ASSESSMENT OF OPERATIONAL AND SAFETY IMPACTS OF VARIOUS TRAFFIC CONTROL DEVICES

By

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ABSTRACT

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Fatal crashes have been increasing, both in Michigan and across the United States, despite continuing improvements in roadway design, vehicle safety, and other areas. Various factors may have contributed to this trend, including increased in-vehicle distractions, higher speed limits, legalization of marijuana, and other factors. Studies have suggested that driver error is a critical reason associated with more than 90 percent of all traffic crashes. Driver behavior can be improved by several engineering strategies, such as the use of better and more efficient traffic control devices, such as signs, signals, and pavement markings. To that end, this research assesses the operational and safety impacts of a series of traffic control devices.

The use of dynamic message signs (DMS) as a medium to display safety messages to drivers has become popular among transportation agencies. Despite their widespread use, evaluations as to the resultant impacts on traffic crashes have been very limited. This study addresses this gap in the extant literature and assesses the relationship between traffic crashes and the frequency with which various types of safety messages are displayed. A series of count models are estimated to examine total, speeding-related, and nighttime crashes based upon historical messaging data while controlling for other site-specific factors. Ultimately the results provide important insights regarding messaging strategies for transportation agencies.

This research also evaluates driver response to advisory speed signs. Posted speed limit signs are used to inform drivers of the legal maximum allowable speed. In contrast, advisory speed signs provide recommendations to drivers as to safe travel speeds at specific roadway locations.

Various studies have investigated the safety impacts of speed limit changes, particularly on high-speed rural highways. One area of particular concern on such roadways is the approach to exit ramps that require substantive speed reductions, such as loop ramps. To date, there has been limited research examining the safety impact of the differential between the mainline speed limit and the lower exit ramp advisory speeds. This study addresses this gap through the estimation of a series of safety performance functions. The findings from this study show the safety of these locations is related to speed differential, as well as other factors such as the length of the upstream deceleration lane. These factors should be considered when considering speed limit policy impacts in the vicinity of full and partial cloverleaf interchanges.

Lastly, this study assesses the use of dynamic speed feedback sign (DSFS) as a means to reduce vehicle speeds in speed transition zones, where speeds are reduced as drivers enter rural communities. DSFS have been evaluated in several settings, including high-speed exit ramps and horizontal curves. However, research is limited as to the effectiveness of this sign for other purposes, such as these high-speed transition areas. This is particularly important as the limits on some of these roadways have recently been increased, making speed control a particular concern. This study addresses this gap through a before-and-after evaluation of DSFS at five different sites in northern Michigan. A series of speed models were estimated, which provide insights on the effectiveness of DSFS.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

KEY TO ABBREVIATIONS

AADT	Average Annual Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
CMS	Changeable Message Sign
DMS	Dynamic Message Sign
DOT	Department of Transportation
DSFS	Dynamic Speed Feedback Sign
FARS	Fatality Analysis Reporting System
ITS	Intelligent Transportation System
LED	Light Emitting Diode
LIDAR	Light Detection and Ranging
MDOT	Michigan Department of Transportation
MSP	Michigan State Police
MUTCD	Manual on Uniform Traffic Control Devices
NB	Negative Binomial
NHTSA	National Highway Traffic Safety Administration
PCMS	Portable Changeable Message Sign
RADAR	Radio Detection and Ranging
SPF	Safety Performance Function
TDMS	Traffic Data Management System
VMT	Vehicle Miles Traveled

CHAPTER 1: INTRODUCTION

1.1 Background and Study Objectives

Reports from the Centers for Disease Control and Prevention stated that traffic fatality is the leading cause of death in the United States (U.S.) for people aged between 1 and 54 (Centers for Disease Control and Prevention, 2021). According to the traffic fatality database from the National Highway Traffic Safety Administration (NHTSA), fatal crashes in this country saw a u-shaped trend in the last 15 years from 2005 to 2019 as shown in Figure 1.1 (National Highway Traffic Safety Administration, 2020). The first four years showed a consistent decline in fatal crashes before resting at a uniform phase for a period of five-year between 2009 and 2014. The trend increased from 2014, and in 2019, 33,255 fatal crashes were recorded, which had an increase of 10.1 percent from 2014. These crashes have resulted in 36,096 traffic fatalities, which makes up for 1.1 fatalities for every 100 million vehicle miles traveled (VMT) and approximately 11 fatalities in every 100,000 population. In Michigan, the total number of fatal crashes recorded in 2019 was 902. Both the U.S. and Michigan fatal crashes saw a similar trend since 2005 (Figure 1.1). The increasing trend of total road-related deaths was also recorded among vulnerable road users (e.g., motorcyclists, bicyclist, pedestrian, etc.) within the last decade (National Highway Traffic Safety Administration, 2020).

These increases may have resulted from various factors, including increases among in-vehicle distractions such as cell phone use while driving, increases in speed limits on rural highways, relaxation of helmet law, legalization of marijuana, and some other factors. Several studies have suggested that driver error is a critical reason associated with more than 90 percent of all traffic crashes (Hendricks et al., 2001; National Highway Traffic Safety Administration, 2008; Treat et al., 1979). Consequently, facilitating fundamental changes in driver behavior is crucial to achieving substantive progress toward overarching goals such as Vision Zero, "a strategy to eliminate traffic fatalities and serious injury while increasing safe, healthy, equitable mobility for all" (Vision Zero Network, n.d.).

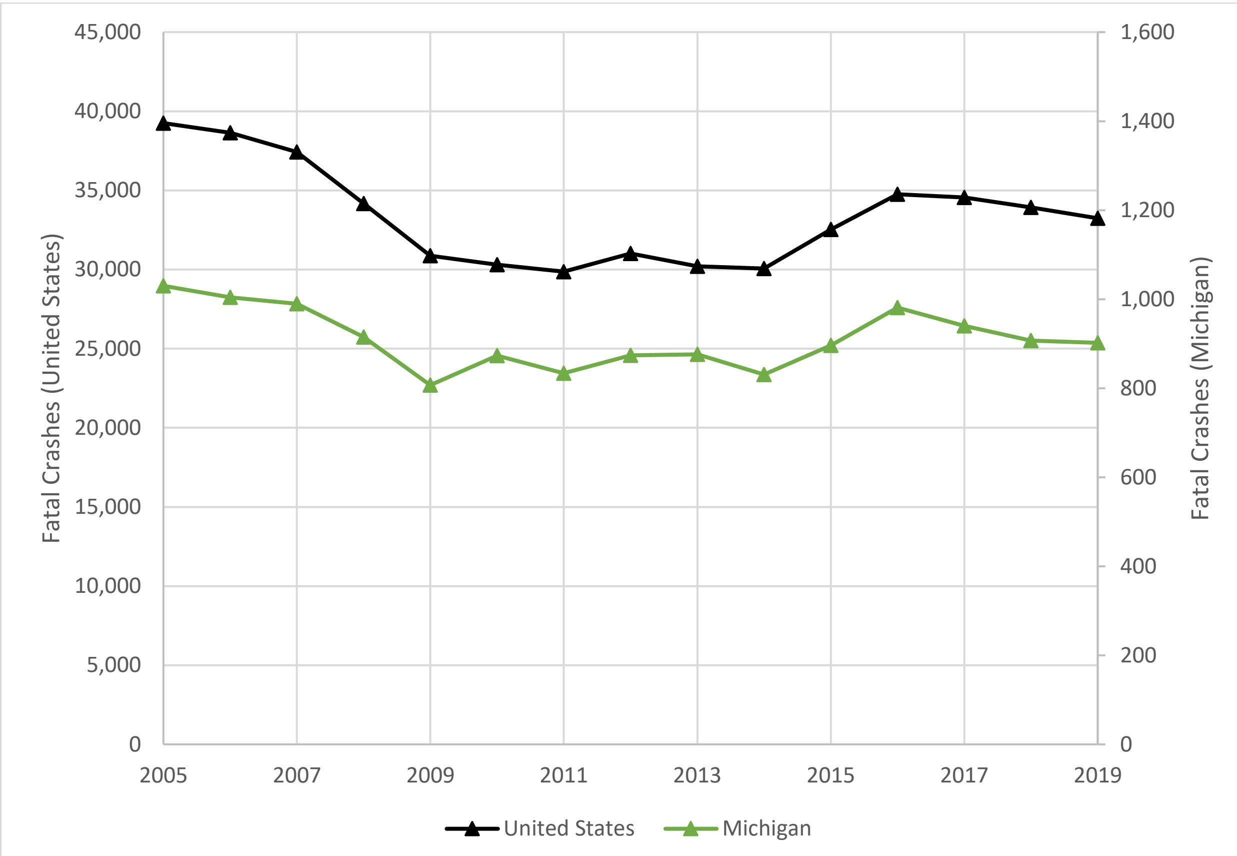


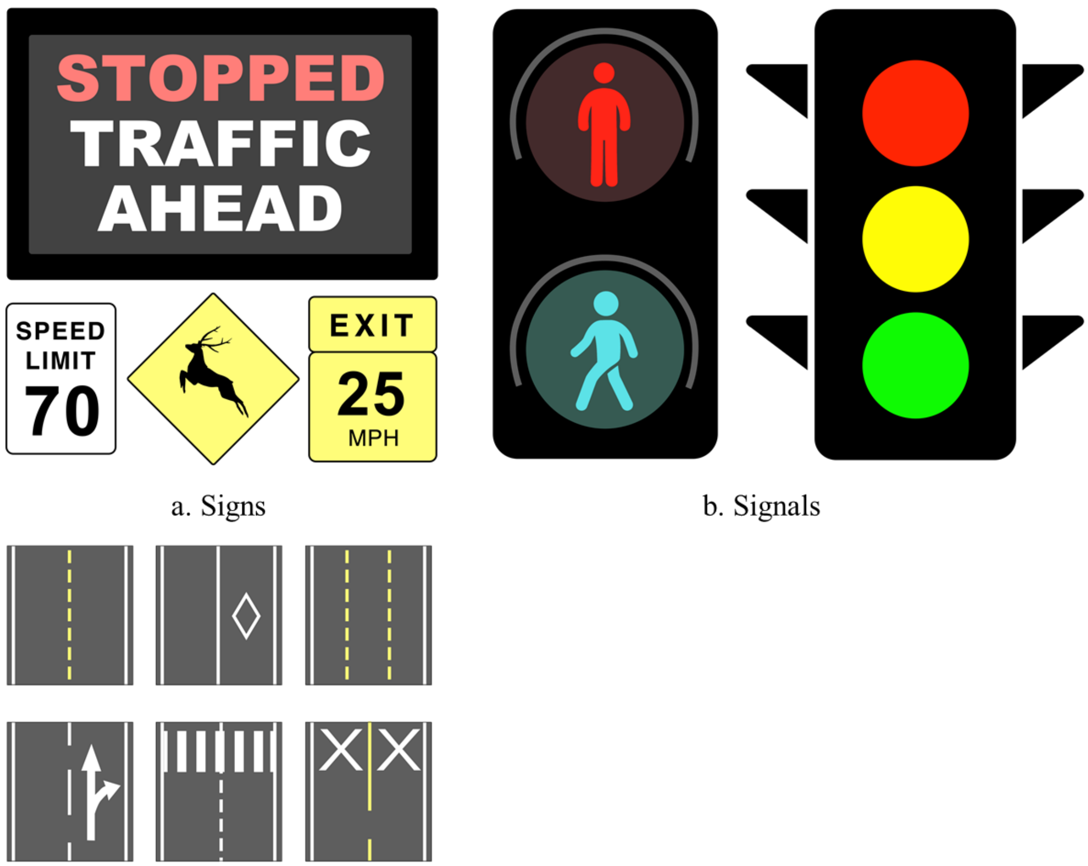
Figure 1.1 Annual Fatal Crashes in the United States vs. Michigan (National Highway Traffic Safety Administration, 2020)

Changes in driver behavior toward better safe driving can be achieved by implementing various engineering strategies to the road environment, particularly on better and more efficient traffic control devices. According to the Manual on Uniform Traffic Control Devices (MUTCD), traffic control devices can be defined as tools to inform road users of the regulation and facilitate warning and guidance by using visual or tactile indicators to traverse the roadway network safely and efficiently (FHWA, 2009). Historically, the first traffic control device used in transportation system was the road sign, for directional purposes (FHWA, 2021a). Between 1910 and 1920, Michigan was one of the first states in the country to develop and use devices other than road signs such as painted centerline, stop sign, and three-colored traffic signal to control the flow of traffic (FHWA, 2021a).

In general, traffic control devices can be divided into three main groups: 1) signs, 2) signals, and 3) road markings as shown in Figure 1.2 (FHWA, 2009). Under the sign category, this falls into three subcategories. The first one is the regulatory sign which provides information to road users on the traffic laws or regulation such as speed limit sign, stop sign, and no parking sign. Failure to adhere to these signs often constitutes a traffic violation. The second type of sign is the warning sign, where it alerts road users the driving hazards that drivers might not expect such as deer crossing corridor, sharp horizontal curvature, or slippery road due to icy condition. These signs are installed only based on engineering study or judgment. The last sign is the guide or information sign. This type of sign provides road users route and amenity information such as route designations, destinations, directions, distances, time, and others. In the last ten to fifteen years, transportation agencies started to use dynamic message sign (DMS) or also known as changeable message sign (CMS) as a guide or information sign. Information such as travel time and traffic conditions (e.g., congestion ahead, lane closure, downstream crash, etc.) are among the messages being displayed on this sign.

Traffic signals are ubiquitous devices in traffic control environment. They are installed based on engineering study that considered the nine traffic signal warrants (e.g., crash history, school area, pedestrian volume, peak hour, etc.) (FHWA, 2009). The typical three lights with lane indicator are commonly used throughout the country. However, the color, flashing system, and signal position (i.e., vertical or horizontal) may vary from state to state (Reliance Foundry, n.d.).

Overall, traffic signals are installed to improve safety and operation of intersections. The last main category of traffic control devices is the road markings. They are used to provide guidance to road users to traverse the roadway network safely and efficiently. Often time, road markings are used to support other traffic control devices. In other occurrences, they are used as standalone devices to communicate with road users on regulations, guidance, or warning that other device could not do such as chevron marking.



a. Signs

b. Signals

c. Road markings

Figure 1.2 Different Types of Traffic Control Devices

To this date, various types of traffic control devices have been developed and implemented on the transportation network, particularly on traffic signs. Many of these signs have been examined and proved their effectiveness in improving driver behaviors towards better safe driving based on prior literatures. Placement of conventional warning signs such as curve and ramp advisory speed signs, pedestrian warning signs, animal crossing signs, speed reduction zone signs and downgrade warning signs on high-risk corridors have been shown to positively impact driver behaviors (i.e., number of crashes and average vehicle speed decreased after the installation of these signs) (Al-Ghamdi & AlGadhi, 2004; Clark et al., 1996; Found & Boyce, 2011; Lee & Abdel-Aty, 2009; Moomen et al., 2019; van Houten & van Huten, 1987).

