day during clear weather conditions, the average travel time was found to be 8.1 minutes throughout the morning peak, 11.6 minutes throughout the evening peak and 7.6 minutes throughout the midday hours. On the other hand, during adverse weather conditions,
average travel times were 14.2 minutes, 12.5 minutes, and 8.1 minutes during the morning peak, evening peak and midday hours. This shows an average of 30% increase in travel time during adverse weather conditions. Contrary to midweek days, the average travel times during the weekends (Figure 13b), are not bimodal and there are also no significant gaps between clear weather and adverse weather average travel times. It was found that during the weekends, on average the travel times during adverse weather conditions are 10% longer.

Similarly, travel times are highly variable and unreliable during adverse weather conditions. Figures 14a and 14b demonstrate this by showing the average travel time and the differences between 95th and 5th percentile travel times (as a grey band) during clear and adverse weather conditions respectively. For a typical midweek day, the standard deviation of travel time was found to be 2.3 minutes during clear weather conditions and 4.1 minutes during adverse weather conditions showing an 80% increase. The large discrepancy between average and 95th percentile travel times which is also known as Buffer Index (BI) in particular makes it difficult for drivers to accurately assess how long the route will take them on any given weekday. BI which is a measure of travel time reliability was found to be 20.5% during clear weather and 37.2% during adverse weather conditions. This means than on average travelers must add these additional percentages to their average travel times when planning trips to ensure on-time arrival to their destinations.
Speeds and Flows: Both directions of OR-217 follow bimodal speed and flow distributions during midweek days, typical of commuter-heavy freeways, with distinguishable peaks for volumes and valleys for speeds in the morning and evening (see Figures 15a and 16a). As can be seen in Figure 15a, during clear weather conditions, average speeds may decrease to as much as 45 mph. Considering adverse weather conditions, average speeds decrease to as much as 35 mph. Between the two peaks, flows subside slightly and speeds recover, but not all the way to free-flow levels. From Figure 15a it can also be inferred that morning peak during adverse weather conditions, starts about an hour earlier and ends half an hour later compared to clear weather conditions. There is no significant difference between the afternoon peak hours for the two weather conditions.

On weekends, there is only one distinguishable peak in flow levels during the midday hours extending all the way to 6:00 pm. This increase in flow slightly reduces the speeds on the corridor but not as much the typical weekdays (see Figures 15b and 16b).
There is no significant change in average speeds during adverse weather conditions as compared to clear weather conditions.

Figure 15. Average speeds during (a) Midweek Days (b) Weekends

Figure 16. Average flows on both lanes during (a) Midweek Days (b) Weekends
Spatial and Temporal Variation of Speeds: Bottleneck formation is a major problem along OR-217 during the peak hours. The effects of these bottlenecks quickly propagate upstream to engulf over half the corridor under average speeds of 30 mph or less for several hours. The congestion patterns on the NB direction for three representative days (a typical midweek day, a Friday and a weekend) are shown in Figure 17. For the NB direction, a bottleneck typically forms just north of Denney Road (MP 2.68) around 7:00 AM and extends all the way back to the southern terminus of the corridor, lasting about two hours. In the afternoon, a very similar bottleneck forms around 3:00 PM but the congestion lasts for more than three hours. Although bottlenecks form during the weekends, but they are not as severe as the weekdays.

![Figure 17. Spatial and temporal variations of speeds for three representative days - OR 217-NB](image)

Similarly, for the SB direction, a bottleneck typically forms near Greenburg Road (MP 5.11) and extends upstream for several miles for a few hours. During the PM peak,
bottleneck forms near Denney Road (MP 3.12), but the congestion caused by this bottleneck lasts for much longer than the morning peak (see Figure 18).

Figure 18. Spatial and temporal variations of speeds for two representative days - OR 217-SB

4.1.2 Typical Crash Patterns

Due to closely spaced interchanges and a proclivity for congestion, OR-217 is prone to crashes particularly rear-end collisions. In 2013, ODOT reported that the freeway had 322 crashes on the mainline which equates to a crash rate of 1.06 crashes per million vehicle miles, higher than the statewide average of 0.92 for urban non-interstate freeways (TDS, 2014). As shown in Figure 19, more than three quarters of the reported crashes from 2009 to 2013 were rear-end collisions. This was one of the main reasons that VAS was implemented along OR-217. Almost half of the crashes along OR-217...
from 2009 to 2013 involved at least one injury. The majority of these injuries were moderate and non-incapacitating and came from rear-end collisions.

Crashes on OR 217 are not distributed equally along the corridor or throughout the course of a year. Figures 20 and 21 show the number of reported crashes from 2009 through 2013 for each 0.1-mile increment of the freeway. As it is clear from the figures, crashes are more common near on and off-ramps. It is also clear that VAS signs (shown as red lines) were installed near the crash hotspots to reduce the number of crashes.

Figure 19. OR-217 Crashes by Collision Type (2009-2013)
Figure 20. Distribution of Crashes along OR-217 NB (2009-2013)
Figure 21. Distribution of Crashes along OR-217 SB (2009-2013)
Adverse weather conditions also pose a great safety threat to OR-217 corridor. Figures 22a, 22b and 22c show the breakdown of crashes by weather, road surface and light conditions respectively. From 2009 to 2013, although precipitation was reported only for 16% of the time, it accounted for almost a quarter of the crashes on the freeway. This was the reason that VAS system was designed to be responsive to both congestion and weather conditions.

![Figure 22a](image1)
![Figure 22b](image2)
![Figure 22c](image3)

Figure 22. Distribution of crashes by (a) Weather conditions (b) Road surface conditions (c) Light conditions (2009-2013)
4.2 OR-217 Active Traffic Management System

To overcome the challenges described previously, OR-217 has been the subject of several extensive and decade-long studies that recommended capacity and interchange improvements costing nearly $1 billion. To cut costs and to innovatively address the operational and safety issues, the Oregon Department of Transportation (ODOT) built an Active Traffic Management (ATM) system along OR-217 and activated it on July 22, 2014.

This system works by collecting traffic data from a series of dual-loop detectors placed in each traffic lane upstream of the entrance ramps. These detectors measure speed, volume and occupancy and report it every 20 seconds. To minimize any large gap between loop detectors, radar sensors are also installed. These sensors which are manufactured by Wavetronix collect the same data as loop detectors. A total of 11 loop detector and 2 radar sensor stations are located along the SB direction. The NB direction has a total of 9 loop detector and 2 radar sensor stations. The average spacing of these detectors and sensors is 0.54 miles in the NB and 0.52 miles in the SB direction. Ramps are also equipped with loop detectors, but these loops only record vehicle counts. The data obtained from these detectors and radar sensors is stored in Portland Oregon Regional Transportation Archive Listing (PORTAL). PORTAL is a comprehensive and multimodal online transportation data archive which stores data relating to the performance of Portland’s transportation networks. Besides loop detectors and radar sensors, OR-217 is also equipped with four RWIS sensors that measure roadway grip factor, roadway surface conditions, and visibility every five minutes (Crain et al., 2013).
Figure 23 shows a layout of the available instrumentation on the northbound and southbound directions of the OR-217 freeway.
The ATM system along OR-217 is composed of six systems that work together to address the challenges along the corridor. These systems include travel time information, queue warning, congestion-responsive variable speed, weather-responsive variable speed, dynamic ramp-metering and curve warning systems. These systems interact together and share much of the same physical and informational infrastructure. The first four systems are briefly described in the following paragraphs. More focus has been given to the congestion and weather-responsive VSL systems. Figure 24 shows all the ATM technologies that have been deployed along OR-217.

Figure 24. OR-217ATM Technologies (DKS & Associates, 2013)
4.2.1 Travel Time Information System

Using real-time traffic information, the travel time system along OR-217 gives an estimate of the time it should take the drivers to reach common destinations. The drivers can benefit from this system by choosing alternate routes or delaying their trips if necessary. By alerting the drivers of potential levels of congestion along the freeway, the travel time information also improves safety. The key components of travel time messages are major destinations and the associated time (see Figure 25). Currently, the travel time system is activated only during the congested periods. According to ODOT, showing travel times on a regular schedule, even when uncongested, will allow frequent drivers to relate the travel time estimations to the severity of traffic congestion.

Figure 25. Travel Time System along OR-217 (ODOT, 2015)

4.2.2 Queue-Warning System

A queue-warning system has also been installed as part of OR-217 ATM project. This system notifies the drivers of potential standing queues upstream (see Figure 26). These queues can result from regular bottlenecks, or some other causes (e.g. crashes, construction work, etc.). The primary purpose of this system is to reduce the number of
crashes, especially the rear-end type, that are likely related to unpredictable traffic congestion throughout the corridor.

4.2.3 Advisory Variable Speed Limit System

As part of OR-217 ATM project, an advisory VSL system (which will be termed the VAS system throughout the thesis) was also installed along OR-217. According to the Oregon Statewide Variable Speed System, Concept of Operations, advisory speeds was preferred to regulatory speeds due to the following reasons (DKS & Associates, 2010):

- Advisory speeds can be set when conditions warrant, including but not limited to, average speeds, downstream congestion situations, and environmental conditions.
- Advisory speed messages can be turned on and off as needed.
- According to Oregon Revised Statute 811.100, advisory speeds in Oregon can be enforceable through the basic speed rule (DKS & Associates, 2013).

Figures 27a and 27b show the two primary configurations of these signs, either on bridges or metal structures. In total, there are seven overhead VAS signs in the
northbound and the southbound directions (see Figure 23). The VAS system on OR-217 has two main components; a congestion-responsive component and a weather-responsive component, which are described in the following paragraphs.

![Figure 27. VAS sign configurations (a) on Bridge (b) Metal Structures (ODOT, 2015)](image)

The primary purpose of the congestion-responsive component is to minimize the spatial and temporal variations in speeds that can lead to crashes and increased congestion by posting advisory speeds upstream of areas of incidents or congestion. This requires using volume, occupancy, and speeds from relevant loop detectors or radar sensors to determine traffic state at each detector station. Based on pre-specified occupancy and volume thresholds, the system determines an appropriate speed. This speed value is rounded up or down to the nearest 5 mph speed and 5 mph will be added to determine the speed message for the VAS sign (DKS & Associates, 2013). Moreover, the speeds displayed upstream of the most congested segments are stepped down based on how far upstream they are in order to encourage drivers to gradually decelerate before they reach the heaviest congestion. The speeds posted on VAS signs range from 30 to 50 mph in 5 mph increments. In case of stop-and-go traffic conditions when speeds
calculated are below 25 mph, a message of “SLOW” will be generated instead of an advisory speed.

The primary purpose of the weather-responsive component is to notify drivers of adverse weather conditions and display speeds for possible hazardous roadway conditions such as water or ice on the roadway surface. This component of VAS system continuously collects real-time weather data from the RWIS sensors installed along the corridor. Speed reduction values are based on measurements of visibility and grip factors. Should congestion and adverse weather conditions happen simultaneously, the lower of the two calculated speeds is selected and posted on the VAS signs. Figure 28 shows the detection and decision logic for both congestion and weather-responsive components of the VAS system.

Figure 28. (a) Congestion-Responsive VAS Control logic (b) Weather Responsive VAS Control logic (DKS & Associates, 2013)
4.3 Data Collection and Processing

In order to complete a comprehensive evaluation of the VAS system along OR-217, four data sources were used. These sources together with their corresponding data are described in the following paragraphs.

4.3.1 Traffic Data

As described previously, the traffic data (mainly speed, volume and occupancy) is collected by a series of dual loop-detectors or radar sensors along the corridor and is reported in 20 seconds aggregations. Most mainline detectors are placed near on-ramps with most placed just upstream of the on-ramp. Figure 29 visualizes the physical layout of the detector installations.

The traffic data is stored in PORTAL (www.portal.its.pdx.edu), which is the official intelligent transportation systems data archive for the Portland metropolitan region. The tables obtained from PORTAL contain five columns for timestamps (date + time), volume, occupancy, speed and detector ID. These tables were merged with a
separate table containing more detailed information about each detector such as lane number, milepost, influence length and detector type (either loop detector or radar sensor). Data collected from detectors located on ramps were omitted due to unavailable data for a large portion of both the “before” and “after” analysis periods. Python and R were employed for these purposes.

Two primary categories of loop detector malfunctions that are continuously inspected and rectified by ODOT are detector configuration errors and communication failures. Configuration errors consist of problems occurring at detectors or controllers including miscalibration of a detector, incorrect detector location or spacing, and misconfiguration of the controller (Tufte et al., 2007). PORTAL uses a set of tests developed by Texas Transportation Institute (TTI, 2003) to examine these configuration errors. The tests apply to 20 second aggregated data (see Table 4). Each test includes a condition. Data samples that satisfy that condition are considered improbable and are considered a detector malfunction. Data passing this quality control check were used in the analysis. A monthly report that lists detectors in need of maintenance is automatically created by PORTAL and is submitted to ODOT. Communication errors are the second major cause of loop detector data errors. These errors occur if PORTAL periodically reports a reading of no traffic (volume = 0) during highly-congested periods. Information on communication failures is also included in the monthly detector status report sent to ODOT, in the form of a map and a report. To double-check the validity of data obtained from PORTAL, these tests were implemented and erroneous data were filtered-out using the statistical tool R.
To support data analysis, PORTAL aggregates traffic data at five-minute, fifteen-minute and one-hour granularities. For five-minute aggregates, the following procedures are used:

- **Volume**: valid count samples are summed and then rescaled to represent a larger interval count. If all data is available, there are fifteen data samples in a five-minute period. If fewer than fifteen samples are present, then the count is rescaled by the number of missing samples, so as to indicate a five-minute count.

- **Occupancy and Speed**: All valid occupancy (speed) samples in a five-minute period are averaged, Five-minute counts are summed for a larger-interval count.

These five-minute counts, speeds and occupancies are used to aggregate traffic data over larger periods of time (e.g. 15-minutes, 1-hour).
4.3.2 Crash Data

OR-217 reported crash data is obtained from ODOT’s statewide reported crash database. Crashes are included in the database if it involves a fatality, injury, or damages of $1,500 or more. The database contains a wide array of information pertaining to each crash, including time, location, type, and severity. The information contained in the crash reports is compiled from individual driver and police crash reports submitted to ODOT. This database is updated monthly with data currently available up to December 31, 2014, almost five months after system implementation. The crash data for the latest available year is preliminary and subject to change until finalized on approximately June 30, 2016. To compute crash rates for each highway covered by the agency, ODOT has combined the reported crash data with vehicle miles traveled (VMT) in its highway crash rate tables.