Advancement in technology allows these conventional signs to be integrated with other devices such as lighting-warning system for pedestrian crossing sign, stop sign, and advisory speed sign. In some instances, these signs include speed feedback sign that uses Radio Detection and Ranging (RADAR) method to record vehicle speed and display it on the messaging board. The integration of these additional devices to the conventional signs has shown to increase driver's awareness towards the road environment and consequently improve the traffic safety and operation (Costa et al., 2020; Fitzpatrick & Park, 2021; Gates et al., 2020; Srinivasan et al., 2008).

Ultimately, this dissertation is divided into three main study objectives in relation to traffic sign. The main objectives of this dissertation are to:

1. Examine the relationship between different subset of traffic crashes and the frequency with which various types of safety messages are displayed on DMS in the state of Michigan.
2. Assess the safety impact of speed differential between mainline speed limit and exit ramp advisory speeds on ramp proper with the consideration of various roadway geometry.
3. Evaluate the effectiveness of dynamic speed feedback sign (DSFS) as a medium to reduce driver's speed when approaching rural communities from high-speed rural highways in Michigan.

1.2 Dissertation Structure

This dissertation consists of five main chapters. Chapter 1 describes the background on general information related to traffic control devices, as well as a brief description of each study objective. Chapter 2, 3, and 4 represent each of the study objective, respectively. Within these chapters, a specific background on the research problem of interest will be presented, in addition to the data description, statistical method, results and discussions, and a brief summary. Lastly, Chapter 5 presents the conclusions and recommendations for all three study objectives. A brief description of each chapter are as follows:

- Chapter 1: Introduction – This chapter begins with the overview of the trend of fatal crashes in the last 15 years in the U.S. and Michigan. Additionally, this chapter explains different types of traffic control devices based on the MUTCD. The following part in this chapter is presenting the evidence on the effectiveness of having traffic signs on high-risk road based on prior studies. Lastly, this chapter describes the three main study objectives.
- Chapter 2: Examining Trends in Traffic Crashes as they Relate to the Display of Safety Messages on Dynamic Message Signs – This chapter provides detailed explanation on the safety impact on displaying safety messages on DMS. In general, this study utilized the historical data of safety messages that were displayed from 2014 to 2018 from a total of 202 DMS on freeways across the state of Michigan. These data were integrated with traffic volume, roadway characteristics, and crash data for roadway segments that were located downstream of each DMS. A series of random parameters negative binomial models was estimated for different type of crashes based on the message displayed.
- Chapter 3: Safety Evaluation of Freeway Exit Ramps with Advisory Speed Reductions – This chapter demonstrates the safety impact of speed differential on exit ramps proper.

Overall, the speed differential information was integrated with the traffic information, roadway geometry, and crash data for exit ramp proper. A total of 187 exit ramps where advisory speed signs are present in Michigan were evaluated. Several safety performance functions using random effect negative binomial regression were estimated

- Chapter 4: Driver Response to a Dynamic Speed Feedback Sign at Speed Transition Zone Along Rural Highways – This chapter provides detailed description on the effectiveness of DSFS in reducing driver’s speed upon entering rural communities from high-speed rural highways. In general, this study collected data before and after the installation of the sign at five different sites in northern Michigan with varying speed limits of upstream segments and upon entering rural communities. The speed profile of each vehicle entering the speed transition zone was collected using handheld Light Detection and Ranging (LIDAR) devices. Two types of regression models (multiple linear regression and logistic regression) were used to assess the effectiveness of DSFS.
- Chapter 5: Conclusions and Recommendations – This chapter provides the summary findings from Chapter 2, 3, and 4. This chapter also discusses the potential solutions that can be implemented in the real-world environment. Lastly, this chapter also presents the limitations and future research that can be done for each study objective.

CHAPTER 2: EXAMINING TRENDS IN TRAFFIC CRASHES AS THEY RELATE TO THE DISPLAY OF SAFETY MESSAGES ON DYNAMIC MESSAGE SIGNS

2.1 Background and Problem Statements

Between 2005 and 2009, traffic fatalities declined significantly throughout the United States before plateauing from 2009 to 2014. Since 2014, fatalities have increased to a total of 33,255 in 2019, despite continuing improvements in roadway design, vehicle safety, and other areas. These national trends have also largely held in the state of Michigan, where the total number of traffic-related deaths in 2019 was 902 (National Highway Traffic Safety Administration, 2020). Various factors may have contributed to these increases, including increases among in-vehicle distractions such as cell phones use while driving, higher speed limits, legalization of marijuana, and other factors. Studies have suggested that more than 90 percent of traffic crashes are due, in some part, by driver error (Hendricks et al., 2001; National Highway Traffic Safety Administration, 2008; Treat et al., 1979). Consequently, facilitating fundamental changes in driver behavior is imperative.

To this end, over the past few years, various state departments of transportation (DOT) have attempted to use public awareness campaigns to spur changes in driver behavior and raise awareness as to the magnitude of the impacts of traffic crashes on road users and society overall. In addition, supporting public awareness campaigns with strong legislation and strategic enforcement has been shown to improve driver behavior (Peden et al., 2004). Historically, Michigan has used awareness campaigns to improve road safety as far back as the early 1920s by displaying reminders of “Always Be Careful” at busy intersections and attaching tongue-in-cheek messages such as “He tried to make 90!” or “Follow this one to the cemetery” on towed wrecked cars (Loomis, 2015). As part of the Toward Zero Death initiative in Michigan, communications and increased public awareness have been identified as critical to a systemic approach to safety (Michigan Department of Transportation, n.d.).

Intelligent transportation systems (ITS) are a critical element of such an approach. The ITS infrastructure aims at guiding driver decision-making by providing real-time information to inform travel decisions. DMS are generally used to display pertinent information to drivers. This includes communicating messages regarding operational issues such as current time travel and speeds, details of downstream incidents such as crashes or vehicle breakdowns, and the provision of advance warning, advisory, and alternative route messages. In recent years, transportation agencies have begun using DMS to communicate safety messages and crash facts, as shown in Figure 2.1. In 2013, the Michigan Department of Transportation (MDOT) initiated a campaign that has involved displaying the number of Michigan traffic fatalities to date on selected roadway DMS (ABC 10 News, 2013).

While numerous road safety campaigns have aimed to improve traffic safety, only a fraction of these initiatives is formally evaluated. This includes the use of DMS to display safety-related messages. Furthermore, the limited empirical studies that have been conducted in this area show contradictory findings, which are partially reflective of the difficulty in designing and evaluating such studies.

A study in Montana found that average speeds were reduced when slow down animal advisory signs were shown instead of standard travel time messages. Speeds were found to be higher when general transportation messages were displayed and the authors hypothesized that the general message was indicative of a default condition that did not require driver attention, while the display of a different message (i.e., safety message) calls for action to be taken (Hardy et al., 2006). Another study showed little change in mean speed in response to the display of safety messages, although the standard deviation in speeds was significantly reduced due to more uniform speeds (Tay & de Barros, 2010).

Figure 2.1 Example of Fixed Dynamic Message Signs in Michigan

Studies that evaluate message effectiveness often utilize survey or interview methods, such as focus groups. Research conducted to determine the comparative effectiveness of anti-speeding messages showed third-person effects; drivers believed that the safety messages were directed towards other drivers and not themselves (Glendon et al., 2018). In another study, survey respondents were found to have a higher recollection of safety messages compared to weather information, traffic information, and other messages on DMS. The findings in this study have provided some input into the types of messages that resonate with drivers based on locality (Tay & de Barros, 2008). Research has also shown that messages addressing safety issues specific to the community have been positive in making an impact on reducing road crashes compared to more general messaging (Elvik et al., 2009).

A Californian study examined the effect of DMS in displaying safety campaign messages through expert and industry interviews, driver focus groups, and telephone surveys, as well as through the analysis of speed data from highway loop detectors. Respondents indicated that familiarity with a message tended to reinforce positive safety effects. For example, messages that were widely recognizable from safety message campaigns, such as ‘Report Drunk Drivers, Call 911’, showed higher comprehension rates as compared to the catchier tagline of ‘Click It or Ticket’. Despite positive survey responses towards speed-related safety messages, the loop detector field data result shows no change in average driver speeds (Rodier et al., 2010). This is supported by research which indicated that there was a low correlation between self-reported behavior and actual behavior (Prince et al., 2008).

Most state transportation agencies have made use of displaying safety messages on DMS, although planning differs from state to state. Safety messages range from showing current traffic fatality statistics to witty messages such as, “DRINKING AND DRIVING IS PATH TO THE DARK SIDE.” Some agencies utilize the DMS for safety messages as part of a specific awareness campaign such as those in Delaware and Michigan, while others open up for public input on the type of message to be displayed (e.g., Massachusetts held a contest for most humorous safety message submitted) (Mitran et al., 2018).

Since 2012, Michigan has consistently used its DMS to display safety-related messages, including the number of traffic fatalities and other safety messages (e.g., speeding, drunk driving, and distracted driving). Yet, there is limited evidence as to the effectiveness of this initiative. This study addresses this gap in the research literature through an evaluation of the safety impacts of using DMS to display road safety messages. The scientific approach to investigating road safety campaigns can provide evidence-based results on the effects and usability of the intended safety message (Adamos & Nathanail, 2016).

2.2 Data Description and Data Collection Process

As a part of this study, a geospatial dataset was developed that involved the integration of data from various sources. This included historical information detailing the messages that have been displayed on DMS across Michigan, as well as crash, roadway, and traffic volume data for the MDOT-maintained highway network. Detailed information regarding each of these data sources, as well as the data integration process is presented in the following subsections.

2.2.1 Dynamic Message Sign Database

MDOT provided information on all messages displayed on DMS across Michigan. Data were obtained for the period between 2012 and 2018. Figure 2.2 shows the locations of DMS in Michigan based on MDOT region. As of 2018, there were 202 fixed DMS on freeway in the state, with the Metro region (including Detroit) recording the highest number (49 percent), followed by the University (15 percent) and Grand (14 percent) regions as shown in Figure 2.2.

The messages displayed on these DMS covered a wide range of traffic-related information. The majority of the time, the DMS are used to display current travel times to specific locations (e.g., cities, destinations). Occasionally, other types of messages are also displayed, including those related to incident management (e.g., crashes, vehicle breakdowns, wrong-way driver, etc.), adverse weather conditions (e.g., icy roads, snowstorms), America's Missing: Broadcast Emergency Response (AMBER) alerts, speed control (e.g., advisory speeds, variable speed limits), and safety messages.

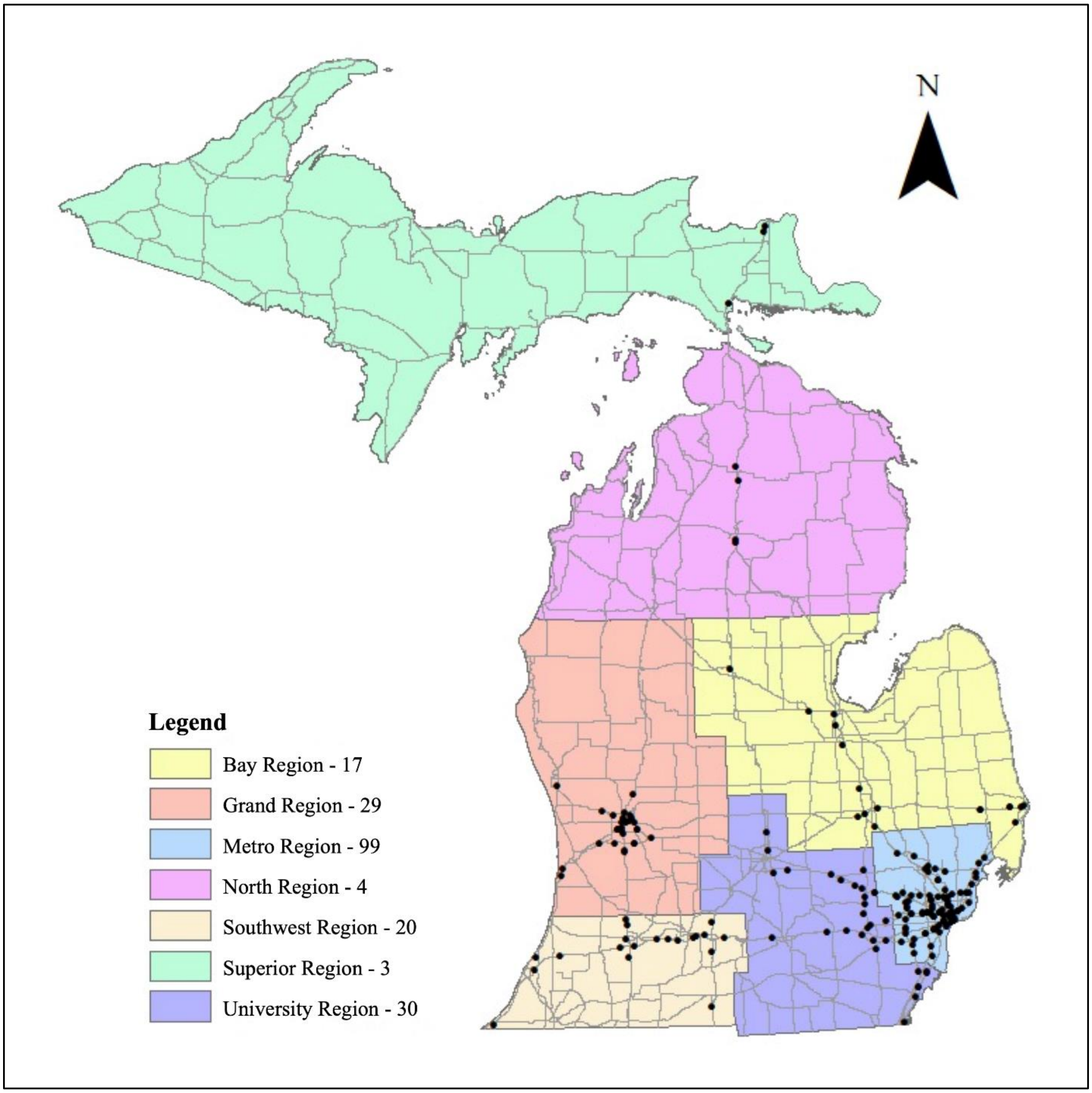


Figure 2.2 Number of Fixed Dynamic Message Signs by MDOT Region

All safety messages displayed on DMS in Michigan were categorized into two broad categories: (1) general safety messages and (2) site-specific safety messages. The general safety messages provided details of important traffic safety issues that do not relate to any specific location or event. These types of messages: (1) aim to increase awareness of traffic safety issues among drivers, (2) refer to safety-related laws and behaviors, or (3) encourage safe driving practices.

In contrast, site-specific safety messages are more targeted and aimed at improving driver awareness of important local conditions. Messages in this category are attributed to events such as a crash occurring at a downstream location, the presence of a work crew, and rare events such as the presence of wrong-way drivers in the area. Segregating site-specific messages is important as they may affect drivers differently than those in the general safety message category. The primary emphasis of this study was to evaluate the potential impacts of the general safety messages.