4.3.3 Weather Data

The weather-responsive component of the system uses the weather data collected from the new RWIS sensors installed along the corridor. Although it is primary source of data governing the operations of the VAS system, this data is not yet available in PORTAL website. Instead, the data comes from the National Oceanic and Atmospheric Administration’s (NOAA) Meteorological Assimilation Data Ingest System (MADIS)-Citizen Weather Observer Program (CWOP). CWOP is a public-private partnership that aims to collect weather data contributed by citizens. The main data collected by CWOP stations are shown in Table 5. The data is collected in 10 minute intervals and it typically undergoes a series of quality checking test before being distributed to the users.
Table 5. Measurements taken from CWOP Stations

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TMP</td>
<td>Temperature (°F)</td>
</tr>
<tr>
<td>RELH</td>
<td>Relative Humidity (%)</td>
</tr>
<tr>
<td>SKNT</td>
<td>Wind Speed (mph)</td>
</tr>
<tr>
<td>GUST</td>
<td>Wind Gust Speed (mph)</td>
</tr>
<tr>
<td>DRCT</td>
<td>Wind Direction (°)</td>
</tr>
<tr>
<td>QFLG</td>
<td>Quality check flag</td>
</tr>
<tr>
<td>ALTI</td>
<td>Altimeter (in.)</td>
</tr>
<tr>
<td>PREC</td>
<td>Precipitation accumulated (in.)</td>
</tr>
<tr>
<td>P24I</td>
<td>24 Hours Precipitation (in.)</td>
</tr>
<tr>
<td>DWP</td>
<td>Dewpoint (°F)</td>
</tr>
</tbody>
</table>

CWOP stations are located very close to the corridor as shown as black dots in Figure 30. For the purpose of this research, one representative CWOP station (CW9129) was chosen in the Tigard County near Scholl Ferry Road on the west side of the corridor.

Figure 30. CWOP stations near OR-217 (MesoWest, 2016)
For checking purposes, another CWOP station (CW6930) was selected on the east side of the corridor. Both stations passed the quality control checks for the periods of data collection.

4.3.4 VAS System Log Data

VAS system log data was obtained from ODOT in an Extensible Markup Language (XML) format. It included information about when and where the system was active and what advisory speeds it was displaying. Since the advisory speed shown in VAS remains for 1 minute before it expires, the log data was available in one minute increments. The data was later fused with traffic data in order to evaluate the system during the periods when VAS system was on and when it was turned off. Advisory VSL activation times for two representative midweek days are shown in Figure 31.
4.4 Evaluation Framework

After data collection and processing, a series of specific evaluation questions and hypotheses were generated to guide the analysis. These questions were developed in a way that it encompasses both the safety and mobility benefits of the VAS system. A series of performance measures were developed for this purpose (see Figure 32). Besides, the compliance behavior of drivers with the system was also studied using carefully designed experiments. Each of these analyses was carried out in the form of either “before and after” or “on and off” scenarios in order to get a clear picture of how OR-217 has changed since the system’s implementation. Different weather, and time scenarios were also considered for each study. The timeline of the analysis period for these studies are different from each other. Figure 32 summarizes the evaluation studies conducted on OR-217 VAS system.

Figure 32. VAS System evaluation studies framework
The mobility impacts of the system will be studied in Chapter 5. Chapter 6 and 7 will investigate the compliance behavior and safety impacts of the VAS system respectively. The methodology, data and the results for each study are detailed in its respective chapter.
CHAPTER 5

STUDY RESULTS: VAS IMPACTS ON FUNDAMENTAL FLOW PARAMETERS

As described in Chapter 3, the homogenization effects of VSL/VAS systems can reduce speed, flow and occupancy differences within and between lanes and hence can result in higher capacity values. However, there is no consensus among different researchers about the actual effects of VSL/VAS on these fundamental traffic flow parameters. This motivated this chapter of the thesis to further investigate the subject using empirical data. This chapter is divided into 4 sections. Section 1 provides information about the study design. Section 2 provides details about the methods used for evaluation purposes. Many statistical and curve-fitting methods are described under this section. Results and discussions are provided in section 3. The last section provides an introduction to an alternative methodology to determine the system impacts on fundamental traffic flow parameters.

5.1 Study Design

To examine the effect of the VAS system on fundamental traffic flow parameters, a series of before-and-after comparisons were made to account for the effect of three variables; weather conditions, time of day and day of week. Normal and adverse weather conditions, morning and evening peak periods and midweek days versus Mondays and Fridays were all part of the comparisons conducted in the analysis. As was shown, the VAS system is turned on mostly during the peak hours, so morning peak and evening
peaks were used for the analysis. Also, due to different traffic conditions on Mondays and Fridays, there were treated separate from the rest of weekdays.

In this analysis, data from two detector stations in each direction were collected. For the northbound direction, these included Greenburg (MP 4.65) and Scholls Ferry (MP 3.85). For the southbound direction, B-H-Hwy (MP 1.92) and Allen (MP 2.55) were selected. These stations were chosen because they are affected by the shockwaves arriving from downstream active bottlenecks and hence they reach capacity during the morning (6:00 AM to 10:00 AM) and evening peak hours (3:00 PM to 8:00 PM). These detector stations are also located near the center of the corridor and thus less likely to be influenced externally by conditions on Interstate 5 and US-26. Additionally, the data quality and availability of these stations was found to be superior to that of other stations.

The different scenarios considered in the series of comparisons are shown in Figure 33 for MP 4.65 in the northbound direction. In total, 32 scenarios were considered for the “before” and 32 scenarios were considered for the “after” periods.

Since this was a “before-after” evaluation, it was necessary to select appropriate time periods to act as sources for the “before” and “after” datasets. For this reason, (August to December 2012) was chosen as “before” and (August to December 2014) as the “after” period. These five months account for weather variations as October to December are the wettest months in Portland and August and September are fairly dry. August to December of 2013 was not chosen as the “before” sample because the construction activities on OR-217 during that time resulted in significant disruptions to data collection from the detectors. Days with faulty or missing data and days with a major
accident were removed from the analysis. As a result one week of data was collected for both clear and adverse weather conditions for both before and after periods.

5.1.1 Data Aggregation

Short-term variations in the raw 20-second traffic data, collected from PORTAL was not of major interest in this analysis. To facilitate visual pattern perception, traffic data need to be aggregated. For this study an aggregation period of 2 minutes was used. Unfortunately, PORTAL’s interface does not allow using aggregation periods other than (5 min, 15 min or 1 hour). For aggregation purposes, the clean 20-second data was entered into R statistical package and then aggregated into 2-minute intervals using the “aggregate” function. This provided 120 observations for the morning peak and 150 observations for the evening peak hours for each day of the analysis period.
5.2 Methodology

The effects of the VAS system on the fundamental relationships of traffic flow parameters was studied primarily using the flow-occupancy diagrams for the “before” and “after” periods. The first step in this study was to examine the statistical significance of changes in the flow-occupancy distributions as a whole. This was done using a kernel density-based global two-sample comparison test which is described shortly. However, this test does not provide insights on the changes within the distribution. Such trends could be obtained using curve-fitting procedures. To do this, the determination of critical occupancy was necessary. As described previously, critical occupancy represents the cutoff point between normal (free-flow) and congested traffic conditions. Its value is calculated by a trial and error method called iterative searching procedure described later. After the determination of critical occupancy, regression was used to fit lines to the data. Linear regression was applied due to its simplicity. To get a better understanding of the difference between the diagrams, slopes of the lines for “before” and “after” periods were compared. As previously described, the mean speed is proportional to the slope of flow-occupancy curves, and therefore, comparison of slopes can help to better understand the effects of the VAS on speeds. Using Analysis of Covariance (ANCOVA), which is described later, it was possible to compare the slopes.

5.2.1 Kernel Density-Based Global Two-Sample Comparison Test

A classical problem in statistical inference is testing the equality of k-distributions from independent random samples without using any parametric (e.g. normal)
assumption on the underlying populations. For one-dimensional continuous data, non-parametric tests based on the differences in the cumulative distribution functions (CDFs) are in general found to be very effective. The most common one-dimensional goodness-of-fit tests are Kolmogorov-Smirnov (K-S), Mann-Whitney, Wald-Wolfowitz, Anderson-Darling (A-D) and Cramer-von Mises-Smirnov tests. Kolmogorov-Smirnov test, which uses the maximum absolute difference between the distribution functions of the samples is the most attractive among these tests. This is because the (K-S) test is distribution-free. It also uses each individual data point in the samples, and is independent of direction of ordering of the data (Lopes et al., 2007).

Adapting goodness-of-fit tests to multi-dimensional space (e.g. flow-occupancy) is generally seen as a challenge. Many studies suggest that continuous multi-dimensional data should be binned into different groups. However, binning data faces the hurdle of what is called in the literature "the curse of dimensionality": a high dimensional space is mostly empty, and binning tests can only start to be effective when the data sets are very large (Scott, 2007).

Although many studies including (Bickel, 1969), (Friedman and Rafšky, 1979), (Liu and Singh, 1993) and (Lopes et al., 2007) have examined the possibility of extending the one-dimensional non-parametric goodness-of-fit tests to a multidimensional space, these multivariate approaches have not met with the same wide acceptance as their univariate counterparts, because it consistently has not yielded intuitive inferences when applied to experimental data (Duong et al., 2012). One approach that has shown great promise in comparing multivariate samples is the kernel-
density based global comparison test. Readers are highly encouraged to refer to (Simonoff, 1996) for detailed discussions about this method. (Duong et al., 2012) has developed a test statistic that is asymptotically normal under the null hypothesis, which allows density-based comparisons of multivariate data. Their procedure is detailed in the following paragraphs.

Let \( X_1; X_2 \ldots X_{n_1} \); and \( Y_1; Y_2 \ldots Y_{n_1} \); be \( d \)-variate random samples from their respective common densities \( f_1 \) and \( f_2 \). For this case \( X_1; X_2 \ldots X_{n_1} \) represent the flow-occupancy values for “before” and \( Y_1; Y_2 \ldots Y_{n_1} \) represent these values for the “after” period. So \( f_1 \) represents the flow-occupancy probability density function in the “before” sample, and likewise for \( f_2 \). The kernel density estimates of \( f_1 \) and \( f_2 \) are:

\[
\hat{f}_1(x; H_1) = \frac{1}{n_1} \sum_{i=1}^{n_1} K_{H_1}(x - X_i)
\]

\[
\hat{f}_2(x; H_2) = \frac{1}{n_2} \sum_{j=1}^{n_2} K_{H_2}(x - Y_i)
\]

Where \( K \) = kernel function with \( K_{H_l}(x) = |H_l|^{-\frac{1}{2}} K(H_l^{-\frac{1}{2}} x) \) and \( H_l \) = bandwidth matrix with \( l = (1, 2) \). Given the above density functions, the null and alternative hypothesis are formulated as follows:

\( H_0: f_1 = f_2 \)

\( H_1: f_1 \neq f_2 \)

The measure of discrepancy is the integrated squared error (ISE) defined as follows:

\[
T = \int [f_1(x) - f_2(x)]^2 dx
\]

\( T \) can also be written as:

\[
T = \psi_1 + \psi_2 - (\psi_{1,2} + \psi_{2,1})
\]
Where:

\[ \psi_1 = \int f_1(x)^2 \, dx, \psi_2 = \int f_2(x)^2 \, dx, \text{ and } \psi_{1,2} = \int f_1(x) f_2(x) \, dx. \]

Given the value of \( T \), the test statistic (\( \hat{T} \)) is calculated as follows:

\[ \hat{T} = \hat{\psi}_1 + \hat{\psi}_2 - (\hat{\psi}_{1,2} + \hat{\psi}_{2,1}) \]

Where

\[ \hat{\psi}_1 = \frac{1}{n_1^2} \sum_{i_1=1}^{n_1} \sum_{i_2=1}^{n_1} K_{H_1}(X_{i_1} - X_{i_2}) \]

\[ \hat{\psi}_2 = \frac{1}{n_2^2} \sum_{j_1=1}^{n_2} \sum_{j_2=1}^{n_2} K_{H_2}(Y_{j_1} - Y_{j_2}) \]

\[ \hat{\psi}_{1,2} = \frac{1}{n_1 n_2} \sum_{i=1}^{n_1} \sum_{j=1}^{n_2} K_{H_1}(X_i - Y_j) \]

\[ \hat{\psi}_{2,1} = \frac{1}{n_1 n_2} \sum_{i=1}^{n_1} \sum_{j=1}^{n_2} K_{H_2}(X_i - Y_j) \]

This test statistic can be interpreted as the comparison of intra-sample pairwise differences \( X_{i_1} - X_{i_2} \) and \( Y_{j_1} - Y_{j_2} \) to the inter-sample pairwise differences \( X_i - Y_j \). So if the latter are larger than the former, then that the samples are different from each other.

Given that asymptotic normality holds and assuming that null hypothesis is true, the \( z \)-score can be calculated as follows:

\[ Z = \frac{\hat{T} - \hat{\mu}_T}{\hat{\sigma}_T \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \]

The estimation procedure for mean parameter (\( \hat{\mu}_T \)) and variance parameter (\( \hat{\sigma}_T \)) can be found in (Chacon and Duong, 2010). The \( p \)-value is then computed from this \( z \)-
score using a statistical software or tables. This entire procedure is programmed in R-programming language and is available in “ks” library (Duong, 2016). The end result of the analysis is the test-statistic and its associated p-value.

5.2.2 Determination of Critical Occupancy ($o_{cr}$)

Visual inspection of flow-occupancy data always show increasing flows for increasing occupancies until a certain occupancy value is reached. This occupancy value which is also called the critical occupancy, divides the data into two regimes; uncongested and congested. A double-regime linear regression model as defined by (May, 1990) can then be used to fit the data.

To find this breakpoint, iterative searching procedure as described by (Crawley, 2007) was used. The model that was used to fit the data was:

$$Y \sim x \cdot I(x < c) + x \cdot I(x > c)$$

In this equation, $c$ is the cutoff value that needs to be determined. $I(x < c)$ and $I(x > c)$ are two dummy variables introduced to the model. $I(x < c)$ is one if $x$ is less than $c$ and will be zero if $x$ is greater than $c$. The multiplication in the model doesn’t show it in its mathematical sense, instead shows the interaction of the variables.