Approximately, 60 million messages were recorded to be sent to display on all DMS in Michigan from 2012 to 2018. In identifying messages related to safety, this study employed a keyword-searching method using R Studio version 1.4.1717 (the R-code is presented in the Appendix section) and Microsoft Excel 2016. After reviewing hundreds of messages, a series of keywords were selected that were common amongst those messages that were safety-focused. Among the general safety messages, 27 different keywords were utilized, including impaired, drunk, buzz, sober, seat belt, move-over, phone, text, among others. Additional keywords were used to classify the site-specific safety messages. Table 2.1 shows all keywords used to identify all safety messages for both categories.

After identifying all messages containing these keywords, a quality assurance review was conducted. This process was used to eliminate non-safety related messages that may have been inadvertently flagged by the same keywords, as well as to correct errors in the categorization of safety message (i.e., general versus site-specific).

Table 2.1 Keywords used to Identify Safety Messages

Message Types	Keywords
General Safety Messages	“young”, “impaired”, “seat belt”, “light”, “leaving lane”, “death”, “buzz”, “signal”, “work zone”, “tread”, “move over”, “motorcycle”, “drink”, “ice”, “phone”, “tailgate”, “drunk”, “school”, “ticket”, “fine”, “speeding”, “sober”, “buckle”, “text”, “deer”, “cyclist”, and “headlight”.
Site Specific Safety Messages	“crash”, “wrong way”, “ped”, “accident”, and “work crew”

For example, the keyword “ice” was chosen to identify messages like “ice and snow take it slow” or “use caution watch for ice on ramps and bridges”. However, this keyword will also flag non-safety related messages such as “amber alert 1998 purple Voyager MI license ABC1234” as this message contains the keyword “ice” in the word “license”. Consequently, these messages were manually removed from the data.

In other cases, some of the keywords used may have resulted in the safety messages being classified in the wrong category. For example, the keyword “crash” would yield site-specific safety messages such as “crash ahead on US-23 north after M-59 exit 67”. However, this keyword will also filter some general safety messages such as “texting and driving increases crash risk by 23 times”. In this case, these messages were manually reclassified into the correct category.

Table 2.2 provides examples of general safety messages that were displayed on DMS during 2018. For analysis purposes, these messages were classified into seven different groups: impaired driving, distracted driving, seat belt use, fatality statistics, work zone related, aggressive driving, and others.

Table 2.2 Example of General Safety Messages

Category	Message
Impaired Driving	Impaired driving 42% of traffic deaths in Northern Michigan Drive sober or get pulled over Buzzed driving is drunk driving don't do it Fans don't let fans drive drunk You drink & drive you lose Don't drink and drive Want to arrive? Don't drink and drive Don't drink and drive get a ride
Distracted Driving	Texting and driving increases crash risk by 23 times. Just drive, your phone can wait Stay alert. 63% of traffic death occur on dry roads A steering wheel is not a hands-free device Put your phone in park One text or call could wreck it all U text U drive U pay Don't text and drive. Drive with care
Seat Belt Use	Click it or ticket No seat belt, 32% of traffic deaths in Northern Michigan Buckle up every trip every time Buckle up. You've seen how other people drive
Fatality Statistics	152 traffic deaths to date. Down 34 from March 2017 91 traffic deaths to date. Up 24 over February 2017
Work Zone	Work zone safety is in your hands. Drive to zero crashes Work zone safety is everybody's responsibility Traffic fines are double in work zones
Aggressive Driving	Ice and snow don't cause crashes, drive too fast for conditions causes crashes Winter is here obey the basic speed law In ice and snow take it slow Avoid a crash don't tailgate Use caution watch for ice on ramps and bridges Stop speeding before it stops you Keep a safe following distance on ice & snow
Others	Deer crashes increase by 100% October-November Don't veer for deer Headlights on day and night Save a life look twice for motorcycle Heads up for cyclists Move over or slow down for emergency vehicles and tow trucks Use turn signal before changing lanes Lane departures. 76% of traffic deaths in northern Michigan Traffic crashes are leading cause of death for ages 15-24 Winter is here, check tires for sufficient tread

Table 2.3 provides a summary of the total number of messages (or DMS-days) per year that a safety message was displayed from 2012 through 2018. To clarify, these quantities represent the sum of the number of days that safety messages were displayed across all 202 fixed DMS throughout the state. Separate counts are provided for general and site-specific safety messages. For the general safety messages, these data show a persistent increasing trend in the number of messages displayed from 2012 to 2016. In 2017, the number dropped by more than 40 percent. One contributing factor towards this decrease was that until 2016, messages showing the number of traffic fatalities to date were displayed weekly on Wednesdays. However, starting in 2017, MDOT changed the frequency from four times a month to once a month

Table 2.3 Number of Unique Safety Messages Displayed, 2012-2018

Year	General Safety Message	Site-Specific Safety Message
2012	998	1,114
2013	3,320	2,930
2014	8,773	4,061
2015	14,125	4,864
2016	17,394	9,731
2017	8,826	6,742
2018	12,115	6,110

It should also be noted that when safety messages are combined with travel time messages, every time the travel time information is updated, its paired safety message is also refreshed, resulting in duplication of the same safety message. Consequently, the unique number of safety messages displayed by day was obtained by removing these duplicate messages from each DMS location. For the purposes of this study, the five most recent years of DMS message data were used, covering the period from 2014 through 2018.

2.2.2 Michigan State Police Crash Database

Crash data were obtained from the Michigan State Police for the same five-year period from 2014 to 2018. These data include detailed information at the crash-, vehicle-, and person-level for every police-reported crash that occurred in Michigan. The objective of this study was to explore the relationship between the annual number of crashes and the frequency in which safety messages were displayed. Consequently, data were collected for total crashes, as well as for two subsets of crashes that were frequent targets of safety messages. These included crashes occurring between 10:00 pm and 3:00 am and crashes due to speeds too fast for conditions. These two subsets were investigated to determine whether targeted messages focused on impaired driving and speeding/tailgating showed any relationship to the frequency of crashes due to such behaviors.

Crashes during the 10:00 pm-3:00 am time period were used instead of crashes coded as alcohol-involved given concerns as to underreporting of crashes. Data show that injury crashes involving alcohol are more prevalent during this period in Michigan (Michigan Traffic Crash Facts, n.d.). For crashes due to speed too high for road conditions, it is obtained from a standard field from a crash report form that describes any hazardous actions by the at-fault drivers. These actions include speed too fast for conditions, failed to yield, improper turn, etc.

Crash data were obtained for the segment immediately downstream of each DMS throughout the state. This allows for an explicit comparison as to trends in the number of crashes with respect to the frequency with which safety messages are displayed. If safety messages have a meaningful impact on driver behavior, crashes would be expected to occur less frequently at locations that display such messages more frequently. Further details are provided in the following section detailing data integration.

2.2.3 Roadway and Traffic Database

Roadway and traffic information was obtained from a roadway inventory file maintained by MDOT. The file consists of data for 122 attributes from all state-maintained roads in Michigan. The data is disaggregated into segments of varying lengths based upon where changes occur with respect to traffic volumes or key geometric characteristics (e.g., number of lanes, speed limits, lane and shoulder widths, pavement conditions, etc.). For the purposes of this study, short segments were aggregated, where possible. For each road segment, the pertinent information obtained from the inventory file included the segment length, annual average daily traffic (AADT), speed limit, number of lanes, lane width, shoulder widths, and median width.

2.2.4 Data Integration and Summary

Data from these three sources were integrated to create a segment-level dataset. As noted previously, the primary emphasis was on examining whether the annual number of crashes on a downstream segment was impacted by the frequency with which safety messages were displayed on a DMS immediately upstream of that segment. Here, the assumption is that drivers will have noticed and read the safety messages that are displayed, and in turn, this information may impact their driving behavior and resultant crash risk. Figure 2.3 shows the layout of road segments downstream of DMS.

After all segments were selected, roadway geometry, traffic volume, and crash information were integrated using unique route identifiers and mile point information that was common across these datasets. For each downstream segment, the DMS message database was used to calculate the number of days during each year that safety messages were displayed. This allows for an assessment as to whether increases or decreases in the number of messages displayed on a DMS impacts the frequency of crashes.

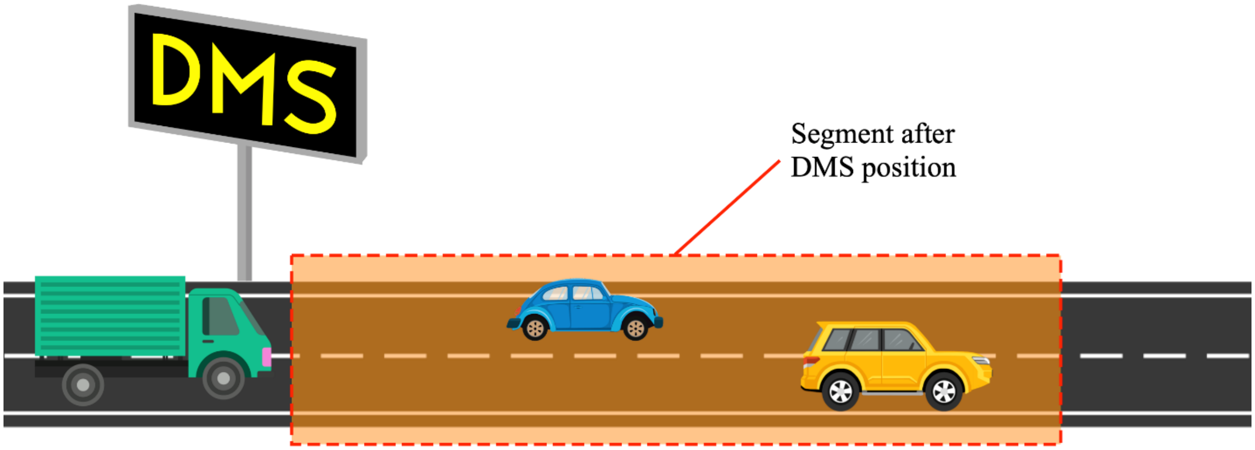


Figure 2.3 Layout of Downstream Segments near DMS

Table 2.4 provides descriptive statistics for the segments that were included in the final database. AADT values ranged from 2,469 to approximately 100,000 vehicles per day, with an average of 43,098. The vast majority of the DMS are located in urban areas, particularly the MDOT Metro region, which comprised 50 percent of the sample. The geometric characteristics were largely similar across the freeway network, with the exception of median width.

Table 2.4 also includes details as to the frequency with which various types of safety messages were displayed. On average, DMS displayed safety messages 61 days per year, with the number of messages ranging from 0 to 280 messages across the entire sample of devices. The rate at which specific types of safety messages were displayed was also tabulated for several of the more frequent types of messages. Messages related to speeding or tailgating messages were the most commonly used subset of messages. These messages were shown approximately 12 days per year on each DMS, up to a maximum of 132 days. Messages related to driver impairment and drunk driving were displayed five days per year per DMS on average.

Table 2.4 Descriptive Statistics

Variable	Min.	Max.	Mean	Std. Dev.
Segment Information				
Annual average daily traffic (veh/day)	2,469	98,359	43,098	23,884
Length (mi)	0.38	2.15	1.27	0.34
Speed limit: 55 – 65 mph (1 if yes; 0 otherwise)	0	1	0.16	0.37
Speed limit: 70 – 75 mph (1 if yes; 0 otherwise)	0	1	0.84	0.37
Number of lanes	2	6	2.86	0.85
Lane width (ft)	11	12	12.00	0.07
Median width (ft)	8	200	50.33	35.91
Right shoulder width (ft)	8	14	10.48	1.08
Left shoulder width (ft)	3	17	8.53	2.08
Michigan DOT Regional Information				
Metro (1 if yes; 0 otherwise)	0	1	0.50	0.50
Grand (1 if yes; 0 otherwise)	0	1	0.14	0.35
University (1 if yes; 0 otherwise)	0	1	0.14	0.35
Southwest (1 if yes; 0 otherwise)	0	1	0.10	0.30
Bay (1 if yes; 0 otherwise)	0	1	0.08	0.28
North (1 if yes; 0 otherwise)	0	1	0.02	0.14
Superior (1 if yes; 0 otherwise)	0	1	0.01	0.12
Number of days safety messages were displayed per DMS per year				
Total	0	280	60.63	45.95
Speeding/tailgating	0	132	12.10	14.83
Impaired/drunk driving	0	37	5.47	6.67
Crashes by type per year				
Total Crashes	0	142	27.68	26.06
Crashes due to speed too fast	0	50	6.04	5.95
Crashes between 10:00 PM and 3:00 AM	0	20	2.89	3.24

Note: Min. = minimum; Max. = maximum; Std. Dev. = standard deviation

Table 2.4 also provides details of the annual number of police-reported crashes that were observed on each segment. The total number of crashes per segment ranged from zero to nearly 150 per year, with an average of 27.7 crashes per segment per year. The average number of speeding related crashes was 6.0 per year while crashes between 10:00 pm and 3:00 am averaged 2.9 per year. Figures 2.4, 2.5, and 2.6 provide graphical representations of the relationships between crash rate per million vehicle mile travel (VMT) and the number of days that specific safety messages were displayed. There was no clear trend between total crashes and the total number of safety messages (of any type) displayed (Figure 2.4). However, for the two subsets of crashes (Figure 2.5 and 2.6), both plots show a general decrease in crashes as the frequency of safety messages is increased. This relationship appears to be stronger for nighttime crashes as compared to crashes where excess speed was an issue.

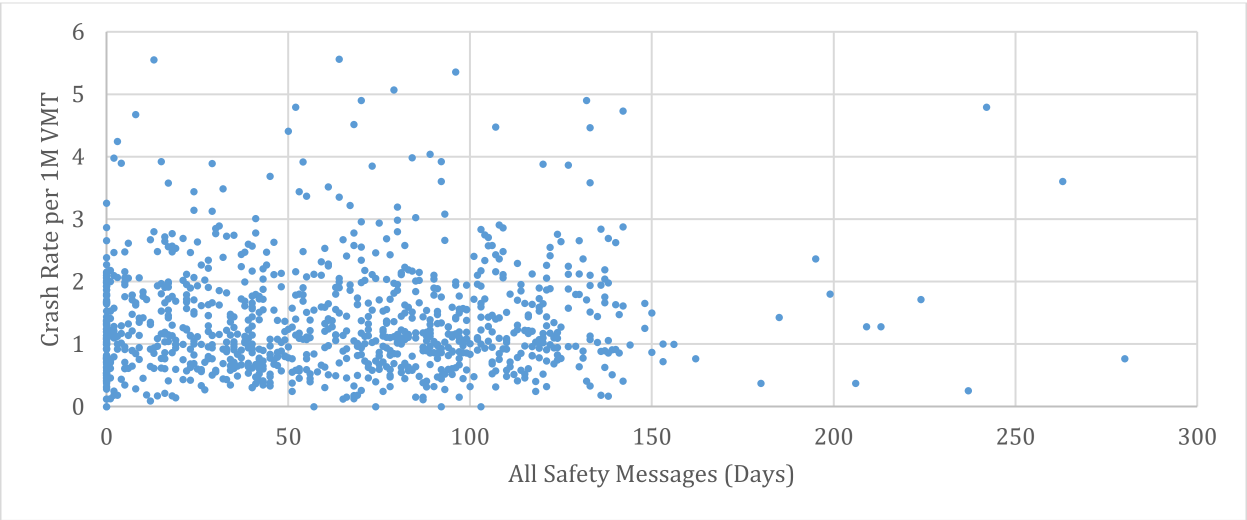


Figure 2.4 Total Crashes vs. Number of Days All Safety Messages were Displayed

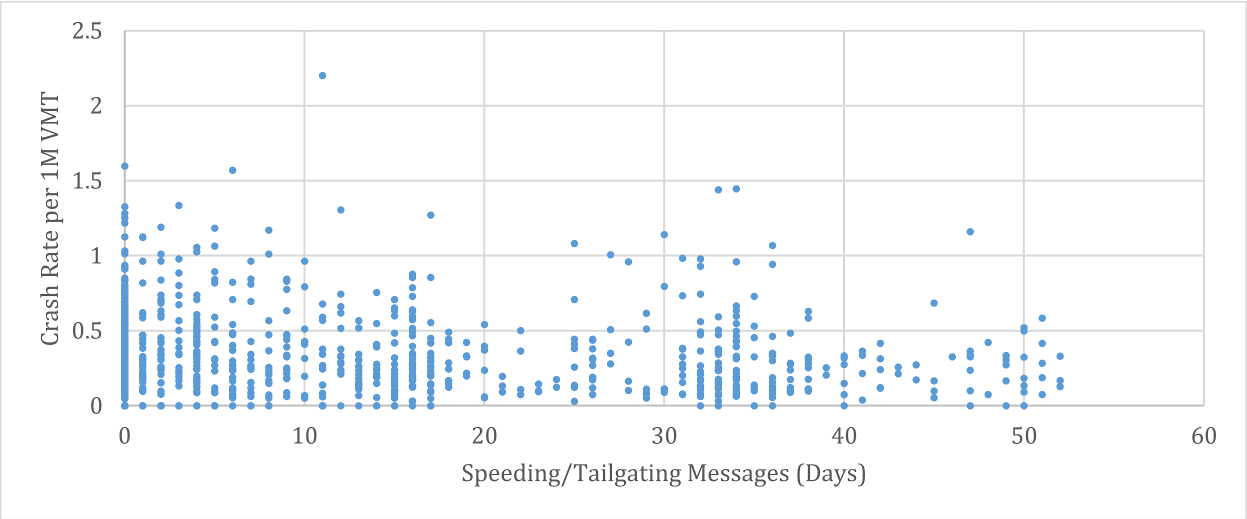


Figure 2.5 Speeding-Related Crashes vs. Number of Days Speeding/Tailgating Messages were Displayed

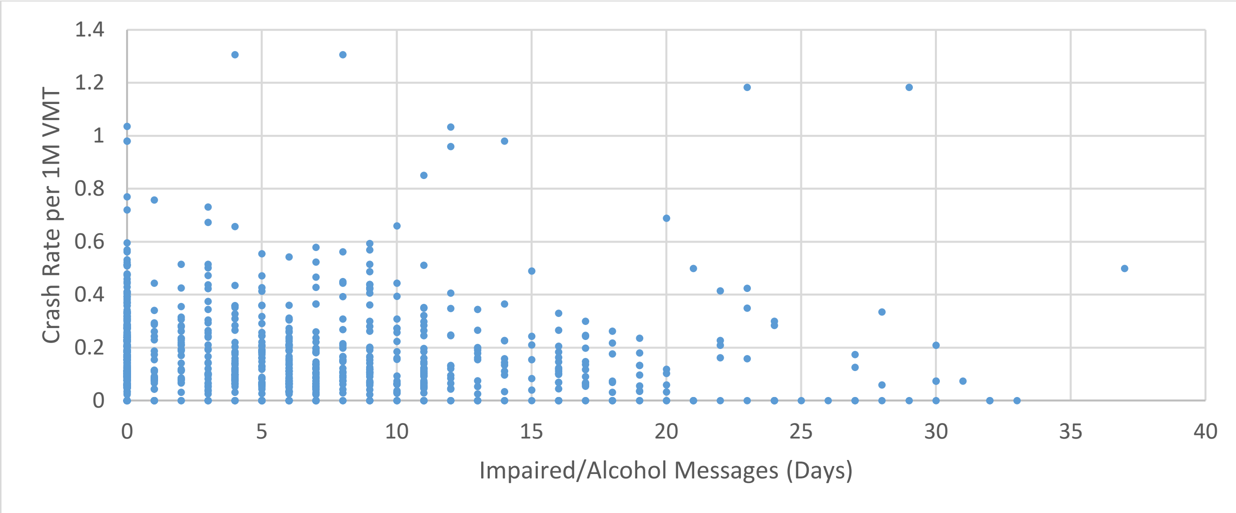


Figure 2.6 Crashes from 10 pm to 3 am vs. Number of Days Impaired Driving Messages were Displayed

2.3 Statistical Methods

To better understand the relationship between the frequency of traffic crashes and the number of times that safety messages were displayed on DMS, a series of regression models were estimated for total, speed too fast, and nighttime crashes. As the annual numbers of crashes on specific road segment are comprised of discrete and non-negative integers, negative binomial regression models have emerged as a preferred statistical method for the analysis of crash data. Within the context of this study, the probability of segment i experiencing y_i crashes during a specific year of the analysis period can be calculated as shown in Equation 2.1:

$$P(y_i) = \frac{\Gamma((1/\alpha)+y_i)}{\Gamma(1/\alpha)y_i!}\left(\frac{1/\alpha}{(1/\alpha)+\lambda_i}\right)^{1/\alpha}\left(\frac{\lambda_i}{(1/\alpha)+\lambda_i}\right)^{y_i} \tag{2.1}$$

where Γ(.) is a gamma function, α is an overdispersion parameter, and λ_i is equal to the expected number of crashes on segment i. The λ_i parameter is related to a series of site-specific characteristics as shown in Equation 2.2:

$$\lambda_i = EXP(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k + \varepsilon_i) \tag{2.2}$$

where X_1 to X_k are a series of independent variables (e.g., traffic volumes, geometric characteristics, the number of safety messages displayed), β_1 to β_k are a series of parameters estimated from the regression model, and EXP(ε_i) is a gamma-distributed error term with mean equal to one and variance of α.

Within the context of this study, a random parameters framework is introduced in order to account for unobserved heterogeneity. Given the fact that each site is observed five times (once per year from 2014 to 2018), this may introduce correlation in the crash counts within the individual sites over time as individual sites are likely to experience more (or less) crashes than other similar segments due to important site-specific factors that are not included in the model. This may potentially lead to biased, inefficient, or inconsistent parameter estimates. In the random parameters negative binomial model, the constant term and the parameter estimates of independent variables are allowed to vary across locations, as shown in Equation 2.3:

$$\beta_i = \beta + \varphi_i, \qquad (2.3)$$

where φ_i is a randomly distributed error term with mean zero and variance σ^2. This error term takes the same value for an individual site over each year of the study period and is allowed to vary across sites. The expected crash count from Equation 2.2 is then conditional on the distribution of φ_i. This results in the following log-likelihood function:

$$LL = \sum_{\forall i} ln \int_{\varphi_i} g(\varphi_i) P(n_i|\varphi_i)\, d\varphi_i, \qquad (2.4)$$

where g(·) refers to the probability density function of φ_i. Estimation is conducted by simulated maximum likelihood and 200 Halton draws are used as a more efficient alternative for numerical integration than random draws.

2.4 Results and Discussion

This section presents the results of three random parameters negative binomial models that were estimated to investigate the relationship between crashes and the frequency in which safety messages are displayed. Each model includes a variable that specifies the percentage of days per year that safety messages were displayed on a DMS while controlling for other variables of interest. These variables include AADT, segment length, median width, and shoulder widths.

For each model, parameter estimates are presented, along with the standard errors, t-statistic, and p-value. When interpreting the results from each model, a positive parameter estimate indicates that crashes increase as the independent variable is increased. The converse is true for negative parameter estimates. In general, random parameters are estimated if the standard deviation of the parameter estimates are statistically significant; otherwise, the parameters will be fixed across the population. Table 2.5 presents the results for total crashes with respect to any type of safety messages.

Table 2.5 Model Results for Total Crashes

Variable	Estimate	SE	*t*-Value	*p*-Value
Intercept	-8.063	0.253	-31.910	<0.001
Standard deviation	0.275	0.010	27.31	<0.001
LN (AADT)	1.146	0.020	56.100	<0.001
LN (Segment length, mile)	0.652	0.037	17.610	<0.001
Standard deviation	0.319	0.029	10.940	<0.001
Percent of days with any type of safety message	0.0003	0.001	0.340	0.732
Median width (ft)	-0.002	0.000	-6.160	<0.001
Standard deviation	0.003	0.000	14.900	<0.001
Right shoulder width (ft)	-0.046	0.011	-4.350	<0.001
Left shoulder width (ft)	-0.064	0.005	29.030	<0.001
Standard deviation	0.033	0.001	29.030	<0.001
Overdispersion parameter	0.042	0.003	14.000	<0.001

Note: LN = natural logarithm; AADT = average annual daily traffic; SE = standard error

Four variables including the intercept were found to be random parameters, and three variables, AADT, percentage of days on which messages were displayed, and right shoulder width were fixed across the population. The results from Table 2.5 show that the frequency of DMS safety messages has virtually no relationship with the total number of crashes (p-value = 0.732).

Several of the geometric characteristics were shown to have a strong relationship with crash frequency. Crashes were found to be virtually elastic with respect to traffic volumes (i.e., a one-percent increase in volume resulted in a one-percent increase in crashes) and crashes were reduced as the median or shoulder widths were increased. While the effects of these variables tended to vary from segment to segment (as reflected by the standard deviation parameters), roads with wider lanes, shoulders, and medians tended to experience fewer crashes in the vast majority of instances.

It should be noted that this initial analysis considered safety messages of any type, including general information (e.g., fatalities to date), as well as more targeted, behavior-specific messages (e.g., distracted driving, drinking and driving, speeding and tailgating). As many of these types of messages are somewhat ambiguous and do not target specific problem behaviors of interest, a series of subsequent analyses narrowed in on two behaviorally-focused types of messages to see if any trends emerged within specific subsets of crashes. Table 2.6 displays the model results for crashes occurring between 10:00 pm and 3:00 am as a function of alcohol/impaired driving related messages.

All variables were found to be random parameters except for median width and right shoulder width. The results from Table 2.6 show that crashes tend to decrease as the frequency of messages increases. However, this mean effect was not statistically significant (p-value = 0.329) but was shown to vary substantially from location to location based on the standard deviation (p-value < 0.001). The effects of the other variables tended to be relatively consistent to the results for total crashes, though in this case, the effects of median width and right shoulder width tended to be homogeneous across segments.

Table 2.6 Model Results for Nighttime Crashes

Variable	Estimate	SE	*t*-Value	*p*-Value
Intercept	-7.528	0.580	-12.980	<0.001
Standard deviation	0.368	0.023	16.340	<0.001
LN (AADT)	0.904	0.048	18.970	<0.001
Standard deviation	0.005	0.002	2.650	0.008
LN (Segment length, mile)	0.463	0.080	5.770	<0.001
Standard deviation	0.315	0.066	4.810	<0.001
Percent of days with alcohol/impaired messages	-0.013	0.014	-0.980	0.329
Standard deviation	0.040	0.010	4.190	<0.001
Median width (ft)	-0.002	0.001	-1.710	0.087
Right shoulder width (ft)	-0.039	0.025	-1.570	0.116
Left shoulder width (ft)	-0.091	0.011	-7.960	<0.001
Standard deviation	0.025	0.003	9.360	<0.001
Overdispersion parameter	0.082	0.020	4.100	<0.001

Note: LN = natural logarithm; AADT = average annual daily traffic; SE = standard error

Lastly, Table 2.7 presents results for crashes where the driver was speeding or otherwise traveling too fast for conditions as determined using standard fields on the police crash report form. Interestingly, analysis of these data showed that crashes decrease significantly based upon the frequency with which speeding and tailgating related messages are displayed. A one percent increase in the frequency of message display is associated with an average decrease of 1.5 percent in these types of crashes. It should be noted that speed limit increases occurred on more than 600 miles of rural freeway during calendar year 2017. Most of these increases occurred outside of the study area, but it is possible that associated enforcement and education/outreach campaigns may have had some effect. The effects of other variables (e.g., traffic volumes, segment length, median width, shoulder width) remain similar as compared to prior analyses.

Table 2.7 Model Results for Crashes due to Speed too Fast

Variable	Estimate	SE	*t*-Value	*p*-Value
Intercept	-7.650	0.473	-16.160	<0.001
Standard deviation	0.106	0.017	6.170	<0.001
LN (AADT)	0.942	0.040	23.740	<0.001
Standard deviation	0.009	0.002	5.910	<0.001
LN (Segment length, mile)	0.765	0.067	11.390	<0.001
Standard deviation	0.314	0.050	6.280	<0.001
Percent of days with speeding/tailgating messages	-0.015	0.005	-3.080	0.002
Standard deviation	0.028	0.003	8.980	<0.001
Median width (ft)	-0.013	0.001	-1.960	0.050
Standard deviation	0.003	0.000	8.650	<0.001
Right shoulder width (ft)	-0.055	0.019	-2.980	0.003
Standard deviation	0.022	0.002	13.370	<0.001
Left shoulder width (ft)	-0.021	0.009	-2.290	0.022
Standard deviation	0.046	0.002	21.860	<0.001
Over dispersion parameter	0.090	0.011	8.182	<0.001

Note: LN = natural logarithm; AADT = average annual daily traffic; SE = standard error

2.5 Summary

This study evaluates the relationship between the number of crashes and the frequency in which safety messages were displayed on DMS using a random parameter negative binomial regression model. Three different crash models (total crashes, nighttime crashes, and speeding-related crashes) were estimated with respect to the type of messages displayed. The results showed that in general, safety messages did not show any meaningful differences in terms of total crashes. Note that, this model includes all types of safety messages (e.g., statistics on traffic fatality). However, when specific types of messages were evaluated in relation to the pertinent crash type, clear trends were observed. Nighttime crashes decreased marginally as the frequency of alcohol and impaired driving messages increased. The most pronounced effects were related to speed-related crashes where statistically significant reductions were observed when the frequency in which speeding-related messages is increased.

The subsets of the safety messages tested in this study are commonly associated with traffic safety campaigns (e.g., “Drive Sober or Get Pulled Over” campaign, anti-speeding campaign). The recent memorandum from the FHWA stated that the use of DMS for displaying safety messages should be associated with traffic safety campaigns only (e.g., drunk driving, distracted driving, seatbelt use, etc.) (Kehrli, 2021). The memo also stated that, safety messages should not be displayed continuously and frequently. Thus, the findings from this study largely reinforce the FHWA memorandum.