Using visual inspection, $c$ can be estimated to be within a range of values. One example for one location during clear weather is shown in Figure 34a. As can be seen, the $c$ value is expected to be between 15 to 25%. A model was fitted for all the values within the range and the residual mean square error ($RMSE$) was computed for each of them (Figure 34b). The model that resulted in lowest $RMSE$ was selected. The same procedure was replicated for all the scenarios for the before and after data. The calculated $c$-values
were used to fit a double-regime linear regression model to the data (see Figure 34c). It is
clear from Figure 34b that many $c$ values can result in a RMSE which is very close to the
minimum RMSE. It can be argued that these values would result in different capacity
values after fitting regression lines. However, it was found that these points had minimal
effect on capacity increase or decrease. The amount of increase or decrease was in the
range of 60 to 70 vphpl. Future studies can take this into consideration by calculating a
confidence interval for the capacity values.

![Figure 34](image)

Figure 34. Steps for finding the $o_{cr}$ (a) determining a range of values using inspection (b) determining the critical occupancy that results in minimum RMSE (c) Double-regime linear curve fitted to data

5.2.3 Comparison of Slopes

Analysis of Covariance (ANCOVA) was used to compare the slopes of the lines
fitted to the data for before and after periods. ANCOVA which is basically a blending of
Analysis of Variance (ANOVA) and regression is used to compare two or more regression lines by testing the effects of a categorical factor on a dependent variable while controlling the effect of a continuous covariate. For this case, the categorical factors are “before” and “after” periods. The interaction of categorical factor and the covariate is studied to reach a conclusion regarding the statistical significance of the difference between slopes. Statistically speaking, two models were generated:

\[
Y_1 = \beta_0 + \beta_1 x + \beta_2 g \\
Y_2 = \beta_0 + \beta_1 x + \beta_2 g + \beta_3 x g
\]

In this equation, \( \beta_i \) are the model coefficients and \( g \) is the categorical factor. The first model assumes that the slopes of the lines are the same (\( \beta_1 \)) and they are offset by an amount equal to (\( \beta_2 \)). The second model includes an interaction term (\( \beta_3 \)) between the slope of the line and the categorical factor \( g \). Using ANOVA, if the test indicates that the second model fits the data better than the first model, null hypothesis or the assumption of lines being parallel can be rejected.

5.3 Results

Using the methodology described in the previous section, regression lines were fitted to all the 32 scenarios described in Figure 33. The fundamental diagrams for clear and adverse weather conditions for MP 4.65 in the NB direction are shown in Figures 35 and 36 respectively. Flow rate is averaged between the two lanes and is measured in vehicles per hour per lane (vphpl), occupancy is expressed as a percentage and speed is measured in miles per hours (mph).
The solid lines in the figures show the results for the after periods and the dashed lines show the results for the before period. Blue lines represent the morning peak and red lines the evening peak. *R*-squared goodness of fit measure for each curve is also reported. Fundamental diagrams for MP 2.55 in the SB direction are shown in Figure 37 and Figure 38 for clear and adverse weather conditions respectively. For most of the scenarios, $R^2$ as high as 90% was found. The scenarios depicted here are only for MP 4.65 and MP 2.55. The results for MP 3.85 and MP 1.92 are included in Appendix A.

Figure 35. Flow-occupancy curves for clear weather conditions for MP 4.65
Figure 36. Flow-occupancy curves for clear weather conditions for MP 2.55

Figure 37. Flow-occupancy curves for adverse weather conditions for MP 4.65
Changes in traffic conditions before and after the implementation of VAS were analyzed using two separate methods: the nonparametric kernel density-based global two-sample comparison test and the parametric flow–occupancy curve fitting. Table 6 reports the \( p \)-values resulted from the kernel density-based global two-sample comparison test. Using a 90% confidence level, a \( p \)-value less than 0.1 indicates statistically significant difference between before and after scenarios. As can be seen, with the exception of four scenarios, there was a statistically significant difference in the flow–occupancy diagrams after the implementation of VAS. However, the comparison test only shows whether the before and after conditions are statistically different, and curve fitting can provide insights on the changes from before to after conditions. Following sections provide a

Figure 38. Flow-occupancy curves for adverse weather conditions for MP 2.55
5.3.1 Comparison of Critical Occupancies

The critical occupancies for all 16 scenarios for both before and after periods are reported in Table 6.

**Clear vs Adverse Weather Conditions:** A comparison of the critical occupancies for clear and adverse weather conditions shows no tangible evidence that critical occupancies change with weather conditions. For some cases a small decrease and for others a small increase was found. This confirms the results previously reported by other studies including (Papageorgiou, 2008) and (Kianfar et al., 2015).

**Before and After Comparison:** As is shown in Table 6 and Figures 35 through 38, for 11 out of the 16 scenarios investigated, the critical occupancies have decreased for the after periods compared to the before period. Overall, the amount of decrease in those scenarios ranged between 0.3 and 12.7 percent with average decrease being in the order of 4 to 5 percent.

5.3.2 Comparison of Speeds

As previously described, slopes of the flow-occupancy curves can provide an indication about the average speed at the study sites; the flatter the slope the lower the average speed.
Clear vs Adverse Weather Conditions: A careful examination of Figures 35 through 38 reveals that speeds have decreased during adverse weather conditions. This observation is logical and expected as inclement weather has always been thought to affect operating speeds.

Table 6. Critical occupancies, slope comparison and kernel-based two sample test results before and after VSL implementation

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Weather</th>
<th>Scenario Description</th>
<th>Critical Occupancy (%)</th>
<th>Under-critical Occupancy-Slope Comparison</th>
<th>Over-critical Occupancy-Slope Comparison</th>
<th>Kernel-based Test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Before</td>
<td>After</td>
<td>% Change</td>
<td>P-val</td>
</tr>
<tr>
<td>1</td>
<td>Clear Weather</td>
<td>Morning Peak-MP 4.65-Midweek Days</td>
<td>18.20</td>
<td>17.50</td>
<td>-4.0%</td>
<td>0.058</td>
</tr>
<tr>
<td>2</td>
<td>Clear Weather</td>
<td>Evening Peak-MP 4.65-Midweek Days</td>
<td>18.00</td>
<td>17.50</td>
<td>-2.9%</td>
<td>0.000</td>
</tr>
<tr>
<td>3</td>
<td>Clear Weather</td>
<td>Morning Peak-MP 4.65-Monday, Fridays</td>
<td>19.50</td>
<td>18.00</td>
<td>-8.3%</td>
<td>0.109</td>
</tr>
<tr>
<td>4</td>
<td>Clear Weather</td>
<td>Evening Peak-MP 4.65-Monday, Fridays</td>
<td>18.30</td>
<td>18.33</td>
<td>0.2%</td>
<td>0.000</td>
</tr>
<tr>
<td>5</td>
<td>Adverse Weather</td>
<td>Morning Peak-MP 4.65-Midweek Days</td>
<td>17.60</td>
<td>17.10</td>
<td>-2.9%</td>
<td>0.334</td>
</tr>
<tr>
<td>6</td>
<td>Adverse Weather</td>
<td>Evening Peak-MP 4.65-Midweek Days</td>
<td>17.70</td>
<td>18.00</td>
<td>1.7%</td>
<td>0.000</td>
</tr>
<tr>
<td>7</td>
<td>Adverse Weather</td>
<td>Morning Peak-MP 4.65-Monday, Fridays</td>
<td>19.58</td>
<td>18.00</td>
<td>-8.8%</td>
<td>0.024</td>
</tr>
<tr>
<td>8</td>
<td>Adverse Weather</td>
<td>Evening Peak-MP 4.65-Monday, Fridays</td>
<td>17.90</td>
<td>17.10</td>
<td>-4.7%</td>
<td>0.028</td>
</tr>
<tr>
<td>9</td>
<td>Clear Weather</td>
<td>Morning Peak-MP 2.55-Midweek Days</td>
<td>18.18</td>
<td>18.13</td>
<td>-0.3%</td>
<td>0.257</td>
</tr>
<tr>
<td>10</td>
<td>Clear Weather</td>
<td>Evening Peak-MP 2.55-Midweek Days</td>
<td>16.50</td>
<td>16.00</td>
<td>-3.1%</td>
<td>0.000</td>
</tr>
<tr>
<td>11</td>
<td>Clear Weather</td>
<td>Morning Peak-MP 2.55-Monday, Fridays</td>
<td>17.50</td>
<td>18.00</td>
<td>2.8%</td>
<td>0.006</td>
</tr>
<tr>
<td>12</td>
<td>Clear Weather</td>
<td>Evening Peak-MP 2.55-Monday, Fridays</td>
<td>17.00</td>
<td>16.00</td>
<td>-6.3%</td>
<td>0.308</td>
</tr>
<tr>
<td>13</td>
<td>Adverse Weather</td>
<td>Morning Peak-MP 2.55-Midweek Days</td>
<td>18.50</td>
<td>17.50</td>
<td>-5.7%</td>
<td>0.004</td>
</tr>
<tr>
<td>14</td>
<td>Adverse Weather</td>
<td>Evening Peak-MP 2.55-Midweek Days</td>
<td>16.50</td>
<td>20.00</td>
<td>17.5%</td>
<td>0.000</td>
</tr>
<tr>
<td>15</td>
<td>Adverse Weather</td>
<td>Morning Peak-MP 2.55-Monday, Fridays</td>
<td>16.40</td>
<td>17.00</td>
<td>3.5%</td>
<td>0.003</td>
</tr>
<tr>
<td>16</td>
<td>Adverse Weather</td>
<td>Evening Peak-MP 2.55-Monday, Fridays</td>
<td>18.33</td>
<td>16.00</td>
<td>-14.6%</td>
<td>0.006</td>
</tr>
</tbody>
</table>

Note: Italic p-values are statistically significant at 90% confidence level
Before and After Comparison: Using ANCOVA, it was possible to see any statistical difference between the slopes of the lines for the before and after periods. Table 6 reports the *p*-values and *F*-statistic of the ANCOVA test for congested (over-critical occupancies) and uncongested traffic conditions (under-critical occupancies). *P*-values less than 0.1 indicate that the slopes of the lines for the after period are statistically different from the slopes of the line for the before period at 90% confidence level.

During clear weather conditions, the eight scenarios shown in Figures 35 and 37 consistently suggest flatter slopes for the after period compared with the before period. Further, the decrease in slope is more evident for the congested region compared to the uncongested region. This observation is very consistent with the statistical results shown in Table 6. Specifically, in 5 out of 8 scenarios for clear weather conditions, the decrease in slope of the flow-occupancy curves was found to be statistically significant at 90% confidence level.

During adverse weather conditions, Figures 36 and 38 shows relatively different patterns in regards to the flow-occupancy curves compared to clear weather conditions. For uncongested traffic conditions, 3 out of 8 scenarios showed slight increase in speed, as suggested by the slightly steeper regression lines. This happened mostly during evening peak hours. However, the results for morning peak are very consistent with what was previously found for clear weather conditions. As for congested traffic conditions, the results are very different. It can be seen in Figures 36 and 38 that the slopes of the regression lines for congested traffic conditions are almost parallel for the morning peak. This observation suggests that that during congested conditions of morning peak hours,
the VAS system had minimal effect in reducing speeds. Unlike morning peak period, the slopes of flow-occupancy lines in Figure 36 and 38 suggest decrease in speed during evening peak hours.

5.3.3 Comparison of Capacities

The Highway Capacity Manual (HCM) defines capacity as “the maximum hourly rate at which persons or vehicles reasonably can be expected to traverse a point or a uniform section of a lane or roadway during a given time period under prevailing roadway, traffic, and control conditions.” (TRB, 2010). According to many studies including (Zhang and Levinson, 2004) and (Banks, 2006), the current definition of capacity is somewhat controversial as it does not provide a satisfactory method of operationalizing the definition of capacity. Terms such as reasonable expectation and sustainable flows, have not become instrumental in practice. For this reason capacity is generally defined as the maximum flow prior to a traffic breakdown on a corridor. Breakdown is a traffic phenomenon associated with a sharp drop in speed and possibly flow at bottleneck locations during a high-demand period. Two measures are generally of great use for a capacity study; pre-queue flow (known as capacity) and queue-discharge flow (QDF). Pre-queue flow (PQF) is defined as any period of near-constant flow that ends in local flow breakdown. Queue discharge flow (QDF) is defined as the discharge from an active bottleneck. Flow drop which occurs after a bottleneck activates and a queue forms upstream is simply the difference between PQF and QDF. The pre-queue flow and queue-discharge flow values were obtained from best fits at critical occupancy.
Table 7 reports the PQF, QDF and flow drops for period before and after VAS implementation.

Clear vs Adverse Weather Conditions: An examination of Table 7 and a visual inspection of Figures 35 through 38 clearly shows that capacity or the maximum flow rate observed has decreased during adverse weather conditions, which is largely expected. The amount of decrease was in the order of 150 vphpl which is equivalent to around 8% capacity reduction.

Before and After Comparison: A careful examination of pre-queue flows (capacity) from Table 7 and Figures 35 through 38 for the before and after periods indicate that capacity is likely to decrease in the after period given the new shape of the flow-occupancy curves. This possible decrease in capacity is consistent among all the scenarios included in the analysis for the clear and adverse weather conditions. This can be partly attributed to the decrease in speed when the VAS system is activated during congested and uncongested conditions. These results are very consistent with the recent researches on the subject.
In theory, capacity on any particular uninterrupted flow facility usually occur at a certain speed called the critical speed. On limited access facilities, the critical speed is relatively high and may only be 10% to 20% lower than the free-flow speed. If traffic is made to move at speeds slower than the critical speed due to congestion or external factors (e.g. extreme weather, reduced speed limits, etc.), it is unlikely for the maximum

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Weather</th>
<th>Scenario Description</th>
<th>Pre-queue Flow (vphpl)</th>
<th>Queue-discharge Flow (vphpl)</th>
<th>Flow Drop (vphpl)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Clear Weather</td>
<td>Morning Peak-MP 4.65-Midweek Days</td>
<td>2051</td>
<td>1945</td>
<td>-5.4%</td>
</tr>
<tr>
<td>2</td>
<td>Clear Weather</td>
<td>Evening Peak-MP 4.65-Midweek Days</td>
<td>2055</td>
<td>1957</td>
<td>-5.0%</td>
</tr>
<tr>
<td>3</td>
<td>Clear Weather</td>
<td>Morning Peak-MP 4.65-Monday, Fridays</td>
<td>2199</td>
<td>2015</td>
<td>-9.1%</td>
</tr>
<tr>
<td>4</td>
<td>Clear Weather</td>
<td>Evening Peak-MP 4.65-Monday, Fridays</td>
<td>2093</td>
<td>2031</td>
<td>-3.1%</td>
</tr>
<tr>
<td>5</td>
<td>Adverse Weather</td>
<td>Morning Peak-MP 4.65-Midweek Days</td>
<td>1936</td>
<td>1790</td>
<td>-8.2%</td>
</tr>
<tr>
<td>6</td>
<td>Adverse Weather</td>
<td>Evening Peak-MP 4.65-Midweek Days</td>
<td>1995</td>
<td>1772</td>
<td>-12.6%</td>
</tr>
<tr>
<td>7</td>
<td>Adverse Weather</td>
<td>Morning Peak-MP 4.65-Monday, Fridays</td>
<td>2014</td>
<td>1915</td>
<td>-5.2%</td>
</tr>
<tr>
<td>8</td>
<td>Adverse Weather</td>
<td>Evening Peak-MP 4.65-Monday, Fridays</td>
<td>1888</td>
<td>1903</td>
<td>0.8%</td>
</tr>
<tr>
<td>9</td>
<td>Clear Weather</td>
<td>Morning Peak-MP 2.55-Midweek Days</td>
<td>2237</td>
<td>2183</td>
<td>-2.5%</td>
</tr>
<tr>
<td>10</td>
<td>Clear Weather</td>
<td>Evening Peak-MP 2.55-Midweek Days</td>
<td>2106</td>
<td>1871</td>
<td>-12.5%</td>
</tr>
<tr>
<td>11</td>
<td>Clear Weather</td>
<td>Morning Peak-MP 2.55-Monday, Fridays</td>
<td>2247</td>
<td>2189</td>
<td>-2.6%</td>
</tr>
<tr>
<td>12</td>
<td>Clear Weather</td>
<td>Evening Peak-MP 2.55-Monday, Fridays</td>
<td>2103</td>
<td>1978</td>
<td>-6.3%</td>
</tr>
<tr>
<td>13</td>
<td>Adverse Weather</td>
<td>Morning Peak-MP 2.55-Midweek Days</td>
<td>2146</td>
<td>1920</td>
<td>-11.8%</td>
</tr>
<tr>
<td>14</td>
<td>Adverse Weather</td>
<td>Evening Peak-MP 2.55-Midweek Days</td>
<td>2018</td>
<td>1930</td>
<td>-4.6%</td>
</tr>
<tr>
<td>15</td>
<td>Adverse Weather</td>
<td>Morning Peak-MP 2.55-Monday, Fridays</td>
<td>1990</td>
<td>1940</td>
<td>-2.6%</td>
</tr>
<tr>
<td>16</td>
<td>Adverse Weather</td>
<td>Evening Peak-MP 2.55-Monday, Fridays</td>
<td>1866</td>
<td>1809</td>
<td>-3.2%</td>
</tr>
</tbody>
</table>
flow rate on the facility under these conditions to reach the normal capacity value. The amount of capacity reduction was found to be 5.9% or 112 vphpl.

Similarly, queue-discharge flows also decreased by an average of 7.6% or 134 vphpl during the after period. The amount of decrease was more dramatic at MP 2.55 in the southbound direction. The reason is again attributed to the sub-critical speeds (speeds below critical speed) posted on the VAS signs. It is possible that the capacity restriction downstream limits the discharge flows during the recovery phase at the analyzed section.

Figure 39 shows the speed-flow diagrams for MP 4.65 NB for clear weather conditions and during midweek days. The free-flow speed for both morning and evening peak hours may well be in the range 63 to 64 mph. A careful examination of the observations around the maximum flow rates suggest that the critical speed or the speed occurring at capacity operations may well be in the range of 50 to 55 mph. Upon reaching the critical speed value, traffic flow and speed decreases as traffic enters the congested regime. As the speeds posted on the VAS signs are less than or equal to 50 mph, traffic flow observed when the VAS is activated tend to be lower than the maximum flow rate or the capacity.

Figure 39. Speed-flow diagrams for one location during clear weather conditions
This could be the reason for the consistent decrease in capacity that is observed during the after period.

To investigate the issue further and to show the consistency of the results, a per-lane analysis was also conducted. This analysis was necessary as the data collection procedure averaged the traffic data across the two lanes producing per station readings. To see if the system has affected capacities per lane, only one detector station at MP 4.65 NB during clear weather conditions and morning peak was chosen. The results for left and right lanes are not averaged and are reported separately as shown in Figure 40.

![Figure 40. Flow-occupancy curves for left and right lanes](image)

The slopes of the lines were found to be significantly different from each other for both lanes at 90% confidence level except the slopes of the lines in the uncongested region for the left lane. These results are generally very consistent with those previously found in Figures 35 and 37. It is also evident in Figure 40 that the capacity on the left lane is lower than that on the right lane for the before period and the difference is even greater during the after period.
For the VAS system on OR-217 corridor, understanding the system activation times in relation to the level of congestion at the study sites could reveal important information. To do this, flow and occupancy observations along with information on VAS activation status at MP 4.65 were used in plotting the curves shown in Figure 41. The results for the morning and evening peak for clear and adverse weather conditions during midweek days are shown in this figure. The figure shows at a glance that

![Figure 41. Flow and occupancy with VSL activation status](image-url)
observations when the VAS was activated mostly fall in the congested region particularly when the system was activated due to higher traffic level in good weather. This means that for congestion-induced VAS activations along OR-217, the capacity decrease observed in this study did not take place often given the limited data used in this figure.

5.4 An Alternative Approach to Determine System Impacts on Fundamental Diagrams

Some studies including Cassidy and Bertini (1999), Soriguera et al. (2015) and Plana et al. (2016), have challenged the traditional methods for processing measured data that will eventually be used to establish the fundamental diagrams. These studies have claimed that the inconclusive results from many studies are to a large extent dependent on the diagnostics in most of these studies which are time-series plots of flow, occupancy and/or average vehicle speed. It is claimed that simply plotting flow-occupancy-speed minute aggregated data would result in a lot of scatter and would limit the reliability of the results.

To overcome these challenges and to have a clearer picture of the effects of a system, studies have estimated stationary periods. Stationary periods of traffic are defined as time intervals where all the macroscopic traffic variables (flow, speed and occupancy) are approximately constant. Firstly proposed by Cassidy, (1998), these stationary periods can be identified by constructing re-scaled curves of cumulative number of vehicles (N-curves) and cumulative occupancy (T-curves) with respect to time by looking for intervals with approximately constant slopes. The amount of re-scaling depends on the background value deducted from the cumulative curves. Figure 42 gives an example, of
cumulative \( N(x, t) \) curve and the re-scaled curve by deducting a background value equal to \( q_0t \). As can be seen, the cumulative \( N(x, t) \) curve is greatly magnified by subtracting the background value. The interval exhibiting a linear trend in cumulative vehicle arrivals, \((t_s, t_e)\) is also shown. By averaging the slope of each curve in these stationary periods, the flow and occupancy values that represent the stationary traffic state are determined.

![Cumulative and re-scaled vehicle arrival curves](image)

Figure 42. Cumulative and re-scaled vehicle arrival curves (Cassidy, 1998)

To just provide an example, data measured by detector station (MP 4.65) will be used to construct the \( N \)-and \( T \) curves. Only one day worth of data and the left lane will be used to construct these curves. Figures 43 and 44 show these curves for morning and evening peak hours respectively. Stationary periods are shown as time intervals between the dashed lines. The slopes of the re-scaled \( N \) and \( T \) curves are approximately constant during these periods. By averaging the slope of the curves at each stationary period, the flow and occupancy values that represent the stationary traffic state were determined and
the flow-occupancy curves were established. These curves are shown in Figure 45 for both morning and evening peak hours. Figure 45 shows a well-defined relation for the observed range of prolonged stationary conditions. The data appear to define a smooth relation between flow and occupancies.

Figure 43. Cumulative and re-scaled vehicle arrival curves – Morning Peak
Figure 44. Cumulative and re-scaled vehicle arrival curves – Evening Peak

Figure 45. Flow-occupancy scatterplot, stationary conditions
Although accurate, the procedure detailed here requires a lot of effort. Besides, the magnitude of the fluctuations in the slopes of these cumulative curves depends on the background values subtracted in order to re-scale them (Cassidy and Windover, 1995). Slightly different stationary periods would be found at each application, depending on the background values selected. For this reason, this procedure was not used to establish the fundamental diagrams for this research. However, it can be applied for future studies on this subject.
CHAPTER 6

STUDY RESULTS: VAS IMPACTS ON DRIVER COMPLIANCE

One of the most important issues in implementing and achieving the stated objectives a VSL system is drivers’ compliance with the posted speeds. While many studies have reported on safety or operational benefits of VSL/VAS systems, there is little that is published on drivers’ compliance with those systems. As such, there is a need to examine drivers’ speed compliance along with the factors affecting it using empirical data from existing systems. This motivated this chapter of the thesis to further investigate the subject using real empirical data. This chapter is divided into 3 sections. Section 1 provides information about the study design. Section 2 provides details about the methods used for evaluation purposes. Results and discussions are provided in section 3.

6.1 Study Design

Driver compliance with the VAS system along OR-217 was investigated by examining the changes in driver speeds and the discrepancy between operating and posted speeds. This study was designed in a way that the effects of many factors affecting compliance can be determined. The factors considered in the analysis were weather conditions, light conditions, VAS sign location and temporal effects. Furthermore, the study was conducted for each lane separately to identify the lanes with speeds above and below the posted speed limits. For various reasons, significant periods of missing data did occur sporadically throughout the analysis period for some stations on the NB direction.
Southbound direction had fewer issues in regards to data quality and missing data. For this reason, only the southbound direction was considered in the analysis. The different cases considered in the analysis are shown in Figure 46.

For this study, 7 months of “after” data was obtained from PORTAL starting from August 2014 (shortly after system deployment on July 22, 2014) to May 2015 inclusive except for the months of October, November and December of 2014. The dynamically controlled ramp metering system was set using fixed-time rates during these three months, and therefore data from this period were not used for this study. Ramp metering was functioning normally during all other periods. The analysis time periods account for weather variations as January to March are the rainy months in Portland and other
selected months are fairly dry. To study compliance with the system only time periods when the system was turned on was used.

6.2 Methodology

Drivers’ compliance with VAS system was investigated by examining changes in driver speeds and the discrepancy between operating and posted speeds. The general framework for data analysis in this study is shown in Figure 47. A description of this chart is presented in the following subsections.

Figure 47. General framework for data collection, processing and analysis
6.2.1 Definition of Free Flow Conditions

For the purpose of compliance and speed analyses, only free-flow conditions need to be considered as only under these conditions, drivers have freedom to comply with or violate the posted advisory speeds. Vogel, (2002) has attested that this exclusion is necessary as without it vehicle speeds can be correlated and any estimations of factors influencing speed choice will be confounded. However, there is little agreement in the literature about the thresholds used to divide uncongested and congested traffic conditions. Some agencies like Main Roads in Western Australia uses a 4 second time headway to define the free-flow conditions (Radalj, 2001). Others use a time headway of 3 seconds (Pasenen and Salmivaara, 1993). (Vogel, 2002), in an empirical study of over 100,000 vehicles moving through an intersection, found an optimal time headway of 6 seconds for distinguishing between free and following vehicles. Some studies have used flow thresholds instead of headways. However, using a systematic process, this study will use a combination of occupancy and speed thresholds to distinguish free-flow and forced-flow conditions.

To do this, the speed, flow and occupancy data were averaged across the two lanes of the freeway and the critical occupancy for each day of the analysis period was determined using a double-regime linear regression model (as detailed in Chapter 5). Critical occupancy was defined as the cut-off point between the uncongested and congested traffic conditions. Data passed from this first filter were then subjected to a speed filter. Any average speed above 50 mph was termed “uncongested” and below 50
mph as “congested”. This speed threshold was used because the legal speed limit on the
freeway is 55 mph and some drivers may choose to travel slightly below this speed.

6.2.2 Data Fusion

Each loop detector station is associated with a variable advisory speed sign
upstream of the detector station. Stations are grouped based on the distance from the
upstream VAS signs. For example as shown in Figure 48, detector stations 1 and 2 are
associated with VAS sign 1 and detector station 3 is associated with VAS sign 2. This
grouping provided the opportunity to study the effects of VAS sign proximity on driver
compliance.

![Detectors and VAS signs Configuration](image)

Figure 48. Detectors and VAS signs Configuration

In order to measure compliance, it was necessary to compare VAS posted speeds
and operating speeds for the same time intervals. Since the VAS system log data was
available for one minute intervals, the free-flow speed, volume and occupancy data for
each lane were aggregated into one minute intervals as well. After the aggregation
process, data for each detector station were fused with its respective VAS station.
6.2.3 Impacts of VAS on Driver Speeds

The basic hypothesis about the effects of a VAS system on driver speeds is that when the system is on (i.e. posting a speed lower than the legal speed limit), drivers tend to lower their speeds thus reducing the overall speeds along the freeway. To test this hypothesis, speeds were divided into 2 mph increments for each lane when the VAS was off and when it was turned on.

The percentage of traffic in each speed bin (2 mph) was measured and operating speed histograms were developed. Since the distribution of speeds on the left and right lanes were different, these histograms were developed and compared for each lane separately when VAS was on and when it was off.

6.2.4 Driver Compliance with VASPosted Speeds

Compliance was evaluated by comparing the observed speeds at detector locations with the VAS posted speeds. Comparison was conducted for each lane separately to identify the lanes with speeds above and below the posted speed limit. Four levels of compliance were defined for the analysis:

a) Drivers exceeding the posted advisory speed by up to 5 mph were termed “Compliant with VAS and the Speed limit”.

b) Drivers exceeding the legal speed limit of 55 mph by up to 5 mph were termed “Compliant with Speed limit”.

c) Drivers with speeds between 60 to 70 mph were termed “Non-complaint - Somewhat Aggressive”.
d) Drivers with speeds higher than 70 mph were termed “Non-compliant - Aggressive”.

Compliance levels were assessed for each milepost in the southbound direction and the results were compared between left and right lanes.

6.3 Results

The VAS signs are usually deployed at times of system congestion or adverse weather, but often the signs are also on during the whole day or on weekends. Figure 49 shows the VAS log (stair step function in blue) and the corresponding weighted average speeds (time series in orange) calculated from lane volumes and speeds for some detector stations along the SB direction of OR-217 for Wednesday March 18, 2015. The VAS signs can display “50”, “45”, “40”, “35”, “30”, and “SLOW” in black text with a yellow background. The same speeds are always displayed for each lane at VAS stations. The sign off state is shown as “OFF” in Figure 49. This figure also shows the percent of time when the VAS system was on during that specific day.