CHAPTER 3: SAFETY EVALUATION OF FREEWAY EXIT RAMPS WITH ADVISORY SPEED REDUCTIONS

3.1 Background

Posted speed limits are used to notify drivers of the legal maximum allowable speeds in consideration of traffic, road, and weather conditions. Since the repeal of the 55-mph National Maximum Speed Limit in 1995, states regain complete authority in setting the maximum speed limits. Subsequently, most of these states have raised their regulatory speed limits to 70 mph or more on interstate highways, including Michigan. In 2017, Michigan increased the statutory speed limits from 70 to 75 mph on more than 600 miles of limited access freeways. As a result of these increases, concerns have arisen regarding potential impacts on traffic safety and operation. Studies have shown speed limit increase to result in increases in average speeds (Freedman & Esterlitz, 1990; Jernigan et al., 1994; Ossiander & Cummings, 2002) and traffic fatalities (Garber & Graham, 1990; Grabowski & Morrisey, 2007). Thus, concerns are heightened at roadway locations that include multiple speed zones, particularly in the interchange influence area where the mainline speed often differs from the advisory speeds for the exit and entrance ramps.

Interchanges are a critical component of the transportation network, providing access to adjacent lands or roads. Poorly designed interchanges can create negative impacts on safety and operations, as well as the environment. The design of exit ramps is an essential aspect of the interchange system. Inadequate deceleration lane lengths or insufficient warning to drivers (e.g., advisory speed sign) at exit ramps can introduce safety problems. According to the Fatality Analysis Reporting System (FARS) database, 2,994 fatal crashes were recorded between 2012 and 2016 at exit and entrance ramps; an average of 599 fatal crashes occurring every year throughout the United States (National Highway Traffic Safety Administration, 2020). In Michigan, 39,276 crashes were recorded at these locations during the same period, including 89 fatal crashes (Michigan Traffic Crash Facts, n.d.).

Given space and economic constraints, many exit ramps require drivers to rapidly adjust their speeds while exiting the freeway mainline. In such instances, advisory speed signs are frequently utilized to alert drivers of impending speed reductions. However, these signs are non-regulatory in nature and essentially serve as recommendations for drivers of safe travel speeds when traversing the ramps. Studies have shown that when advisory speed signs are present on high-risk roads (e.g., exit ramp, sharp curve, work zone) drivers tend to estimate their travel speeds better and, consequently, demonstrate safer driving behavior (Edara et al., 2016; King et al., 2004; Ma et al., 2013; Milošević & Milić, 1990).

With the recent increases in the speed limit on selected freeways in Michigan, concerns have arisen related to the large speed reductions required at various exit ramps throughout the state. Research has shown speed differentials to increase during curve navigation when the speed on the preceding tangent increases (Misaghi & Hassan, 2005). Poor transitions from higher speed to lower speed road segments may create safety concerns as abrupt changes in travel speeds when exiting the freeway can lead to rear-end crashes. Moreover, if drivers do not adjust their speed accordingly when entering and traversing the exit ramp with sharp horizontal curvature, the likelihood of lane departure crashes may increase. Based upon the aforementioned Michigan data, about 32 percent of crashes between 2012 and 2016 at entry and exit ramps involved lane departure crashes (Michigan Traffic Crash Facts, n.d.).

The primary objective of this study is to investigate the safety implications of speed differentials that are introduced between mainline speed limits and exit ramp advisory speeds. A series of safety performance functions (SPF) was estimated to assess this relationship. These SPFs are used to examine how the average annual number of crashes at exit ramps varies as a function of exposure (e.g., annual average daily traffic and segment length) and roadway characteristics such as lane width and road curvature (National Research Council, 2010). The study focuses on all exit ramps with sharp horizontal curvature and the presence of advisory speed sign. A total of 187 exit ramps were selected across Michigan and included in the analysis. Additionally, apart from traffic volume, various characteristics of the roadway, which are a function of the mainline speed limit (e.g., deceleration lane length: higher speed on the mainline will require longer deceleration lane length), were also investigated. Understanding the relationships between speed selection and crash risk at exit ramp is an important concern given continuing discussions around speed limit policies across the United States.

3.2 Literature Review and Problem Statements

Safety is a particular concern in the vicinity of interchanges as these locations are often associated with high crash rates due to several factors, such as weaving and variability in travel speeds. A particular concern is the differential created by vehicles exiting or entering the freeway. Previous studies have shown that a substantial amount of freeway-related crashes occur within this interchange influence area (Khorashadi, 1998; Torbic et al., 2009). One of the strategies to mitigate crashes at exit ramps is through the installation of advisory speed signs.

A Florida study examined 98 entry and exit ramps on a 25-mile stretch of interstate highway to evaluate the relationship between crashes, traffic volumes, and ramp characteristics, including the presence of advisory speed signs. Four different ramp configurations were investigated (diamond, loop, outer connection, and direct/semi-direct ramps) to discern differences in safety performance between these configurations. The study estimated a series of regression models, which showed that crash rates decreased at exit ramps when advisory speed signs were present. Additionally, the study found that crashes were more likely to occur on curved ramps than ramps with straight segments (Lee & Abdel-Aty, 2009). Similar findings were reported from a study investigating the safety impact of dual-advisory speed signs on freeway-to-freeway connectors, where crashes due to speeding decreased significantly after the sign were installed (Voigt et al., 2008).

The presence of advisory speed signs has been shown to improve traffic safety on freeway ramps. However, the recent increase in regulatory speed limit to 75 mph on 600 miles of freeway in Michigan raises concerns on traffic safety and operations at these locations. Since the repeal of the 1974 NMSL, majority of the studies found that crash frequency and the number of fatalities increased as a result of speed limit increase (Dissanayake & Shirazenijad, 2018; Friedman et al., 2009; Himes et al., 2018; Malyshkina & Mannering, 2008; Warner et al., 2019). Traffic safety is impacted not just on roadways where the speed limit is increased but was also seen to influence, either adjacent facilities or even systemwide (Grabowski & Morrisey, 2007; Hu, 2017).

Various studies have assessed the systemwide impact of speed limit increase. This includes a series of studies that have examined the impacts of higher rural interstates speed limits following large-scale speed-limit increases. For example, one study showed that the repeal of the NMSL was associated with a 36 percent increase in overall fatalities. The effect of the increase of rural interstate speed limit was found to influence increase in fatalities on rural interstate facilities as well as statewide facilities for speed limit of 70 mph across all age groups (Grabowski & Morrisey, 2007). A study in Utah examined the impact of raising the regulatory speed limit on rural interstate from 75 to 80 mph on speed variables (Hu, 2017). The study analyzed the effects of speed limit changes on vehicle speeds and speed variance using log-linear models. The results showed that speed variance was 29 percent higher in 80 mph speed zones and 9 percent higher in spillover zones compared to locations where the speed limit was not increased.

Research has been more limited as to the impacts of speed limits and speed limit increases at a more microscopic level, such as the case of freeway exit ramps. Thus, the evaluation of exit ramps is necessary to better understand the safety impact of speed differential between ramp advisory speed and mainline speed limit.

3.3 Data Description and Data Collection Process

The primary objective of this study is to assess the safety impacts of speed differential at freeway exit ramps using the difference between mainline speed limit and exit ramp advisory speed. This study examines Michigan crash data from two different periods, 2014-2016 and 2018-2019. The crash data from 2017 were removed from the analysis due to the speed limit increase from 70 to 75 mph that occurred on more than 600 miles of rural freeways. A total of 187 exit ramps were evaluated which comprises of 30 ramps that are located where the mainline experienced the speed limit increase, and 157 ramps that are located on mainline segments with no changes in the speed limits. The following subsections explain details on the criteria of site selection, as well as the description of each pertinent data source that was used in the analysis.

3.3.1 Site Selection

In this study, there are several criteria that were used for selecting the final sites. First, exit ramps were selected with the consideration of the presence of advisory speed signs at the sites. This is to ensure for the availability of information to calculate the speed differential for each ramp. Second, only exit ramps with advisory speed of 45 mph or less were retained for further analysis. Third, only exit ramps with point of curvature as the controlling feature were included in the final dataset. There are several diamond-type exit ramps (i.e., straight ramps) in Detroit area that had advisory speed signs. However, these signs were placed not due to the horizontal curvature of the ramp, but rather due to limited sight distance available (i.e., vertical curvature). It is expected that the impact of speed differential on these ramps may be different than those targeted ramps. Fourth, only service interchanges were selected in this study. The effect of speed differential on service ramps is expected to be greater between the transitions of roadways of differing speed limit (i.e., freeways to minor arterial roads) than those of the same hierarchy such as freeway to freeway. The fifth and final factor in selecting the site is regarding the number of lanes. Only one-lane exit ramps were considered in the final evaluation.

3.3.2 Data Sources

Different data sources were utilized to understand the safety impact of speed differential at freeway exit ramps in Michigan. Three sources of data were identified and used in this study, which include:

1. Michigan State Police (MSP) crash database
2. MDOT Traffic Data Management System (TDMS)
3. Manual data collection through satellite imagery using Google Earth Pro version 7.3.

These three data sources were combined and integrated into one coherent format using both ArcGIS Desktop version 10.6 (e.g., for spatial joining the traffic data with the ramp segments) and Microsoft Excel 2016 (e.g., for integrating the crash data to the ramp segments). The following subsections provide detailed explanation of each data source.

3.3.2.1 Michigan State Police Crash Database

In Michigan, a traffic crash must be reported when it involves with at least a property damage of $1,000. The reported crash data is maintained by the MSP, and it provides details on each crash which included different levels of crash information: crash-level (e.g., crash severity, time of the crash, weather conditions, contributing circumstances, etc.), vehicle-level (i.e., details associated with each involved vehicle such as vehicle type, direction of travel prior to the crash, etc.), person-level (i.e., attributes pertaining to each individual that involve in a crash such as gander, age, sitting position during the crash, injury-level, etc.).

As previously mentioned, five-year period of crash data were analyzed in this study. Two types of crashes were identified as target crashes, which included total crashes and lane departure crashes. The lane departure crashes were identified based on an attribute from the MSP crash report form (or also known as UD-10 report). This attribute defines lane departure crashes as three different types: (1) single vehicle; (2) two or more vehicles traversing the road; and (3) involvement with parked vehicles. For the purpose of this study, only crashes that involved single- and multiple-vehicle (i.e., category 1 and 2) were included in the analysis. One primary reason that category 3 was not included is because the analyzed segments were the ramp proper, which is unlikely for a vehicle to be parked on this facility.

3.3.2.2 Transportation Data Management System

Traffic data was obtained from Transportation Data Management System (TMDS) website maintained by MDOT as shown in Figure 3.1. MDOT collects and analyzes traffic data for more than 36,000 miles of federal roadways, while local agencies assist MDOT to collect traffic information on non-federal aid roadways. There are two primary methods used by MDOT to collect traffic data which are short counts and continuous counts. For short counts, traffic data is generally collected over a period of 48 hours. This method is known to be the most common method due to easy setup process of the equipment and lower maintenance costs. While for continuous counts, it involves traffic counts for 24 hours per day, for the whole year.

The AADT is estimated based on the average daily traffic volume collected. For continuous counts, it is estimated by summing the number of traffic passing a given point for the whole year divided by the number of days in that year. Whereas for short counts, it is estimated by multiplying the traffic counts with several adjustment factors. These adjustments factors (e.g., seasonal, peak-hour, and day-of-week factors) are obtained based on the data from continuous counts.

In this study, the cash data were analyzed dating back to 2014. However, the AADT data from this website is only available starting 2015. The 2014 AADT was estimated through linear extrapolation based upon years over which such data were available.

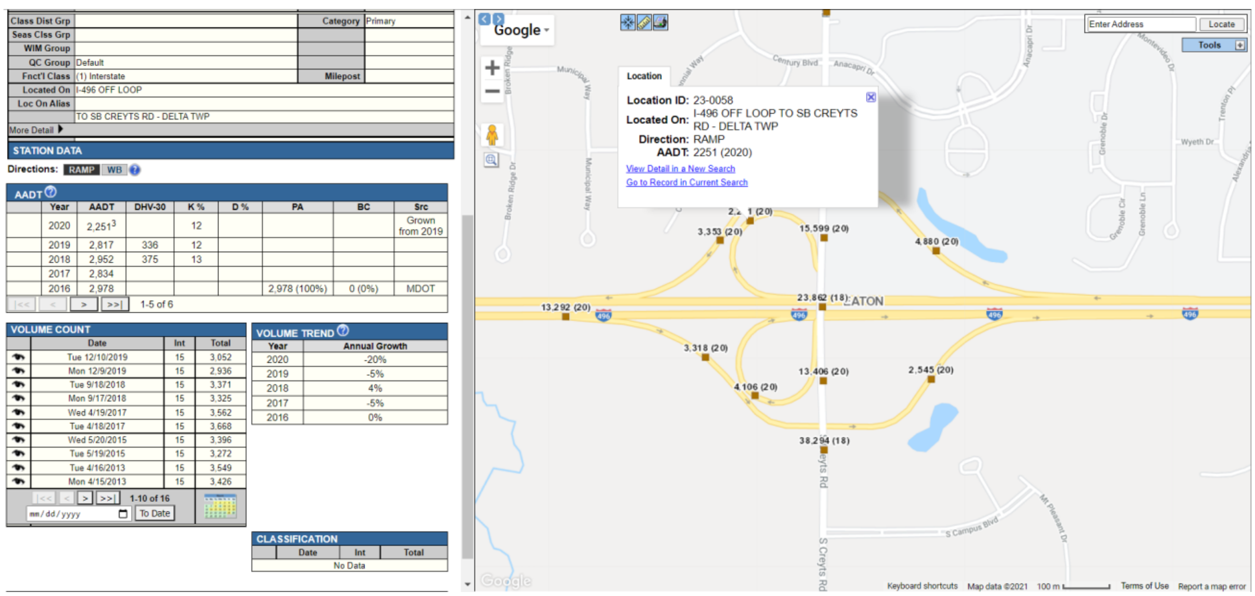


Figure 3.1 Screenshot of TDMS Website

3.3.2.3 Manual Data Collection

Due to the constraint of available information on the characteristics of exit ramps in state-maintained roadway inventory databases, a significant amount of manual data collection was performed using Google Earth Pro version 7.3 (e.g., through satellite imagery and street view). The data collected through this process included signage information (e.g., exit ramp advisory speeds and mainline speed limits), and geometric characteristics such as ramp lengths, taper lengths, deceleration lane length (Figure 3.2), lane configurations (Figure 3.3), ramp configurations, curve radii (Figure 3.4), degree of curvature, lane widths (Figure 3.5), shoulder widths, and grade (e.g., upgrade or downgrade). The measurement for deceleration lane length was based on the guideline from American Association of State Highway and Transportation Officials (AASHTO) Green Book, "A Policy on Geometric Design of Highway and Streets" (American Association of State Highway and Transportation Officials, 2018). Figure 3.2 shows the breakdown when measuring the deceleration lane length. The alphabets in the figure represent:

- A = taper length, measured from the start of the deceleration lane to a distance where the deceleration lane's width is at least 12 ft.
- B = length from which the width of the deceleration lane length achieves 12 ft. to the painted nose area
- C = length from the painted nose to the physical gore area (often time the physical gore area is located at the same location as the point of curvature)
- D = length from the physical gore area to the controlling feature of the ramp. This feature can be either the first point of curvature on the ramp (for loop ramp) or the crossroad terminal (for diamond/straight ramp)

When calculating the deceleration lane length, length B, C, and D were used. According to the AASHTO Green Book, the speed change lane for exit ramp can be extended beyond the horizontal curvature of the ramp, as long as the curve radius is greater than 1,000 ft.