It appears from Figure 49 that when speeds are high (e.g. for most of the day at MP 1.5), at most gantries the system is either off or displays 50 mph. At other times, at other locations, when speeds drop, it appears that the system also displays appropriate speeds (e.g. MP 1.92 during the morning and afternoon peak hours). It is also clear from Figure 49 that there are times and locations where the actual traffic speed is lower than the displayed VAS speed, and also times when the opposite is true. The compliance examination will continue to examine these issues in depth. Figure 49 also shows that the
VAS system was on mostly during the peak hours with a percentage of 100%. During the midday hours the VAS signs were turned off at many locations. According to Riggins et al. (2016), in the months following VAS system initialization, the signs were on less than 20% of the time. Also, measured speed fluctuations during overnight/low flow periods seemed to trigger the system unnecessarily. Beginning in January 2015, after some system calibration, the VAS signs were usually on more than 60% of the time. The problems associated with these intermittent activation of VAS signs will be discussed in details in Chapter 7.

The results of this evaluation are divided into two sections. First, the effects of the VAS system on driver speeds is demonstrated. Second, drivers’ compliance with VAS posted speeds are assessed under the effect of the previously described factors that are thought to affect drivers’ speeds.
Figure 49. Southbound OR-217 VAS displayed speed and vehicle speeds and percent of time VAS system was active, by hour of day, March 18, 2015
6.3.1 Impacts of VAS on Driver Speeds

Figures 50 and 51 show speed histograms for different VAS posted speeds for the left and right lanes respectively. The highest speed displayed at VAS signs is “50 mph” and the lowest is “SLOW”. “SLOW” is normally displayed during very heavy congestion or rainfall.

As can be seen in the figures, the distributions appear to somewhat follow the normal distribution (bell shape curve) with a clear mode. For both lanes, there is a distinct shift towards the left (lower speeds) when the VSL was on. This shift is more distinct when lower speed values were posted on VAS signs. Table 8 indicates that the lower the displayed speeds on VAS, the lower the average speeds and the percentage of drivers complying with VAS. However, when lower speeds are posted on VAS signs, higher percentage of drivers comply with the legal speed limit (SL). For example, although VAS speed compliance was 0% when “SLOW” was posted on VAS, the percentage of drivers complying with the SL has considerably increased for both lanes.

Table 8 also indicates that traffic was traveling 2 to 4 mph faster when VAS was off than when it was on and the drivers on the left lane travel on average 5.2 mph faster than the drivers on the right lane. A student *t*-test was carried out to compare the mean speeds for VAS OFF and VAS ON for each displayed VAS speed. It was found that the difference in mean speeds were statistically significant at 95% confidence level for each VAS speed.
Table 8. Impacts of different VAS posted speeds on average speeds and compliance levels

<table>
<thead>
<tr>
<th>Lane</th>
<th>Speed</th>
<th>Average Speed</th>
<th>% Compliance with SL</th>
<th>% Compliance with VAS Speeds</th>
<th>Sample Size, n</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>VAS OFF</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left Lane</td>
<td>55mph SL</td>
<td>62.19</td>
<td>32.76%</td>
<td>NA</td>
<td>364,542</td>
</tr>
<tr>
<td></td>
<td>VAS ON</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>50mph</td>
<td>61.39</td>
<td>40.50%</td>
<td>15.25%</td>
<td>21,113</td>
</tr>
<tr>
<td></td>
<td>45mph</td>
<td>60.89</td>
<td>44.33%</td>
<td>1.63%</td>
<td>9,425</td>
</tr>
<tr>
<td></td>
<td>40mph</td>
<td>60.48</td>
<td>47.96%</td>
<td>0.00%</td>
<td>5,046</td>
</tr>
<tr>
<td></td>
<td>35mph</td>
<td>60.16</td>
<td>49.81%</td>
<td>0.00%</td>
<td>7,999</td>
</tr>
<tr>
<td></td>
<td>30mph</td>
<td>59.58</td>
<td>55.10%</td>
<td>0.00%</td>
<td>1,764</td>
</tr>
<tr>
<td></td>
<td>SLOW</td>
<td>58.49</td>
<td>65.93%</td>
<td>0.00%</td>
<td>1,582</td>
</tr>
<tr>
<td></td>
<td>VAS OFF</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right Lane</td>
<td>55mph SL</td>
<td>57.30</td>
<td>76.60%</td>
<td>NA</td>
<td>364,542</td>
</tr>
<tr>
<td></td>
<td>VAS ON</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>50mph</td>
<td>56.84</td>
<td>77.00%</td>
<td>37.61%</td>
<td>21,113</td>
</tr>
<tr>
<td></td>
<td>45mph</td>
<td>55.29</td>
<td>86.59%</td>
<td>12.34%</td>
<td>9,425</td>
</tr>
<tr>
<td></td>
<td>40mph</td>
<td>54.96</td>
<td>89.85%</td>
<td>0.61%</td>
<td>5,046</td>
</tr>
<tr>
<td></td>
<td>35mph</td>
<td>54.32</td>
<td>92.49%</td>
<td>0.04%</td>
<td>7,999</td>
</tr>
<tr>
<td></td>
<td>30mph</td>
<td>54.75</td>
<td>89.91%</td>
<td>0.00%</td>
<td>1,764</td>
</tr>
<tr>
<td></td>
<td>SLOW</td>
<td>53.63</td>
<td>93.30%</td>
<td>0.00%</td>
<td>1,582</td>
</tr>
</tbody>
</table>

NA = Not Applicable
Figure 50. Speed Histograms for different VAS speeds on left lane
Figure 51. Speed Histograms for different VAS speeds on right lane
6.3.2 Driver Compliance with VAS Posted Speeds

Using the categories of speed compliance described in the previous section, a per-mile post analysis of compliance was conducted using all traffic data when VAS was on. The results are graphically depicted in Figure 52. As can be seen in this figure, drivers tend to better comply with the posted VAS speeds on the right lane compared to the left lane, with the percentage of VAS compliance being 8% on the left lane and 21% on the right lane. Moreover, 84% of the drivers on the right lane comply with the enforced speed limit of 55mph compared to only 48% on the left lane. This suggests that aggressive drivers are overrepresented on the left lane.

These results are consistent with the findings discussed in the previous section, which indicated that, on average, speeds on the left lane is 5.2 mph faster than that in the right lane. The reason may be attributed to the fact that during free-flow conditions the drivers tend to use the left-lane as a passing lane leaving the right lane for slow moving.

![Figure 52. Percent compliant per milepost for (a) Left Lane (b) Right Lane](image-url)
vehicles including merging and diverging vehicles at locations of interchanges. Figure 52 also shows that driver compliance is not uniform along the corridor.

Figure 53 shows the discrepancy between average speed and VAS posted speed for the left and right lanes. Patterns exhibited in Figure 53 are consistent with those shown in Figure 52. As can be seen, vehicles traveling 20 mph above VAS posted speeds are highly overrepresented on the left lane (32%). The corresponding percentage on the right lane is only 13%. The percentage of drivers with speeds 10 to 20 mph above VAS are also higher for the left lane compared to that on the right lane.

6.3.3 Effects of Weather

To gain a better understanding of drivers’ compliance with the VAS system, it is important to know whether compliance changes under different weather conditions. Figure 54 shows the histograms of the difference between VAS and operating speeds for
clear and adverse weather conditions on the right and left lanes. Mean speed difference for each scenario is shown as a dashed line on each histogram. As can be seen in the figures, the mean speed difference is 1.5 mph higher during clear weather conditions indicating that drivers comply more with the posted speeds during adverse weather conditions. Specifically, it was found that 8% of the drivers on the left lane comply with the posted VAS speeds during clear weather conditions versus 11% during adverse weather conditions. For drivers on the right lane these percentages were 23% and 27% respectively. As discussed earlier, compliance was defined as speeds up to 5 mph above VAS posted speeds.

Figure 54. Speeds differences from VAS posted Speeds for adverse and clear weather conditions
6.3.4 Effects of Light Condition on Compliance

Another factor that is thought to have potential effect on drivers’ compliance is light condition. Similar to the previous investigation, histograms of the difference between VAS and operating speeds were established for daytime and nighttime on each individual lane as shown in Figure 55. In general, the mean speed difference on the left and right lanes during nighttime were reduced by 2 mph and 5 mph respectively compared with daylight conditions. This suggests that darkness is associated with a higher compliance rate with the VAS posted speeds. Specifically, it was found that only 6% of the drivers on the left lane comply with VAS speeds during daylight hours versus 21% during nighttime hours. The corresponding percentages on the right lane are 25% and 27% respectively.

Figure 55. Difference between VAS and operating speeds by light conditions
Another important observation evident in this figure is related to the high number of drivers strictly adhering to VAS as well as the high number of drivers driving notably higher than VAS on the left lane during nighttime. While no definite reason can be thought of that explains this observation, driver population (commuters versus non-commuters) and level of enforcement along the corridor may be related to the two peaks in the histogram.

6.3.5 Effects of VAS Sign Location

It is generally hypothesized that the effectiveness of VAS degrades with distance; i.e. the closer the VAS sign the more its influence on speeds. To test this hypothesis, the distance between the VAS sign to the respective detector station downstream was determined and used in the analysis. Distances longer than 0.5 miles were termed “far” and distances shorter than 0.5 miles were termed “close”. In general, 42% of the data fell in the first category and 58% in the second category. The results are shown in Figure 56.

![Graph showing speed differences from VAS posted speeds for Close and Far VAS Sign distance cases](image)

Figure 56. Speeds differences from VAS posted speeds for Close and Far VAS Sign distance cases
As can be seen in the figure, on average, speed differences are 1 mph lower when VAS signs are close to detector stations. It was found that 14% of the drivers on the left lane complied with VAS speeds when the signs were close to detector stations versus only 6% when signs were far. For the right lane, these percentages were 28% and 23% respectively.

6.3.6 Temporal Effects

Another hypothesis tested in this analysis is the potential effect of time on VAS compliance measured from system deployment. Specifically, it was hypothesized that the level of compliance with VAS speeds may lessen with time. To examine the effect of time on compliance level, one week worth of data was collected for each month of the study period for the southbound direction. The analysis period started from August 2014 (month following deployment) to May 2015 (10 months after system deployment). Levels of compliance with VAS posted speeds were calculated for each month and the results are shown in Figure 57.

![Temporal Effects of VAS on Compliance - SB - VAS & SL Compliant](image)

**Figure 57. Temporal Effects on VAS Compliance**
As can be seen in the figure, compliance levels for the right lane are considerably higher than the left lane. Compliance for both lanes slightly increased during the months of January to March but decreased again during April and May. It is believed that the increase in compliance was due to weather conditions, as January to March are the rainy months in Portland. In general, the results shown in this figure do not support the hypothesis regarding the effect of time on VAS compliance.

6.3.7 VAS Compliance Modeling Using Regression

In order to determine the statistical significance of each factor that affects drivers’ compliance, an ordinary least square (OLS) regression model was developed. The independent variables used to estimate the model were weather, light conditions, VAS posted speed, distance from VAS sign and travel lane. The response variable was defined as the difference between VAS posted speed and operating speeds. The base condition was selected as: adverse weather, nighttime hours, “close” distance category and left lane. To start, the regression assumptions were tested. There are four principal assumptions which justify the use of linear regression models for purposes of inference or prediction:

1) The form of the model is correct (linear vs. non-linear)
2) The errors are normally distributed with the distribution centered at zero
3) The errors are independent
4) The errors have a constant variance (homoscedasticity)

Residual plots and normal plots of residuals were prepared to test the assumptions. These plots can be found in Appendix B. The linear assumption, error
assumptions of normality, independence, and constant variance were all met. The results of the OLS regression model with all variables included are shown in Table 9.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Coefficient, $\beta$</th>
<th>Standard Error</th>
<th>T-stat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>8.2556</td>
<td>0.0448</td>
<td>184.155</td>
</tr>
<tr>
<td>Weather Conditions: Clear Weather</td>
<td>0.1853</td>
<td>0.0325</td>
<td>-62.532</td>
</tr>
<tr>
<td>Light Conditions: Daylight</td>
<td>-2.5494</td>
<td>0.0408</td>
<td>4.761</td>
</tr>
<tr>
<td>Distance: Far</td>
<td>0.1550</td>
<td>0.0326</td>
<td>386.168</td>
</tr>
<tr>
<td>Speed Limit Difference</td>
<td>0.9387</td>
<td>0.0024</td>
<td>5.709</td>
</tr>
<tr>
<td>Lane: Right Lane</td>
<td>-5.1036</td>
<td>0.0321</td>
<td>-159.152</td>
</tr>
</tbody>
</table>

$R$-squared = 0.6633

All the variables included in the model were statistically significant at 95% confidence level. The $R$-squared of 0.66 suggests that two-thirds of the variation in speed difference is explained by the model. To interpret the model it is necessary to comment on the model coefficients. As previously indicated, the model suggests that compared to adverse weather conditions, compliance decreases during clear weather. The model also suggests that the difference in speeds decreases during daylight hours by 2.55 mph. Although compliance increase during nighttime, the difference in speeds are lower during daytime.

Among other model findings; the closer the VAS sign to detector location, the less the speed difference. It is found that speed difference is 0.16 mph higher when VAS signs are located far from detector location. Another hypothesis tested by the model is that the difference between VAS and operating speeds is a function of the difference
between VAS and speed limit. The model suggests that as the posted speeds increase (or difference between VAS and speed limit decreases), the difference between VAS and operating speeds decreases. The model suggests higher levels of compliance when the difference between VAS and speed limit decreases. This is consistent with the findings shown in Figures 50 and 51. Speed difference on the right lane are 5.1 mph lower than that on the left lane.

To further investigate the compliance issue and to find out the most important traffic parameters affecting compliance, a correlation matrix was prepared indicating the strength of the linear relationship between many variables. For the purpose of this study, a correlation coefficient of greater than 0.5 was considered significant. The variables included were, speed difference from VAS posted speeds, average speeds on the freeway, traffic flow levels, occupancy levels and the difference between VAS posted speeds and the static speed limit of 55 mph. The analysis was done separately for each lane. The results for both lanes are shown in Figure 58. The colors in the blue range indicate

![Figure 58. Correlation Matrix for variables affecting compliance on left and right](image-url)
positive correlation and the colors in the red range indicate negative correlation. The size of each circle corresponds to the magnitude of the correlation.

The most important observations that can be discerned from Figure 58 are:

1. The difference between driver speeds and VAS posted speeds on both lanes is significantly correlated to the posted speeds. The coefficient of correlation was found to be positive with a value of 0.8 on both lanes.

2. It is also clear that the differences in VAS posted speeds and average driver speeds are weakly-correlated with the flow and occupancy levels on the freeway. Reasons could be attributed to the fact that only free-flow condition data were considered in the analysis.

3. The correlation between other variables is not important in the compliance study.
CHAPTER 7

STUDY RESULTS: VAS IMPACTS ON SAFETY

With respect of traffic safety, studies have shown that the homogenization effects of a VSL system can lead to fewer collisions. However, very few of these studies have used empirical data in assessing the safety effectiveness of VSL systems. Besides, many of the empirical studies have only used crash data for evaluation purposes. Crashes are very rare events and usually multiyear collection periods are necessary to accumulate crash data that can be used for a meaningful analysis. For this reason, it is generally recommended to measure some other safety indicators in addition to crashes. The present chapter tries to address these problems to an extent by presenting an exhaustive empirical analysis of the VAS effects on traffic crashes and some other surrogate safety measures. This chapter is divided into 3 sections. Section 1 provides information about the study design. Section 2 provides details about the methods used for evaluation purposes. Results and discussions are provided in section 3.

7.1 Study Design

To perform an empirical safety analysis, using crash data is usually attempted or explored first. However, multiyear analysis periods are necessary to accumulate adequate crash data which can be used for a meaningful crash analysis (Tarko et al., 2009). Since the OR-217 ATM project was recently deployed, only a few months of crash data was available for the “after” period. However, it is generally reasoned that even a few months
of crash data can provide some preliminary insights into the safety trends. For this reason, crash rates and crash distribution along the corridor were compared before and after the system installation.

More recently, the use of surrogate safety measures have gained momentum (Gettman and Head, 2003). These measures have been investigated by many researchers and are shown to relate to the level of safety on highway facilities. Although not directly related, these measured can be physically and predictably related to motor vehicle crashes. Surrogate measures can be calculated using traffic flow parameters (mainly speed, flow and occupancy). This study has used two surrogate safety measures to assess the safety effects of VAS along OR-217 (see Figure 59). These measures relate to both

![Figure 59. Hierarchy diagram for cases considered in safety analysis](image-url)
speed and speed variations. A description of these measures are provided in the next section. As mentioned in Chapter 6, significant periods of missing data occurred throughout the analysis period for some stations along the NB direction. For this reason, only the southbound direction was considered in the analysis. Figure 59 shows the hierarchy diagram for the cases considered in the analysis. Clear and adverse weather scenarios were analyzed separately to provide a better understanding of the VAS system during different weather conditions. Besides, each travel lane was considered separately.

To complete a crash analysis study, 5 months of crash data was obtained for both “before” and “after” periods. For this reason, (August to December 2013) was chosen as “before” and (August to December 2014) as the “after” period. These five months account for weather variations as October to December are the wettest months in Portland and August and September are fairly dry. The data was obtained from ODOT’s statewide reported crash database. For the surrogate safety analysis, (August to December 2012) was used as “before” and (August to December 2014) as “after” analysis periods. August to December of 2013 was not chosen as the “before” sample because the construction activities on OR-217 during that time resulted in significant disruptions to data collection from the detectors.
7.2 Methodology

7.2.1 Crash Rates and Crash Distribution

To conduct a crash rate comparison, the first step was to calculate vehicle miles traveled (VMT) for the two five months period using traffic flow datasets previously described. The procedure for calculating VMT are shown in Figure 60 and are described as follows:

- Lane-by-lane 20 second traffic data for each direction are combined into its respective station (e.g., all lanes in a direction). Traffic volumes are summed across all lanes, and traffic speeds are a weighted average (if travel time needs to be estimated), with weighting based on respective traffic volumes.

- Link properties should be estimated from the station data by assuming that each detector has a zone of influence equal to half the distance to the detectors immediately upstream and downstream from it. VMT can be computed by multiplying the traffic volume at a link level with its respective influence length. Travel time can also be calculated by dividing the weighted speeds by the influence length.

- Freeway links were then grouped with other adjacent link to compute the VMTs and travel times in the corridor level.
Figure 60. Estimating Directional VMT from speeds and volumes (TTI, 2003)
Periods of missing data sporadically occurred both during the “before” and “after” periods. Using a factoring procedure, VMTs for days with missing data were estimated and then used to calculate monthly VMTs for both “before” and “after” periods. Total number of crashes for each month were then divided by these monthly VMT totals to determine monthly crash rates per million VMT. Only mainline freeway detectors were included for VMT calculations.

In addition to crash rates, crash distribution along the corridor can provide more insights into the actual effects of VAS on crashes. Only spatial distribution of crashes will be considered in this study. To this end, relative frequency of crashes at each tenth of a mile as a percentage of all reported crashes will be estimated. Using this procedure, we can determine the actual impacts of the system on crash hotspots (locations with high number of crashes).

7.2.2 Surrogate Safety Measures

To overcome the shortcomings of inadequate crash data, this study has used several surrogate safety measures to assess the safety effects of VAS along OR-217. These measures are described in the following subsections.

**Speed**: The first surrogate measure investigated is concerned with the average speeds at the road section level. Several studies including (Finch et al., 1994), (Baruya, 1998) and (Nilsson, 2004) have linked higher speeds with higher crash rates. It has also been found that speed is a major determinant of the severity of a crash (Aarts and Schagen, 2006). An excellent review of empirical studies into the relationship between
speed and crash rates is provided by (Aarts and Van Schagen, 2006). For the purpose of speed analyses, the frequency distribution of VHT (vehicle-hours traveled) for different speed ranges were determined and the results were compared for periods when VAS was on and when it was off. VHT was calculated from VMT and weighted average speeds along the corridor (described in previous section). Combined with average speeds, this performance measure is able to provide an estimate of the percentage of time vehicles spent traveling at certain speed. Free-flow conditions were considered for the analysis, as unlike congested conditions, driver speeds are not notably affected by traffic levels and drivers still have higher level of control over their selected speeds.

**Speed Variations:** The second surrogate measure is related to the variations of speed at a point location as well as along the freeway. This measure has been found to be correlated to rear-end collisions and therefore has been used as a crash precursor in several studies. This study is particularly concerned with two types of speed variations; temporal and spatial variations. Two types of spatial variations of speeds were investigated: longitudinal speed variation along the corridor and lateral speed variation across the two travel lanes.

**Temporal Variations:** Temporal variation of speed was measured using the coefficient of variation of speed (CVS), which is the standard deviation of speed divided by the average speed. A higher CVS value is believed to indicate a higher potential for collision. Unlike the spatial variations of speed, CVS was measured using data for only two detector stations. For this purpose, Allen (MP 2.55) and Greenburg (MP 5.11) were
selected for the SB direction. These stations were chosen due to their good data quality as well as their location. Allen is located near a bottleneck region and is mostly congested during the peak hours. On the other hand, Greenburg is located downstream of a recurrent congestion region where free-flow conditions are usually maintained throughout the day except non-recurrent congestion that occasionally takes place at this location due to inclement weather conditions or accidents. These stations were selected to capture the effects of different traffic levels on speed variations.

In order to analyze the system impacts on speed variations, 20-second traffic data from the five months “before” (August to December 2012) and “after” (August to December 2014) periods were obtained. VAS ON and VAS OFF scenarios were not considered as it was impossible to find midweek days with VAS system turned off for the entire day. With all the 20-second traffic data obtained for the “before” and “after” periods, average speed readings for each 20 second interval at each detector during the entire five months period were calculated controlling for the effects of weather. This produced 4,320 average speed observations per detector on each lane of the freeway for all weather conditions. This can be a representative of the entire five month analysis period, as only midweek days were considered in the analysis, and trip patterns are more uniform for these days. To analyze the variability of these average speed readings, standard deviations of each 5-minute interval were computed. Doing so provided 288 standard deviation readings for each detector. Standard deviation of speed was then divided by the average speed corresponding to the same 5-minutes period to calculate the CVS, which is a normalized variability measure (see equation below).
\[ CVS_i = \frac{(\sigma_s)_i}{\bar{s}_i} \]

Where

\[ n = \text{Number of lanes;} \]
\[ (\sigma_s)_i = \text{Standard deviation of speed on lane } i \text{ computed over period } \Delta t; \]
\[ \bar{s}_i = \text{Average speed on lane } i \text{ computed over period } \Delta t; \]

**Spatial Variations:** Spatial variations of speed can be quantified by either measuring the average speed differences between successive detector stations (longitudinal variations) or measuring differences speed differences between lanes (lateral variations). Free-flow conditions need to be considered to quantify this measure.

To calculate longitudinal speed variations, \( \Delta \) or the average speed differences between successive stations were calculated over 1 minute for periods when VAS was on and when it was turned off. These \( \Delta \) values were then averaged to determine the average speed variation along the entire freeway. This analysis was done for each lane of the southbound direction of the corridor. The equation for \( \Delta \) is as follows:

\[ \Delta_i = \frac{\sum_{k=1}^{z}|\bar{s}_{i,k} - \bar{s}_{i,k-1}|}{z - 1} \]

Where

\[ \bar{s}_{i,k} = \text{Average speed on lane } i \text{ and detector station } k \text{ computed over period } \Delta t; \]
\[ \bar{s}_{i,k-1} = \text{Average speed on lane } i \text{ and detector station } k-1 \text{ computed over } \Delta t; \]
\[ z = \text{Total number of detector stations along the studied direction of the corridor.} \]
Lateral variation of speed has been correlated with angled collisions in areas with significant lane-changing activities (Stipancic and Miranda-Moreno, 2015). The variation of speed across the lanes is quantified by measuring the average speed difference between the two lanes, $\Delta s$ for each 5-minute interval.

$$\Delta s = \frac{1}{n-1} \sum_{i=1}^{n-1} |\bar{s}_i - \bar{s}_{i+1}|$$

Where

$n = \text{Number of lanes};$

$\bar{s}_i = \text{Average speed on lane } i \text{ computed over period } \Delta t;$

$\bar{s}_{i+1} = \text{Average speed on lane } i+1 \text{ computed over period } \Delta t.$

For consistency purposes, (MP 2.55 and MP 5.11) were considered for quantifying this measure. These surrogate measures can help in assessing safety along the freeway as they consider the temporal, longitudinal, and lateral variations of speed along the corridor.
7.3 Results

7.3.1 Crash Rates and Crash Distribution

Table 10 provides a comparison of crash rates for the “before” and “after” scenarios as defined previously. As shown in the table, although the total VMT along the corridor for the selected months of 2014 saw an increase of 11% compared to the same period in 2013, the total and the rear end crash rates were reduced by more than 10%. Furthermore, injury and PDO crashes decreased by 9 and 18% respectively. However, wet and icy surface condition crashes increased by 20.5%. This increase may partly be attributed to an 8% increase in the number of hours with precipitation for the post-deployment period.

<table>
<thead>
<tr>
<th>Month</th>
<th>VMT</th>
<th>Total Number of Crashes</th>
<th>Total Crashes per MVMT</th>
<th>Rear-end Crashes per MVMT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2013 (Before)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>August</td>
<td>19,358,946</td>
<td>20</td>
<td>1.03</td>
<td>0.93</td>
</tr>
<tr>
<td>September</td>
<td>15,090,471</td>
<td>23</td>
<td>1.52</td>
<td>1.33</td>
</tr>
<tr>
<td>October</td>
<td>16,090,690</td>
<td>35</td>
<td>2.18</td>
<td>1.80</td>
</tr>
<tr>
<td>November</td>
<td>18,019,297</td>
<td>30</td>
<td>1.66</td>
<td>1.33</td>
</tr>
<tr>
<td>December</td>
<td>15,291,751</td>
<td>47</td>
<td>3.07</td>
<td>2.29</td>
</tr>
<tr>
<td>Total</td>
<td>83,851,155</td>
<td>155</td>
<td>1.85</td>
<td>1.50</td>
</tr>
<tr>
<td></td>
<td>2014 (After)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>August</td>
<td>18,143,760</td>
<td>17</td>
<td>0.94</td>
<td>0.83</td>
</tr>
<tr>
<td>September</td>
<td>18,675,847</td>
<td>18</td>
<td>0.96</td>
<td>0.91</td>
</tr>
<tr>
<td>October</td>
<td>18,282,616</td>
<td>29</td>
<td>1.59</td>
<td>1.37</td>
</tr>
<tr>
<td>November</td>
<td>18,184,595</td>
<td>34</td>
<td>1.87</td>
<td>1.70</td>
</tr>
<tr>
<td>December</td>
<td>21,212,242</td>
<td>37</td>
<td>1.74</td>
<td>1.27</td>
</tr>
<tr>
<td>Total</td>
<td>94,499,059</td>
<td>135</td>
<td>1.43</td>
<td>1.22</td>
</tr>
<tr>
<td>%Change</td>
<td>+11.27%</td>
<td>-14.81%</td>
<td>-12.81%</td>
<td>-10.51%</td>
</tr>
</tbody>
</table>
Figures 61 and 62 show the relative frequency of crashes at each tenth of a mile as a percentage of all reported crashes for the northbound and southbound directions of OR-217 respectively. The blue bars represent relative frequencies for the “before” period and the green bars are for the “after” period. For example, about 9.6% of all crashes during the “before” period occurred at milepost 2.0, while about 1.7% of all crashes during the “after” period occurred at the same milepost. The red lines in the schematic next to the figures show the locations of VAS signs. As can be seen in the figures, before the system installation crashes were mostly clustered near VAS signs. The signs were installed near these crash hotspots to help reduce the number of these crashes. As can be seen the system has decreased the number of crashes significantly near the VAS signs. One study has looked into the temporal distribution of crashes along the same corridor (Downey and Bertini, 2016). This study found that the system has decreased the proportion of crashes during the morning peak hours. However, results from that study was based on very limited historical crash data.
Figure 61. Relative crash frequencies by one-tenth of mile for NB before and after VAS
Figure 62. Relative crash frequencies by one-tenth of mile for SB before and after VAS
7.3.2 Surrogate Safety Measures

Given the limited amount of crash data used in the crash before-after analysis, this study has also used several surrogate measures for a safety evaluation of OR-217. Two primary aspects of speed have been used in this study in estimating safety surrogate measures namely speed and speed variations. Since speed varies across both time and space, a temporal and spatial analysis of speed variations have been implemented.

**Speed:** Figure 63 shows the frequency distribution of VHT (vehicle-hours traveled) percentage for different speed ranges on the southbound direction of OR-217 for periods when VAS was on and when it was off during clear and adverse weather conditions respectively. The effect of VAS system on speeds is clearly demonstrated in this figure. Specifically, a notable shift to the left of the speed histograms clearly
indicates that the activation of VAS was effective in lowering the speeds during both clear and adverse weather conditions.