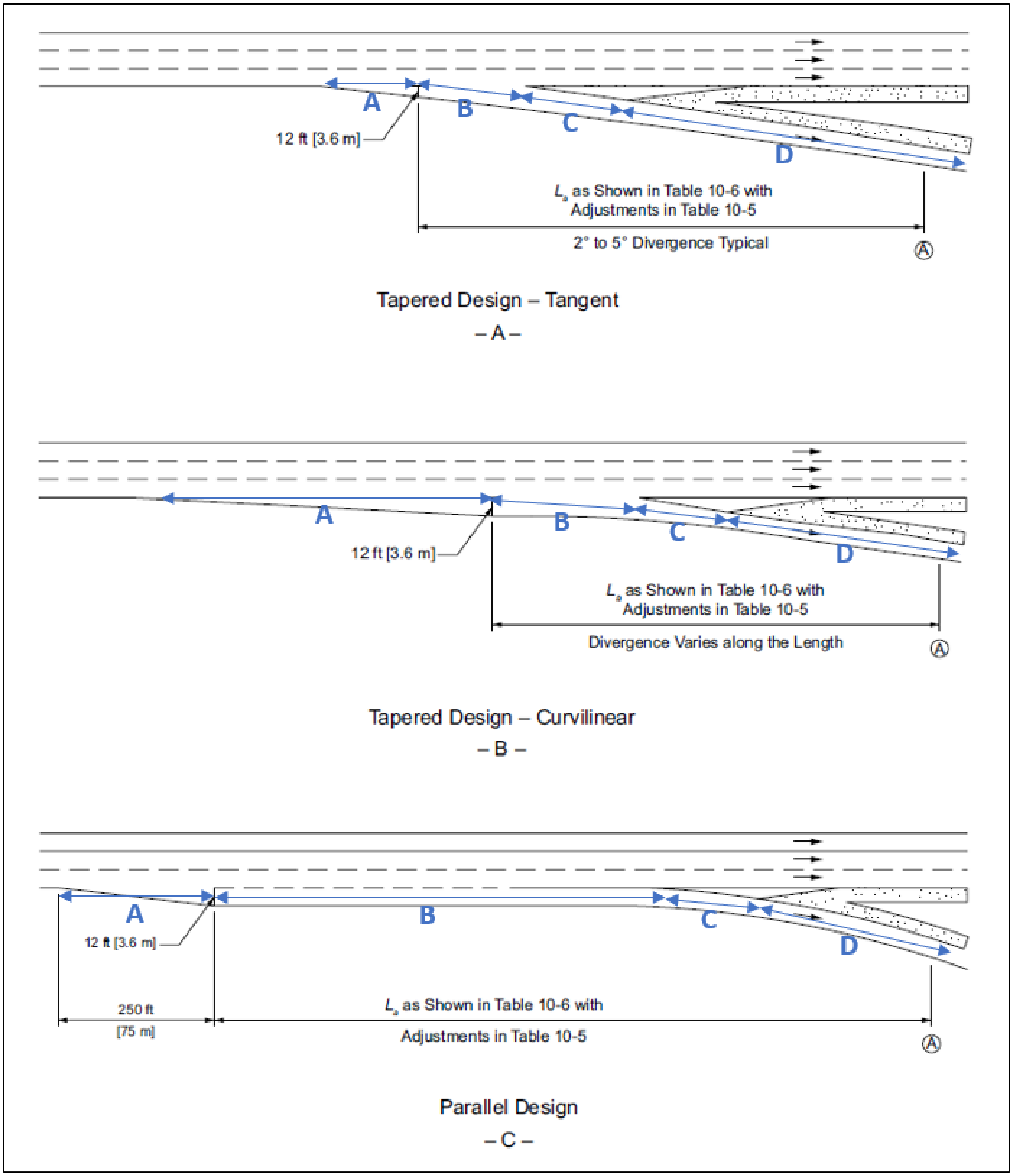


Figure 3.2 Deceleration Lane Length Measurement from AASHTO Green Book (American Association of State Highway and Transportation Officials, 2018)

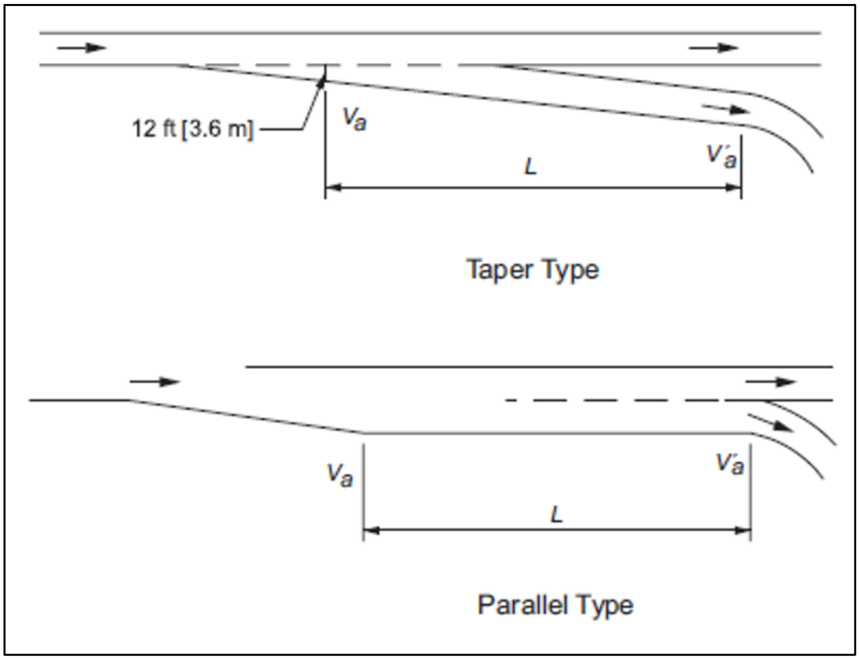


Figure 3.3 Lane Configuration from AASHTO Green Book (American Association of State Highway and Transportation Officials, 2018)

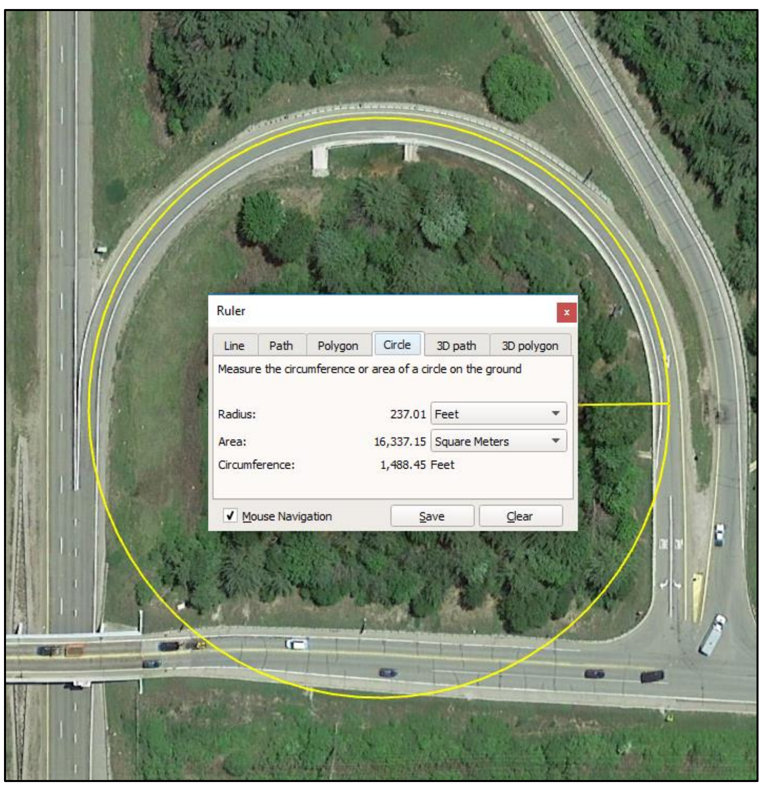


Figure 3.4 Ruler Tool from Google Earth Pro for Curve Radius Measurement

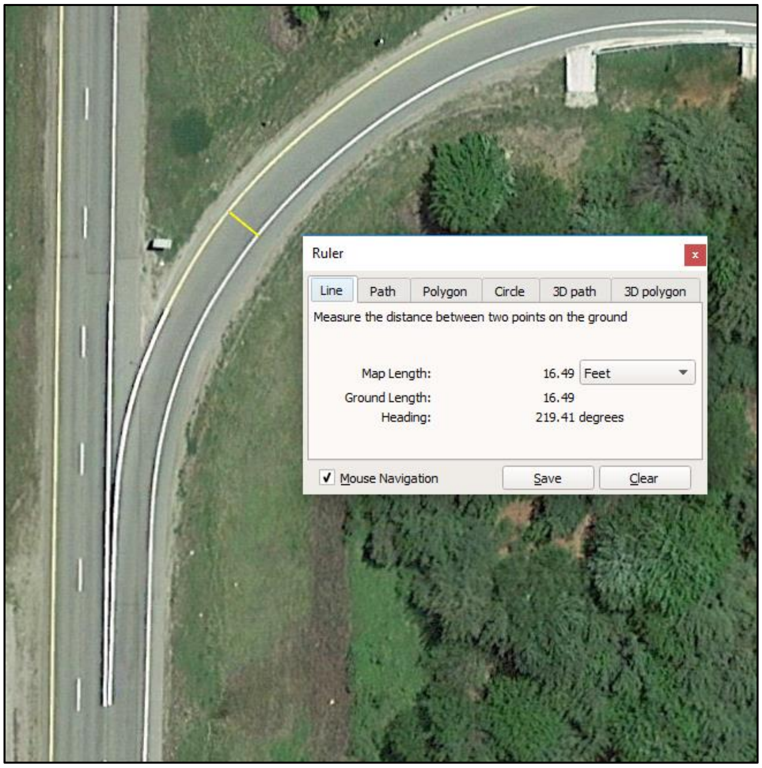


Figure 3.5 Ruler Tool from Google Earth Pro for Lane Width Measurement

In addition to the site measurement for deceleration lane length, the minimum recommendation length from AASHTO Green Book was also identified for each ramp. Figure 3.6 shows the minimum length required for speed change lanes for exit terminal based on the freeway design speed and the design speed of the controlling feature (point of curvature). In this study, the speed limits and curve advisory speeds were used to estimate the design speeds of freeway and the controlling feature of ramp, respectively. Using the historical practices by transportation agencies, a 10 mph was added to the speed limit and curve advisory speed for design speed estimations. Additionally, further investigation was performed with the assumption of design speed is equal to the speed limit or advisory speed, as well as 5 mph above. However, the findings showed consistent results across these scenarios. When determining the minimum length required, the grade was assumed to be less than three percent.

Table 10-6. Minimum Deceleration Lane Lengths for Exit Terminals with Flat Grades of Less Than 3 Percent

U.S. Customary										
Deceleration Lane Length, L_a (ft) for Design Speed of Controlling Feature on Ramp, V' (mph)										
Highway Design Speed, V (mph)	Diverge Speed, V_a (mph)	Stop Condition	15	20	25	30	35	40	45	50
		Average Running Speed at Controlling Feature on Ramp, V'_a (mph)								
		0	14	18	22	26	30	36	40	44
30	28	235	200	170	140	—	—	—	—	—
35	32	280	250	210	185	150	—	—	—	—
40	36	320	295	265	235	185	155	—	—	—
45	40	385	350	325	295	250	220	—	—	—
50	44	435	405	385	355	315	285	225	175	—
55	48	480	455	440	410	380	350	285	235	—
60	52	530	500	480	460	430	405	350	300	240
65	55	570	540	520	500	470	440	390	340	280
70	58	615	590	570	550	520	490	440	390	340
75	61	660	635	620	600	575	535	490	440	390
80	64	705	680	665	645	620	580	535	490	440

V = design speed of highway (mph)
V_a = average running speed on highway (i.e., diverge speed) (mph)
V' = design speed of controlling feature on ramp (mph)
V'_a = average running speed at controlling feature on ramp (mph)
L_a = deceleration lane length (ft)

Figure 3.6 Screenshot from AASHTO Green Book 2018 on the Minimum Deceleration Lane Length for Exit Ramp with Flat Grades of Less Than 3 Percent (American Association of State Highway and Transportation Officials, 2018)

Moreover, this study also collected information on ramp configurations. Figure 3.7 shows examples of ramp configurations based on a study that was conducted in 1997 (Bauer & Harwood, 1997). There are three common types of ramp configurations that can be found in Michigan, which include diamond, partial cloverleaf loop, and free-flow loop.

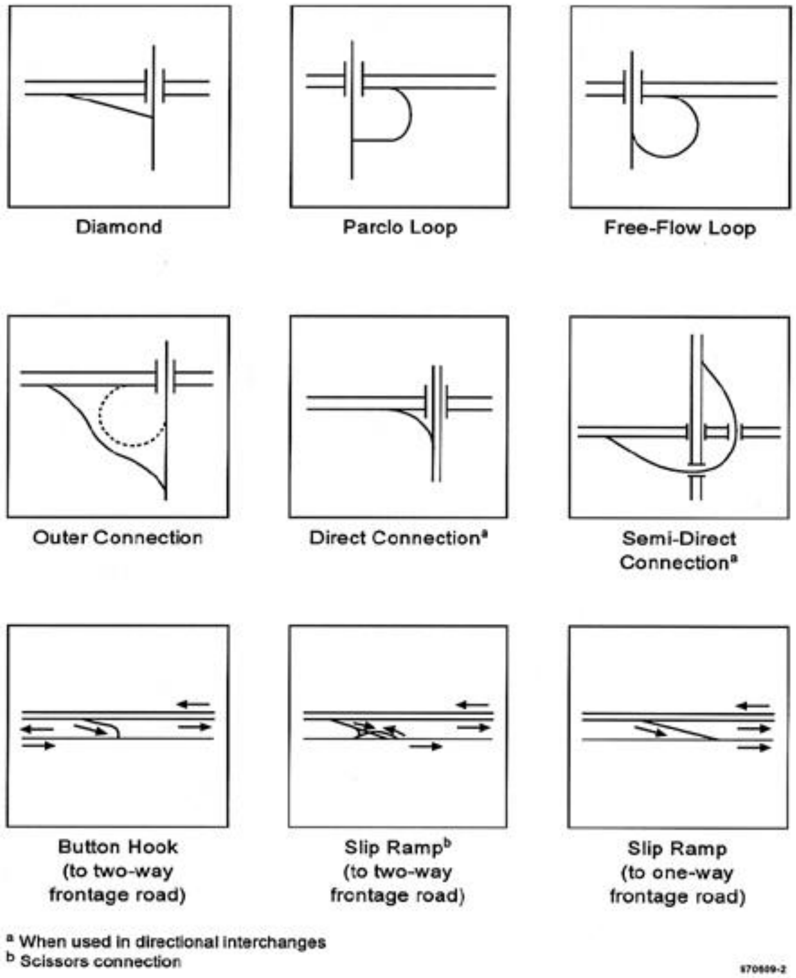


Figure 3.7 Ramp Configuration (Bauer & Harwood, 1997)

3.3.3 Data Summary

Table 3.1 shows the descriptive statistics of 187 freeway exit loop ramps in Michigan. The variables from this table can be categorized into four main groups: traffic and roadway information, geometric characteristics, speed-related variables, and crash data. The mean value of annual average daily traffic recorded across 187 ramps was 3,014 vehicle/day with a minimum of 135 vehicle/day and a maximum of 16,779 vehicle/day. These ramps are located on three different freeway classifications which comprises of 78 percent of Interstate system, 19 percent of U.S. highway, and approximately 3 percent Michigan highways.

Table 3.1 Descriptive Statistics for Ramp Characteristics

Variable		Min.	Max.	Mean	Std. Dev.
Ramp annual average daily traffic (vehicle/day)		135	16779	3013.80	2669.62
Segment length (mile)		0.01	0.51	0.19	0.10
Freeway class	Interstate Highway	0	1	0.78	0.41
	U.S. Highway	0	1	0.19	0.39
	Michigan Highway	0	1	0.03	0.16
Ramp configuration	Outer connection	0	1	0.03	0.18
	Direct connection	0	1	0.02	0.12
	Diamond	0	1	0.17	0.38
	Free-flow loop	0	1	0.28	0.45
	Parclo loop	0	1	0.50	0.50
Measured deceleration lane length (feet)		0	5465	985.88	732.18
Minimum deceleration lane length from AASHTO (feet)		340	645	549.90	50.24
Measured deceleration lane length is less than AASHTO recommendation (1 if yes; 0 if no)		0	1	0.25	0.44
Percentage of AASHTO Green Book recommended value on the deceleration lane length		0	1021	181.26	134.54
Lane width (feet)		11	17	15.36	0.96
Right shoulder width (feet)		2	11	7.41	1.40
Left shoulder width (feet)		2	8	4.62	1.15
Curve radius (feet)		115	820	268.27	92.63
Mainline speed limit	≤ 70 mph	0	1	0.93	0.26
	75 mph	0	1	0.07	0.26
Exit ramp advisory speed	15 mph	0	1	0.01	0.09
	20 mph	0	1	0.04	0.20
	25 mph	0	1	0.58	0.49
	30 mph	0	1	0.22	0.41
	35 mph	0	1	0.07	0.25
	40 mph	0	1	0.06	0.23
	45 mph	0	1	0.02	0.15
Speed differential	25 to 35 mph	0	1	0.17	0.38
	40 to 45 mph	0	1	0.76	0.43
	50 to 55 mph	0	1	0.07	0.25
Lane configuration	Parallel	0	1	0.75	0.43
	Taper	0	1	0.25	0.43
Crossroad	Overpass	0	1	0.66	0.47
	Underpass	0	1	0.32	0.47
Total crashes		0	23	1.95	3.26
Lane departure crashes		0	15	0.76	1.42

Note: Min. = minimum; Max. = maximum; Std. Dev. = standard deviation

A total of five different ramp configurations were recorded in the final dataset (refer to Figure 3.7 for reference). The most common ramp configuration observed was the partial cloverleaf (or also known as parclo) loop (50 percent), followed by the free-flow loop (28 percent). Notice that, about 17 percent of the ramps were diamond type (typical diamond type ramps do not have advisory speed). However, these ramps had controlling features that require drivers to reduce their speed due to sharp horizontal curvature. The remaining ramp configurations recorded in the dataset were outer (3 percent) and direct (2 percent) connections.

The following summarizes several measurements on deceleration lane length, lane width, and shoulder widths. The average measured length of deceleration lane was 986 ft, with a minimum of 0 ft and a maximum of 5,465 ft. There were two sites with no speed change lane prior entering the ramp curve; and there were several weaving ramps (i.e., speed change lane that connects upstream entrance terminal with downstream exit terminal) with speed change lane greater than 2,000 ft. For the minimum deceleration lane length from AASHTO, the average recorded was approximately half of the average measured length. Additionally, more than 25 percent of the ramps had deceleration lane length less than the minimum recommendation from AASHTO. Furthermore, the percentage difference between AASHTO's minimum length and site measurement (i.e., site measurement divided by the minimum length from AASHTO) was also calculated. On average, these ramps had deceleration lane length greater than the recommendation value (i.e., exit ramps with percentage values of 100 or more are reflective of cases that meet these minimum recommendations). For lane and shoulder widths, they were measured at three different locations along the ramp proper for accuracy. The mean value for lane, right shoulder, and left shoulder widths were 15 ft., 7 ft., and 5 ft., respectively.

This study also collected three different speed-related variables, as presented in Table 3.1. The mainline speed limit ranged from 55 mph to 75 mph. This study categorized them into two groups: 70 mph or less and 75 mph. Approximately, 16 percent of the ramps were located on the mainline that experienced speed limit increase back in 2017. Table 3.1 also shows seven categories of exit ramp advisory speed ranging from 15 to 45 mph, with 5 mph increment. The majority of the sites had an advisory speed of 25 mph, which covers approximately 58 percent of the data. The third speed-related variable from Table 3.1 is the speed differential. This variable was calculated by taking the difference between mainline speed limit and exit ramp advisory speed. For the purpose of this study, the speed differential was categorized into three, between 25 and 35 mph, 40 and 45 mph, and 50 and 55 mph. The majority of the exit ramp with 50 or 55 mph speed differences were due to the speed limit increase. The advisory speed of the exit ramp is also associated with the curve radius. Based on Table 3.1, the minimum curve radius recorded was 115 ft., with an average of 268 ft.

One of the primary objectives of this study is to determine the impacts of the variables mentioned before on two different types of crashes: total crashes and lane departure crashes. These crashes were analyzed separately to understand how crash risk changes for different subsets of crashes. On average, 1.95 crashes occur per segment annually, while lane departure crashes recorded 0.76 crashes every year on each segment. Figure 3.8 shows a box plot of lane departure crashes versus speed differentials at the sample of exit ramps. In general, this plot shows crashes increase with increase in speed differential from 25 to 45 mph. This trend drops off when the speed differential is greater than 45 mph, though it is important to note this figure does not consider other factors that may be correlated with such crashes.

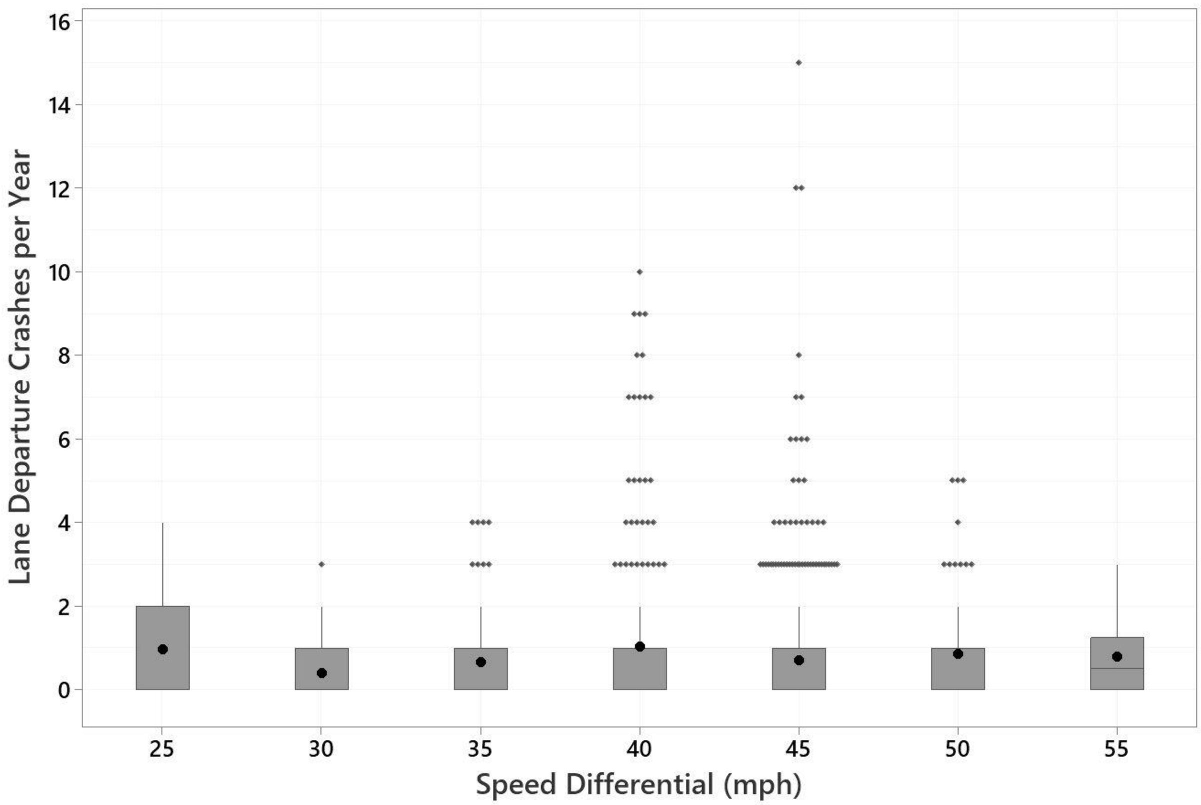


Figure 3.8 Box Plot of Lane Departure Crashes per Year vs. Speed Differential

3.4 Statistical Methods

Crashes are known to be random, discrete, and non-negative integers. Two types of regression models are frequently used to develop SPFs: Poisson and negative binomial (NB) models. Under the Poisson model, the probability of exit ramp *i* experiencing y_i crashes during a specific time period can be calculated using Equation 3.1.

$$P(y_i) = \frac{e^{-\lambda}\lambda_i^{y_i}}{y_i} \quad (3.1)$$

Based on Equation 3.1, λ_i is the Poisson parameter for exit ramp *i,* which is the expected number of crashes for exit ramp *i* and it can be calculated using Equation 3.2.

$$\lambda_i = EXP(\beta_1 X_1 + \cdots + \beta_k X_k) \times L \quad (3.2)$$

From Equation 3.2, X_1 to X_k are the independent variables (i.e., traffic volumes, difference between mainline speed limit and exit ramp advisory speed, lane width, etc.); β_1 to β_k represent the estimate coefficient from the regression model; and L is the segment length. For Poisson model, one of the assumptions that must be followed is the average number of crashes must equal to the variance. However, often times the variance will be greater than the mean, which is known to be over-dispersed. One of the solutions to overcome the overdispersion of crash data is by using NB model. For NB model, λ_i can be expressed as:

$$\lambda_i = EXP(\beta_1 X_1 + \cdots + \beta_k X_k + \varepsilon_i) \times L \quad (3.3)$$

where $EXP(\varepsilon_i)$ has a gamma distribution with mean equal to one and variance of α for overdispersion parameter. The variance of crashes at a given exit ramp with the overdispersion parameter included can be calculated using Equation 3.4. When this parameter approaches zero, the model definition of negative binomial converges to the Poisson definition, where the mean number of crashes equals its variance.

$$Var(y_i) = E(y_i) + \alpha E(y_i)^2 \quad (3.4)$$

This study utilized a random effects framework to account for unobserved heterogeneity. Since the exit ramps are repeated five times in the dataset (i.e., once per year), this may raise concerns on the correlation in the number of crashes within each site over time. Due to important site-specific variables that are not captured by the model, some exit ramps are likely to experience higher (or lower) number of crashes when compared to other similar exit ramps. Failure to account for this correlation may result in underestimating the standard error of estimate coefficient, which would lead to higher z-statistics, resulting in inaccurate conclusion. Introducing the random effects framework to the model allows the constant term to vary across sites but remain the same within each site.

In developing the SPFs, this study treated the segment length as an offset variable, constraining its parameter estimate to one. This creates an assumption that if crashes are expected to occur on a given one-mile segment of roadway, the expected number of crashes would double for a two-mile segment of roadway with similar characteristics. Eventually, the estimate coefficients from SPF can be used to interpret the changes in crash rates in response to a unit change in the independent variables. For Poisson and negative binomial regression models, the change in crash rates can be calculated using Equation 3.5, where $\Delta\lambda$ is the percentage change in crash rates.

$$\Delta\lambda = 100(e^{\beta_k X_k} - 1) \tag{3.5}$$

This study used R Studio version 1.4.1717 to estimate the random effect negative binomial model.

3.5 Results and Discussion

In this study, the SPFs take the form of negative binomial regression models given the overdispersion that was present in the crash data. Two separate models were estimated, including one model for total crashes and another for lane departure crashes. The results of these models are presented in Table 3.2 and Table 3.3, respectively. Both models have the same series of independent variables, including exposure variables (i.e., segment length and AADT), categorical variables indicating the two groups of speed differential, deceleration lane length associated with the AASHTO guidelines, and right shoulder width. Each model provides the parameter estimates, along with the associated standard error, t-statistic, and p-value.

Table 3.2 shows the results for total crashes based on 187 exit ramps with advisory speed signs throughout Michigan. The results show that crashes increase consistently as the speed differential increases. Exit ramps with speed differential between 40 and 45 mph experienced about 16.3 percent more crashes when compared to ramps with speed differential between 25 and 35 mph. While for exit ramps with speed differential between 50 and 55 mph, crashes are expected to increase by 36.2 percent compared to the baseline variable.

Table 3.2 Model Results for Total Crashes

Parameter	Estimate	SE	*t*-Value	*p*-Value
Intercept	-3.840	0.675	-5.689	<0.001
LN (AADT of ramp)	0.857	0.074	11.502	<0.001
Speed differential: 25 to 35 mph (baseline)	na	na	na	na
Speed differential: 40 to 45 mph	0.151	0.170	0.887	0.375
Speed differential: 50 to 55 mph	0.309	0.235	1.317	0.188
Percentage of AASHTO Green Book recommended value of deceleration lane length	-0.0013	0.001	-2.579	0.010
Right shoulder width (ft)	-0.106	0.042	-2.557	0.011
Overdispersion	0.265	0.051	5.205	<0.001

Note: LN = natural logarithm; AADT = average annual daily traffic; SE = standard error

The results from Table 3.2 also demonstrate the relationships between total crashes and other predictor variables of interest. Traffic volume showed a nearly elastic relationship as crashes increased by 0.85 percent for a one-percent increase in AADT. Consistent with the trend in previous study (Kweon & Kockelman, 2005), the right shoulder width exhibits a decreasing trend on crash rates as the width increases. Result shows that an increase in one foot of right shoulder width was associated with a 10.0 percent reduction in crashes. For the deceleration lane length, a one-percent increase in the deceleration lane length (as compared with AASHTO recommendation) was associated with a 0.13 percent decrease in crashes.