Using a per-lane speed analysis, it was determined that speed along the corridor was on average around 5 mph higher on the left lane compared to the right lane. It was also found that during periods when VAS was on, average speeds on the left lane and right lane were 60.2 mph and 54.9 mph respectively. The corresponding speeds when VAS was off were 62.2 mph and 57.3 mph respectively. This suggests that on average VAS system has reduced average speeds by around 2 mph both for the left and right lanes.

Further the figure above clearly shows that the VAS has increased drivers’ compliance with the regulatory speed limit of 55 mph. If compliance is defined as speeds up to 5 mph above the speed limit of the freeway, VAS has resulted in motorists driving at speeds of 60 mph and lower 78% of the time. This percentage was only 66% during periods when VAS was off, showing a net increase of 12%. This however does not provide a measure of compliance with the VAS posted speeds, as there are different VAS speed postings depending on traffic and weather conditions. However increasing compliance even with the regular (static) speed limit during off-peak hours could lead to improved safety along the freeway. Detailed discussions about driver compliance with the system was provided in Chapter 6.
Speed Variations

**Temporal Variations:** Temporal variation of speed is measured at a fixed location using the coefficient of variation of speed (CVS). This coefficient is calculated for Allen (MP 2.55) and Greenburg (MP 5.11) stations and the results are shown in Figures 64 and 65. Average CVS values for the two lanes are reported separately for clear and adverse weather conditions. CVS values typically range from as low as 0.02 to as high as 0.45. Variations on both lanes peak during the morning and afternoon peak hours while seeing a clear decrease during the midday hours. This peaking characteristics is particularly clear for MP 2.55 which experiences congestion during the morning and afternoon peak hours. For MP 5.11, CVS is at its maximum values from 12:00 AM to 4:00 AM.

Comparing “before” and “after” periods, it was clear that for both stations, VAS has resulted in decreased CVS during the morning and midday hours. This amount of decrease was significant at 95% confidence level. However, the effect of VAS on reducing speed variation during the evening peak hours is not as clear, as there was slight decrease in three instances and increase in one instance (MP 2.55 – clear weather). For 12:00 AM to 5:00 AM period when vehicles operate at free-flow speeds, VAS has increased speed variation. This may be attributed to the fact that, under very low traffic condition, VAS may contribute to creating more speed disparity between drivers who choose to follow the posted VAS speed and those who don’t see a need to adjust their original speeds, this disregarding the VAS system.
Figure 64. Temporal variations of speed for different weather conditions (MP 2.55)
Figure 65. Temporal variations of speed for different weather conditions (MP 5.11)


Spatial Variations: Studies have shown that higher speed variance is associated with higher crash rates. Speed varies with time and over space and therefore both spatial and temporal variations of speed should be considered. The first spatial speed variability measure is the longitudinal variation of speed. Longitudinal variation of speed is calculated by measuring average speed differences between successive detector stations during free-flow conditions i.e., when vehicles have the freedom to choose their own speeds. It is wise to assume that the less the speed differences between stations (Δ), the less the acceleration and deceleration cycles and the less the potential for a collision.

Using the procedures detailed in the previous section, average speed differences between detector stations were determined and then averaged to calculate the average speed difference between any two successive stations along the entire corridor. Figure 66 illustrates the comparison between “VAS ON” and “VAS OFF” scenarios for different weather conditions. Each bar in the figure represents the average speed difference between two consecutive detector stations. The overall average is illustrated as a line over the length of the VAS deployment area. Underlined p-values is as an indication of a statistically significant difference at 95% confidence level. Overall, for periods when VAS was off, the average speed differences were higher towards the starting end of the corridor. This pattern was more evident for the right lane. Apparently, VAS has decreased the speed differences near the start and increased these differences towards the middle of the freeway. In all cases, the overall average is higher for periods when VAS was on. This pattern goes against the hypothesis, as VAS is supposed to harmonize the traffic speeds by reducing the longitudinal speed differences.
Possible reasons were searched for this unexpected pattern and data was examined carefully in an attempt to understand the pattern shown in these figures. It was found that the VAS speed was posted in most occasions intermittently for very brief periods of time. Specifically, using VAS log data, it was found that most of the VAS speeds during uncongested hours, are only one minute observations. Figure 67 provides an illustration of VAS system displayed speeds on a time-space platform for two different weather conditions.
days. On September 17, 2014, during uncongested hours (12:00 AM to 5:30 AM), most of the speed observations are displayed for one minute before they are expired. Moreover, this intermittent and brief activation of VAS occurred in the absence of congestion or inclement weather which may refer to malfunctioning of the newly deployed system. This is believed to have influenced traffic speeds at different stations, and hence increased speed differences between stations.

To verify this observation, only days with extended periods of VAS operations during uncongested hours were considered. Days in January to March of 2015 were found to qualify for this analysis. One such day is shown in Figure 67, where VAS was in operation almost all day for all stations. In total 3 days with clear weather and 6 days with adverse weather were found with such conditions. Figure 68 illustrates the resulting longitudinal speed differences for each weather scenario and each lane of the freeway. Interestingly, a notable decrease in average speed differences between successive stations were found when considering only these days. On average speed differences on the left

![Figure 67. VAS activation times for two different days –OR-217 SB](image)
lane were 0.6 mph lower when VAS was on. This speed difference was only 0.1 mph for the right lane. This provides evidence that VAS can affect the longitudinal distribution of speed, if it is displayed for extended periods of time for all locations along the freeway. This analysis provides evidence that if VAS is appropriately designed and operated, it can reduce the longitudinal variations of speed along the corridor thus improving safety.

Figure 68. Longitudinal variations of speed for different weather conditions (extended VAS operation)
Lateral Variations of Speed was the second spatial variability measure considered in the analysis. Although, within-lane variation of speed may be more likely to provoke a crash, across-lane variation becomes more relevant to safety when lane changes are taking place (Kockelman and Ma, 2007). Average speed differences across lanes ($\Delta s$), together with the speed profiles for each lane, are provided in Figures 69 and 70 for MP 2.55 and MP 5.11 respectively. To reduce the noise in the pattern of $\Delta s$, a five-point moving average is calculated and is superimposed on the actual data. A quick examination of Figure 69 reveals that $\Delta s$ ranges between 4 and 7 mph before and between 0 and 7 mph after VAS installation. Generally, $\Delta s$ variation with time shows lower values during night and early morning hours and increase gradually to reach it maximum value during midday hours, with two obvious dips in the pattern that occur during the AM and PM peak periods. This is expected due to the fact that speed variation across travel lanes is most restricted during the congested peak periods.

Contrary to MP 2.55, MP 5.11 which mostly operates at speeds higher than 40 mph even during the peak hours does not show bimodal patterns of lateral speed variance (see Figure 70). $\Delta s$ starts from as low as 1 mph during the midnight and early morning hours and rises to more than 6 mph during the midday hours.

To more quantitatively assess the effect of VAS on speed variation, Table 11 is provided to present the measured $\Delta s$ before and after VAS deployment during clear and inclement weather at the same two detector stations. It is clear from Table 2 that for MP 2.55, VAS has decreased the lateral speed variation for the morning, afternoon and midday hours during both clear and adverse weather conditions. On the contrary, for
MP 5.11 downstream of the congested area, where drivers normally travel at free-flow speeds, VAS has contributed to increased speed variation. This may largely be attributed to the fact that, when operating at free-flow speeds, drivers wanting to comply with the VAS shift to the right-lane, leaving the left-lane for passing vehicles.

Figure 69. Lateral variations of speed for different weather conditions (MP 2.55)
Figure 70. Lateral variations of speed for different weather conditions (MP 5.11)
Table 11. Lateral speed variation before and after VAS deployment

<table>
<thead>
<tr>
<th>Weather Conditions</th>
<th>Station</th>
<th>Time Scenarios</th>
<th>Before Avg. Speed (Left Lane)</th>
<th>Before Avg. Speed (Right Lane)</th>
<th>Before $\Delta s$ (mph)</th>
<th>After Avg. Speed (Left Lane)</th>
<th>After Avg. Speed (Right Lane)</th>
<th>After $\Delta s$ (mph)</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear Weather Conditions</td>
<td>MP 2.55</td>
<td>Morning Peak</td>
<td>54.47</td>
<td>48.97</td>
<td>5.50</td>
<td>51.13</td>
<td>46.19</td>
<td>4.94</td>
<td>0.016</td>
</tr>
<tr>
<td></td>
<td>Midday</td>
<td>54.57</td>
<td>47.64</td>
<td>6.93</td>
<td>52.77</td>
<td>46.20</td>
<td>6.57</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Evening Peak</td>
<td>38.30</td>
<td>33.60</td>
<td>4.70</td>
<td>36.17</td>
<td>31.72</td>
<td>4.45</td>
<td>0.007</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MP 5.11</td>
<td>Morning Peak</td>
<td>56.87</td>
<td>51.85</td>
<td>5.02</td>
<td>54.80</td>
<td>48.76</td>
<td>6.05</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>Midday</td>
<td>60.44</td>
<td>54.83</td>
<td>5.61</td>
<td>61.57</td>
<td>53.84</td>
<td>7.73</td>
<td>0.000</td>
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</tr>
<tr>
<td></td>
<td>Evening Peak</td>
<td>57.65</td>
<td>52.04</td>
<td>5.61</td>
<td>56.67</td>
<td>49.88</td>
<td>6.79</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>Adverse Weather Conditions</td>
<td>MP 2.55</td>
<td>Morning Peak</td>
<td>52.03</td>
<td>46.16</td>
<td>5.87</td>
<td>48.09</td>
<td>43.33</td>
<td>4.76</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>Midday</td>
<td>51.89</td>
<td>45.06</td>
<td>6.83</td>
<td>51.54</td>
<td>44.92</td>
<td>6.63</td>
<td>0.064</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Evening Peak</td>
<td>37.90</td>
<td>33.19</td>
<td>4.71</td>
<td>37.31</td>
<td>32.79</td>
<td>4.52</td>
<td>0.166</td>
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<tr>
<td></td>
<td>MP 5.11</td>
<td>Morning Peak</td>
<td>54.02</td>
<td>49.15</td>
<td>4.87</td>
<td>54.02</td>
<td>48.20</td>
<td>5.83</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>Midday</td>
<td>59.71</td>
<td>54.10</td>
<td>5.62</td>
<td>60.78</td>
<td>52.98</td>
<td>7.80</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Evening Peak</td>
<td>53.25</td>
<td>48.06</td>
<td>5.18</td>
<td>53.53</td>
<td>47.32</td>
<td>6.22</td>
<td>0.000</td>
<td></td>
</tr>
</tbody>
</table>

Note: Italic p-values indicate statistically significant results at 95% confidence level.
CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 Summary

Traffic control by means of variable speed limits was first introduced more than three decades ago in Germany. Since then, VSL has been widely practiced in Europe. In the United States, VSL is still a relatively new traffic management approach. However, due to its apparent simplicity and reduced installation costs, it is one of the most attractive and famous ATM strategies. Traditionally, in the U.S. these systems have been deployed to primarily improve safety and occasionally homogenize traffic flow. Recent VSL deployments have taken other measures, including environmental sustainability and travel time reliability into consideration as well.

Despite the considerable interest in VSL systems, there is a lack of understanding of the effectiveness of these systems. The claimed benefits of VSL systems typically imply a reduction in crash and incidents rates, improvement in congestion and a decrease in traffic-related emissions. However, the claimed benefits for most of these studies have been evaluated using theoretical models. Very few studies in literature have used empirical data in their evaluations. In addition, the results of these studies are lacking consensus, with many conflicting findings.

To address the above issues and to develop a deeper understanding of the actual effects of VSL systems, this study has attempted to investigate the impacts of a recently installed advisory variable speed limit system along OR-217 freeway in Portland,
Chapter one starts by providing a background on the concept of variable speed limits and of the OR-217 advisory VSL system in particular. Chapter two and three provide a thorough review of literature on VSL, its implementation examples in the United States and other countries and its reported benefits. Chapter four identifies the numerous mobility and safety challenges along OR-217 corridor and demonstrates the reasons why the corridor was equipped with an advisory VSL system. This chapter also provide a detailed description of the data collection and processing procedures. Chapters five through eight present and discuss the evaluation procedures and results. The following sections provide a summary of the main study findings.

8.1.1 System Impacts on Fundamental Flow Parameters

Chapter five tries to verify some long-time conjectures regarding the VSL impacts on fundamental flow parameters (speed, flow and occupancy). Many studies have indicated that traffic management approaches like VSL can affect these parameters. However, there is no consensus among researchers about these effects. The investigation presented in this thesis, revealed very important insights into the effects of VSL systems on the traffic stream using extensive field data. Study results suggested that the advisory VSL along OR-217 corridor did affect the shape of the flow-occupancy curves in the majority of scenarios investigated. This effect was more evident for the congested region of the flow-occupancy diagram and the patterns of change were more consistent when the system was investigated under normal weather conditions. The analyses also showed that
in the majority of scenarios investigated, the critical occupancy which occurs at capacity operations decreased when VSL was activated. In regards to average speeds at the study sites, it was found that speeds for congested and uncongested conditions have decreased after the VSL deployment, and that the decrease in speeds was more profound in the congested region. This confirms that the system is effective in lowering speeds on the roadway using data from the months immediately after system deployment. The analyses also examined the VSL system effect on capacity and results strongly and consistently suggested that the capacity achieved when the VSL system is activated is likely to be lower than its counterpart when the VSL system was not activated. However, the capacity results would have been different if the regulatory speed limit was closer to the 85th percentile of traffic speeds along the corridor. This means that by increasing the speed limit of 55 mph by at least 10 mph can give us the opportunity to post VAS speeds that are very close to the speeds at capacity (optimum speed). Posting these speeds may result in increased capacity on the freeway.

Nevertheless, the decrease in capacity has not much affected the operations along OR-217 when the VSL was activated due to congestion, as only a few observations of VSL activation in the uncongested region were identified. This may not be the case when the VSL is activated due to adverse weather in the absence of congestion, however, safety benefits brought by lower speeds (e.g. fewer incidents and accidents, lower crash severity, etc.) may well outweigh the operational impacts associated with the expected reduction in capacities.
8.1.2 System Impacts on Driver Compliance

Chapter six investigated the effects of the VAS system on speeds and the levels of drivers’ compliance with VAS speeds along OR-217 corridor. Results from this study provided evidence that, there is a distinct shift toward lower speeds when the VAS system was on and that this shift is more evident when lower speeds were posted on the VAS signs. In regards to drivers’ compliance with VAS, it was found that although lower posted speeds on VAS may reduce driver compliance, it has the potential to significantly reduce average speeds and thus increase compliance with the legal speed limit. It was also found that speeds and drivers’ compliance on the right lane are different from those on the left lane. In general, lower speeds and higher levels of compliance were observed on the right lane. The study concluded that compliance with VAS is not uniform along the freeway and that the farther the detector from the VAS sign, the higher the speeds and the lower the compliance level. In regards to the effect of weather and light condition on compliance, the results suggested that adverse weather and nighttime are associated with higher levels of compliance with VAS signs. Finally, the study provided no evidence that the level of compliance with VAS signs diminishes with time.

8.1.3 System Impacts on Safety

Chapter seven presented the analysis of the safety impacts of the VAS system. The investigation utilized limited crash data and several surrogate safety measures to assess the safety impacts of the VAS system. The surrogate measures included mean speed and speed variation. Two main types of speed variation were considered in the analysis namely: spatial along the corridor and on individual lanes at fixed locations.
Spatial speed variation was further divided into two parts; longitudinal variations of speed and lateral variations of speed. The results of the crash analysis suggested that the implementation of VAS along the corridor has provided safety benefits, as crash rates have significantly decreased in the after period despite an increase in total VMT. However, the exact reduction figures should be treated with caution due to the limited duration of the analysis periods. In regards to safety surrogate measures, a noticeable decrease in average speeds for periods when VAS system was turned on was also observed. Lower speeds are believed to be associated with lower crash frequency and severity. Lower speeds have in turn increased the percentage of drivers complying with the legal speed limit which is a good sign from a safety standpoint.

For longitudinal speed variation along the corridor, study results are mixed. Specifically, higher speed variation was observed for times with intermittent activation and deactivation of VAS system during free-flow conditions. On the other hand, when the VAS system was activated for extended periods of time, longitudinal speed variations were reduced by up to 55%. It is thus recommended to establish appropriate minimum durations for VAS activation and eliminate the intermittent VAS operations which could confuse drivers and introduce more speed variation in the traffic stream. At fixed locations on individual travel lanes, results suggested that the VAS reduced speed variation during the morning and midday hours but had almost no effect during the afternoon peak hours. In addition, results show that VAS increased speed variation during late night to early morning hours. Due to the advisory nature of the VAS system, some drivers may disregard the VAS posted speeds while others comply with the posted
speeds, thus creating more disparity among individual speeds. Lateral speed variation across travel lanes was also investigated in this study. The study found that VAS effect on lateral speed variation is a function of traffic conditions, and thus varies by location. Specifically, VAS was found to increase lateral speed variation at sites where free-flow conditions exist and to decrease lateral speed variation at sites that are part of the congested regions along the corridor. This is somewhat expected given the drivers’ freedom in complying with the VAS system during free-flow conditions.

8.2 Contributions

VSL systems and particularly their effectiveness have raised much controversy among drivers, researchers, and practitioners. The research contributions for this thesis should promote the willingness of traffic agencies to improve their decision making processes. It can also lay a foundation for the future VSL implementations.

This thesis makes several contributions to expanding the knowledge about the effectiveness of congestion and weather-responsive VSL systems. The majority of existing systems are either entirely weather-responsive or congestion-responsive. The system studied has both components. Using a scenario-based analysis, this study could quantify the impacts of the system on mobility, safety and compliance in real time. The main contributions of the research include:

1. Analysis of the mobility impacts of VSL was quantified using the fundamental diagrams and relationship between speed, flow and density with empirical data. The lacking consensus of researchers were addressed in this
study by providing some important information about the actual effects of VSL on the fundamental traffic flow parameters.

2. Measuring driver compliance during periods when VSL system was on or off shed the light on the driver behavior effects of VSL systems. This study was designed in a way that compliance could be measured in real time under different weather, light and other scenarios.

3. Safety impacts of VSL system was also assessed using crash data and some other safety surrogates calculated from empirical traffic flow parameters.

Moreover, this thesis is a valuable addition to the inadequate body of literature on the field evaluations of advisory VSL systems. Previous studies have highlighted that advisory systems are less effective due to no proper enforcement. This study found that, although some performance measures under some specific scenarios have not improved since VSL implementation, many others have improved.

8.3 Recommendations for Future Research

Although this study makes valuable contributions to the developing body of knowledge about VSL systems, it is certainly not without limitations. These limitations should be considered when evaluating the results of the VSL impact analysis and identifying issues for future research.

One limitation in this study is that, it did not investigate the behavior of individual drivers in respect of the VSL system. Although this effort delved deep into the detector data, the presented results are an aggregation of the particular driver’s behavior. It would
be beneficial to investigate the changes in driver behavior by collecting individual vehicle
data.

In addition, this study has considered the combined effects of VSL and ramp
metering. Adaptive ramp metering system was installed and activated on May, 2005.
From time to time the system has been set to use fixed-time rates. This could significantly
impact the safety and mobility performance along the OR-217 corridor. This made it
difficult to separate out changes attributable to the VSL system only. Scarcity of data for
the “after” period (particularly crash data) was another issue this study was facing.
Although the data collected was adequate to provide a meaningful operational analysis, it
was certainly not enough to complete a reliable crash analysis.

Future search should address the above mentioned issues. Additional topics
related to empirical research are mentioned as follows. Some of these researches are
currently underway.

1. Use a more robust approach to estimate stationary periods and establish
   fundamental diagrams. This can provide a very accurate picture of the actual
effects of VSL on fundamental flow parameters.

2. New VAS control strategies can be developed and evaluated. One possible
   strategy that can be tested is the idea of initiating the system before congestion
   builds up. This can provide the opportunity to reduce the traffic speed before
   the start of the traffic breakdown. This in turn may result in increased capacity
   on the freeway.
3. Microscopic VSL effects can be measured using individual vehicle data. This makes it possible to compute interesting traffic parameters, e.g. the homogeneity of speeds, establish time headway distributions, or to count the number of lane changes.

4. Investigate the significance of the surrogate safety measures presented in this thesis by estimating a probabilistic model relating these factors to changes in crash potential. Crash potential refers to long-term likelihood that a crash will occur for given traffic, environment, and roadway conditions. Using the probabilistic model described, the impacts of VSL in reducing crash-potential could be quantified.
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APPENDIX A

FUNDAMENTAL DIAGRAMS FOR MP 3.85 AND MP 1.92
### Scenario 17

**Weather:** Clear Weather  
**Critical Occupancy (%):** 17.58  
**Slope Comparison:** Under-critical Occupancy  
**Kernel-based Test:** Before After % Change P-value F-Stat P-value F-stat P-value  
**Before:** 17.58 | **After:** 17.20 | **% Change:** -2.2% | **P-value:** 0.009 | **F-Stat:** 6.961 | **P-value:** 0.018 | **F-stat:** 5.715 | **P-value:** 0.204  

### Scenario 18

**Weather:** Clear Weather  
**Critical Occupancy (%):** 15.90  
**Slope Comparison:** Over-critical Occupancy  
**Kernel-based Test:** Before After % Change P-value F-Stat P-value F-stat P-value  
**Before:** 1871.56 | **After:** 1734.20 | **% Change:** -7.9% | **P-value:** 0.018 | **F-Stat:** 5.715 | **P-value:** 0.268 | **F-stat:** 3.254 | **P-value:** 0.063  

### Scenario 19

**Weather:** Clear Weather  
**Critical Occupancy (%):** 18.60  
**Slope Comparison:** Under-critical Occupancy  
**Kernel-based Test:** Before After % Change P-value F-Stat P-value F-stat P-value  
**Before:** 142.4 | **After:** 102.6 | **% Change:** -35% | **P-value:** 0.252 | **F-Stat:** 2.674 | **P-value:** 0.074 | **F-stat:** 3.254 | **P-value:** 0.268  

### Scenario 20

**Weather:** Clear Weather  
**Critical Occupancy (%):** 17.50  
**Slope Comparison:** Over-critical Occupancy  
**Kernel-based Test:** Before After % Change P-value F-Stat P-value F-stat P-value  
**Before:** 142.4 | **After:** 102.6 | **% Change:** -35% | **P-value:** 0.252 | **F-Stat:** 2.674 | **P-value:** 0.074 | **F-stat:** 3.254 | **P-value:** 0.268  

### MP 3.85 – Clear Weather

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
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### Scenario 21

**Critical Occupancy (%)**

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<th>Over-critical Occupancy-Slope Comparison</th>
<th>Kernel-based Test</th>
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<td>P-value</td>
<td>F-Stat</td>
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<td>16.85</td>
<td>0.4%</td>
<td>0.003</td>
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<td>15.36</td>
<td>15.98</td>
<td>3.9%</td>
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<tr>
<td>23</td>
<td>15.50</td>
<td>16.34</td>
<td>5.1%</td>
<td>0.000</td>
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<tr>
<td>24</td>
<td>16.23</td>
<td>14.25</td>
<td>-13.9%</td>
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### Scenario 22

**Critical Occupancy (%)**

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<th>Under-critical Occupancy-Slope Comparison</th>
<th>Over-critical Occupancy-Slope Comparison</th>
<th>Kernel-based Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>After</td>
<td>% Change</td>
<td>P-value</td>
<td>F-Stat</td>
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<tr>
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<tr>
<td>24</td>
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<td>-4.2%</td>
<td>1764.98</td>
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**Scenario 23**

**Critical Occupancy (%)**

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<th>Over-critical Occupancy-Slope Comparison</th>
<th>Kernel-based Test</th>
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<td>After</td>
<td>% Change</td>
<td>P-value</td>
<td>F-Stat</td>
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<td>16.78</td>
<td>16.85</td>
<td>0.4%</td>
<td>0.003</td>
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<tr>
<td>22</td>
<td>15.36</td>
<td>15.98</td>
<td>3.9%</td>
<td>0.000</td>
</tr>
<tr>
<td>23</td>
<td>15.50</td>
<td>16.34</td>
<td>5.1%</td>
<td>0.000</td>
</tr>
<tr>
<td>24</td>
<td>16.23</td>
<td>14.25</td>
<td>-13.9%</td>
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**Scenario 24**

**Critical Occupancy (%)**

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<th>Over-critical Occupancy-Slope Comparison</th>
<th>Kernel-based Test</th>
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<td>After</td>
<td>% Change</td>
<td>P-value</td>
<td>F-Stat</td>
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<tr>
<td>21</td>
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<td>1804.34</td>
</tr>
<tr>
<td>22</td>
<td>1820.56</td>
<td>1752.72</td>
<td>-3.9%</td>
<td>1750.92</td>
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<tr>
<td>23</td>
<td>1780.48</td>
<td>1751.48</td>
<td>-1.7%</td>
<td>1740.07</td>
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<tr>
<td>24</td>
<td>1799.69</td>
<td>1726.59</td>
<td>-4.2%</td>
<td>1764.98</td>
</tr>
</tbody>
</table>

---

**MP 3.85 – Adverse Weather**

**Scenario 21**

- Critical Occupancy (%): 16.78 (Before), 16.85 (After), % Change: 0.4%, P-value: 0.003
- Under-critical Slope Comparison: 9.133, F-Stat: 0.219
- Over-critical Slope Comparison: 1.517, P-value: 0.000

**Scenario 22**

- Critical Occupancy (%): 15.36 (Before), 15.98 (After), % Change: 3.9%, P-value: 0.000
- Under-critical Slope Comparison: 44.294, F-Stat: 0.899
- Over-critical Slope Comparison: 0.016

**Scenario 23**

- Critical Occupancy (%): 15.50 (Before), 16.34 (After), % Change: 5.1%, P-value: 0.000
- Under-critical Slope Comparison: 18.056, F-Stat: 0.000
- Over-critical Slope Comparison: 16.152, P-value: 0.088

**Scenario 24**

- Critical Occupancy (%): 16.23 (Before), 14.25 (After), % Change: -13.9%, P-value: 0.009
- Under-critical Slope Comparison: 6.839, F-Stat: 0.030
- Over-critical Slope Comparison: 4.733, P-value: 0.000

**Flow Drop (vphpl)**

- Scenario 21: 89.1 to 80.9 (MP 3.85)
- Scenario 22: 69.6 to 41.0
- Scenario 23: 40.4 to 38.6
- Scenario 24: 34.7 to 151.6

**R² (B) = 0.85**

- **R² (A) = 0.76**

**R² (B) = 0.86**

- **R² (A) = 0.85**

**R² (B) = 0.89**

- **R² (A) = 0.85**

**R² (B) = 0.90**

- **R² (A) = 0.84**
### MP 1.92 – Clear Weather

<table>
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<tr>
<th>Scenario</th>
<th>Weather</th>
<th>Critical Occupancy (%)</th>
<th>Under-critical Occupancy-Slope Comparison</th>
<th>Over-critical Occupancy-Slope Comparison</th>
<th>Kernel-based Test</th>
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</thead>
<tbody>
<tr>
<td></td>
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<td>Before</td>
<td>After</td>
<td>P-value</td>
<td>F-Stat</td>
</tr>
<tr>
<td>25</td>
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<td>-8.0%</td>
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<td>26</td>
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<td>27</td>
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<td>16.34</td>
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</table>

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Weather</th>
<th>Pre-queue Flow (vphpl)</th>
<th>Queue-discharge Flow (vphpl)</th>
<th>Flow Drop(vphpl)</th>
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<tbody>
<tr>
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<td>2033.19</td>
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</table>
### Scenario 29 – Adverse Weather

#### Critical Occupancy (%)

<table>
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<tr>
<th>Scenario</th>
<th>Under-critical Occupancy</th>
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<th>Kernel-based Test</th>
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<tr>
<td>Weather</td>
<td>Slope Comparison</td>
<td>Slope Comparison</td>
<td>Test</td>
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<td>Before</td>
<td>After</td>
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<td>29</td>
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<td>15.50</td>
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<td>32</td>
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</table>

#### Pre-queue Flow (vphpl) & Queue-discharge Flow (vphpl)

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<tr>
<th>Scenario</th>
<th>Pre-queue Flow (vphpl)</th>
<th>Queue-discharge Flow (vphpl)</th>
<th>Flow Drop(vphpl)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weather</td>
<td>Before</td>
<td>After</td>
<td>% Change</td>
</tr>
<tr>
<td>29</td>
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APPENDIX B

TESTING LINEAR REGRESSION ASSUMPTIONS
Additional regression Diagnostics (Fox, 2009)

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<tr>
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</tbody>
</table>

Variance Inflation Factors (VIF) (checking multicollinearity)

- Light = 1.184
- Distance = 1.005
- Speed limit Difference = 1.184
- Weather = 1.025
- Lane = 1.000