Figure 3.9 shows the estimated number of total crashes based on different percentage of AASHTO recommendation value on deceleration lane length and traffic volume while holding other predictor variables constant (i.e., lowest category of speed differential and mean value of right shoulder width). The crash rates demonstrated an almost linear relationship with the traffic volume. This figure also illustrates the trend of the crash risk, where it decreased by 6.3 percent for every 50 percent increase in the length of deceleration lane with respect to AASHTO recommendation value. This finding provides empirical support for deceleration lane lengths that are at or above current AASHTO recommendations. Additional investigation is warranted to better understand the nature of this relationship.

Table 3.3 shows results for lane departure crashes. Similar to the results from the total crash model, lane departure crashes also increase as the AADT increases. However, this subset of crashes is generally less sensitive to traffic volumes as a one-percent increase in AADT corresponds with a 0.59 percent increase in lane departure crashes. This may be reflective of additional variability in the occurrence of such crashes from site to site, or may suggest differences in driver behavior at the higher volume ramps (e.g., lower speeds, better lane-keeping behavior) Additionally, the right shoulder width also showed decreasing trend in the crash rate as the width increases. However, the effect was less pronounced than the total crashes model based on the magnitude of the estimate coefficient. The model from Table 3.3 shows that crashes would be expected to decrease by 7.2 percent for every one-foot increment of right shoulder width.

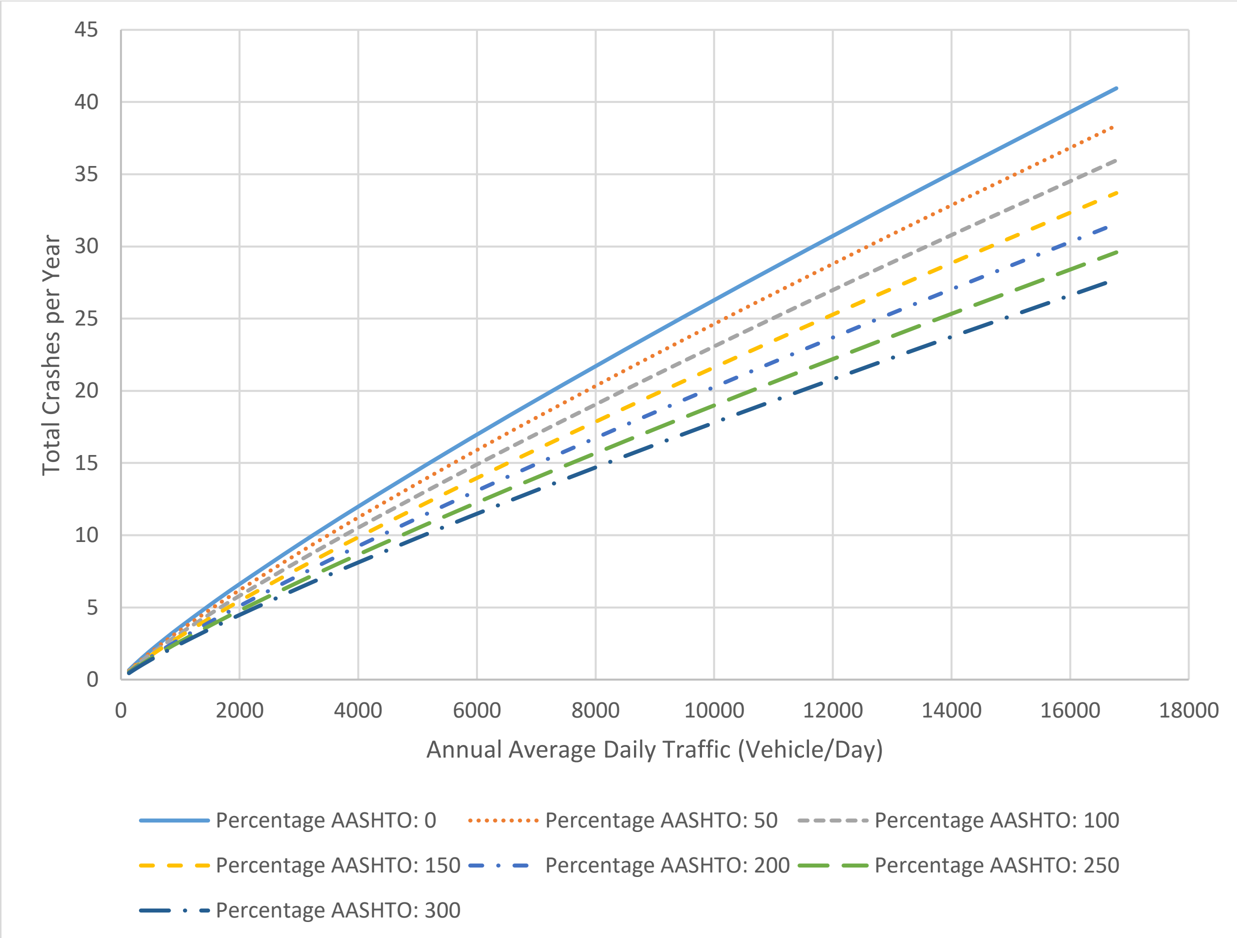


Figure 3.9 Expected Number of Total Crashes with Respect to Traffic Volume and Deceleration Lane Length

Table 3.3 Model Results for Lane Departure Crashes

Parameter	Estimate	SE	*t*-Value	*p*-Value
Intercept	-2.967	0.737	-4.024	<0.001
LN (AADT of ramp)	0.596	0.081	7.324	<0.001
Speed differential: 25 to 35 mph (baseline)	na	na	na	na
Speed differential: 40 to 45 mph	0.258	0.189	1.366	0.172
Speed differential: 50 to 55 mph	0.506	0.260	1.949	0.051
Percentage of AASHTO Green Book recommended value of deceleration lane length	-0.0015	0.001	-2.723	0.006
Right shoulder width (ft)	-0.075	0.045	-1.651	0.099
Overdispersion	0.229	0.050	4.580	<0.001

Note: LN = natural logarithm; AADT = average annual daily traffic; SE = standard error

Finally, the speed differential variables show similar trends compared to the analysis of total crashes. In general, the parameter estimates in the lane departure model are larger in magnitude, which indicates a stronger relationship between lane departure crashes and speed differential as compared to total crashes. This is consistent with a priori expectations as lane departure crashes are expected to be more closely related to driver speed selection behavior. For exit ramps with speed differential between 40 and 45 mph, 29.4 percent more crashes were experienced on average as compared to exit ramps with speed differentials of between 25 and 35 mph. Ramps with speed differentials between 50 and 55 mph are associated with 65.9 percent more crashes as compared to the lowest speed differential category (25-35 mph).

Figures 3.10 and 3.11 graphically illustrate the estimated number of total crashes and lane departure crashes for each speed differential category based on the traffic volume while holding other independent variables constant at their mean values, respectively. The safety performance for each speed differential category demonstrates an increasing trend in the number of crashes as the traffic volume increases for both figures. The total crashes figure shows an almost linear relationship between traffic volume and crash rate for each category of speed differential. While lane departure crashes figure demonstrates an inverse exponential relationship, where crashes increase as the traffic volume increase, but with a decreasing rate. Interestingly, the crash risk is almost double for every 10 mph increment in the speed differential, and this is more pronounced at exit ramps with higher traffic volume for both type of crashes.

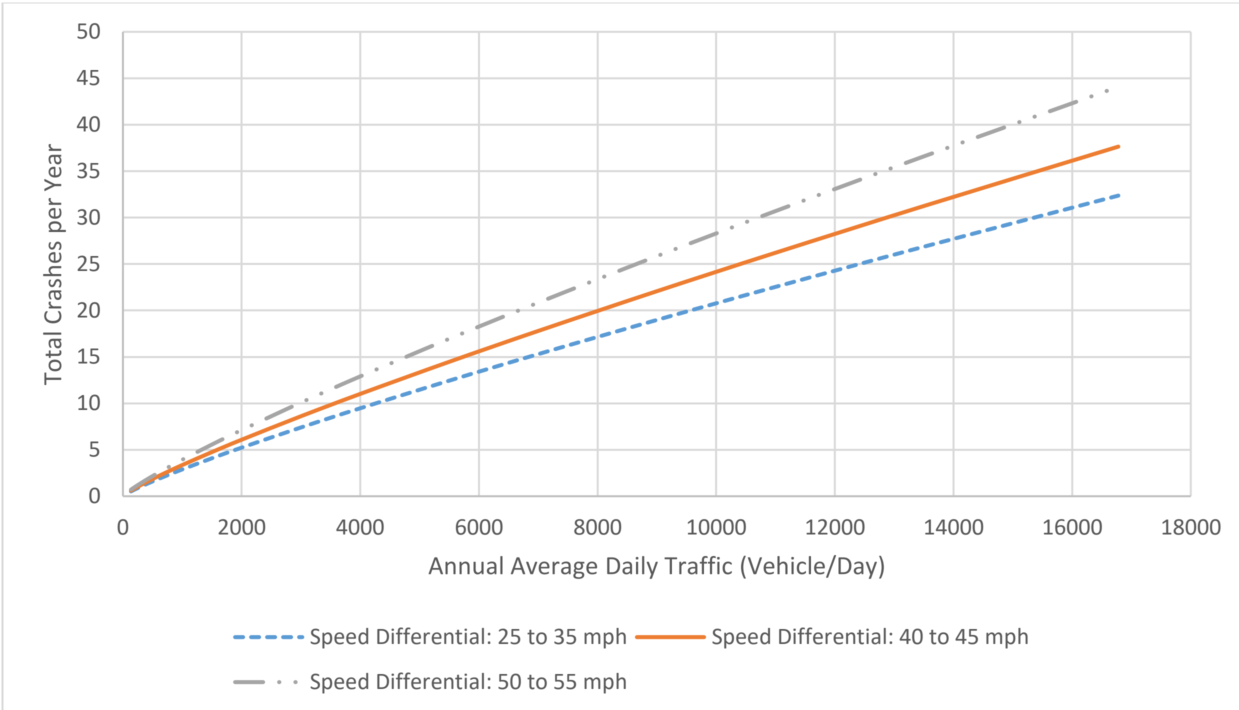


Figure 3.10 Expected Number of Total Crashes by Speed Differential

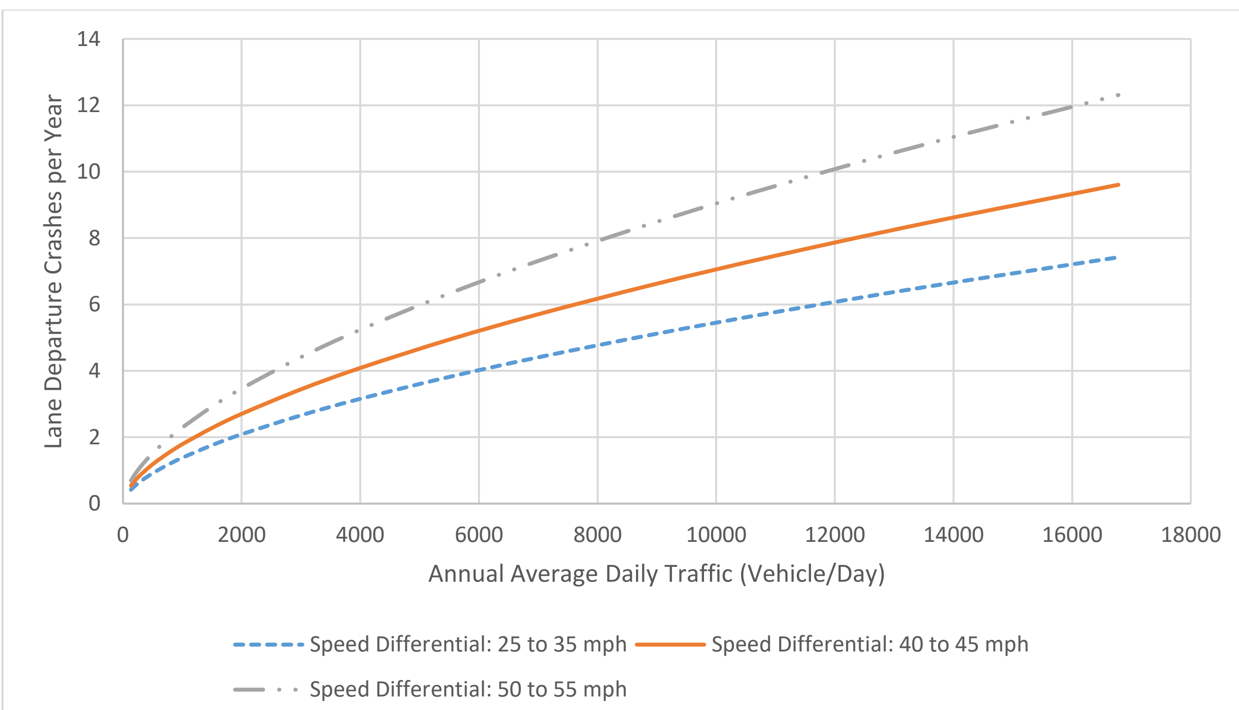


Figure 3.11 Expected Number of Lane Departure Crashes by Speed Differential

The length of deceleration lane is an important aspect of interchange design as these speed-change lanes provide space for drivers to decelerate comfortably as they approach the controlling feature (i.e., the point of curvature of the ramp). The results from Tables 3.2 and 3.3 provide insight into the crash risk associated with the deceleration lane length. In general, crashes decreased as the length of the deceleration lane increased. This finding provides support for longer deceleration lanes, specifically in the case of exit loop ramps. However, additional safety performance may be influenced by site-specific speed and deceleration profiles as they relate both to vehicle fleet characteristics and road design parameters.

According to the 1965 Blue Book, the deceleration lane length depends on three factors: (1) vehicle speed when entering the deceleration lane; (2) vehicle speed at the end of the deceleration lane; and (3) deceleration rate (American Association of State Highway and Transportation Officials, 1965). The minimum guideline of deceleration lane length in this manual was based on the data collected in the 1930s. The recent edition of AASHTO Green Book published in 2018 still includes the same data from the 1930s (although the Green Book versions after 1965 listed the taper length separately). This may influence the results since many changes have occurred since, particularly on the vehicle performance. Based on a study conducted using naturalistic driving data, there are several differences found with the minimum design guideline in AASHTO Green Book (Xu et al., 2019). The study found that vehicles entering the deceleration lane had higher speed compared to the one mentioned in the guideline. Additionally, the study also found that ramp with design speed of 35 mph will have vehicles at the end of the deceleration lane with an average speed of 55 mph, compared to 30 mph from the AASHTO Green Book.

There are several variables that were not included in the models for various reasons. Some variables provide better fit as compared with alternative model specifications. For example, the percentage of AASHTO Green Book recommended value on the deceleration lane length was used instead of the actual length. Nevertheless, the number of crashes per year showed a negative correlation with the length of deceleration lane length, as shown in Figure 3.12. Crashes decreased exponentially as the deceleration lane length increases.

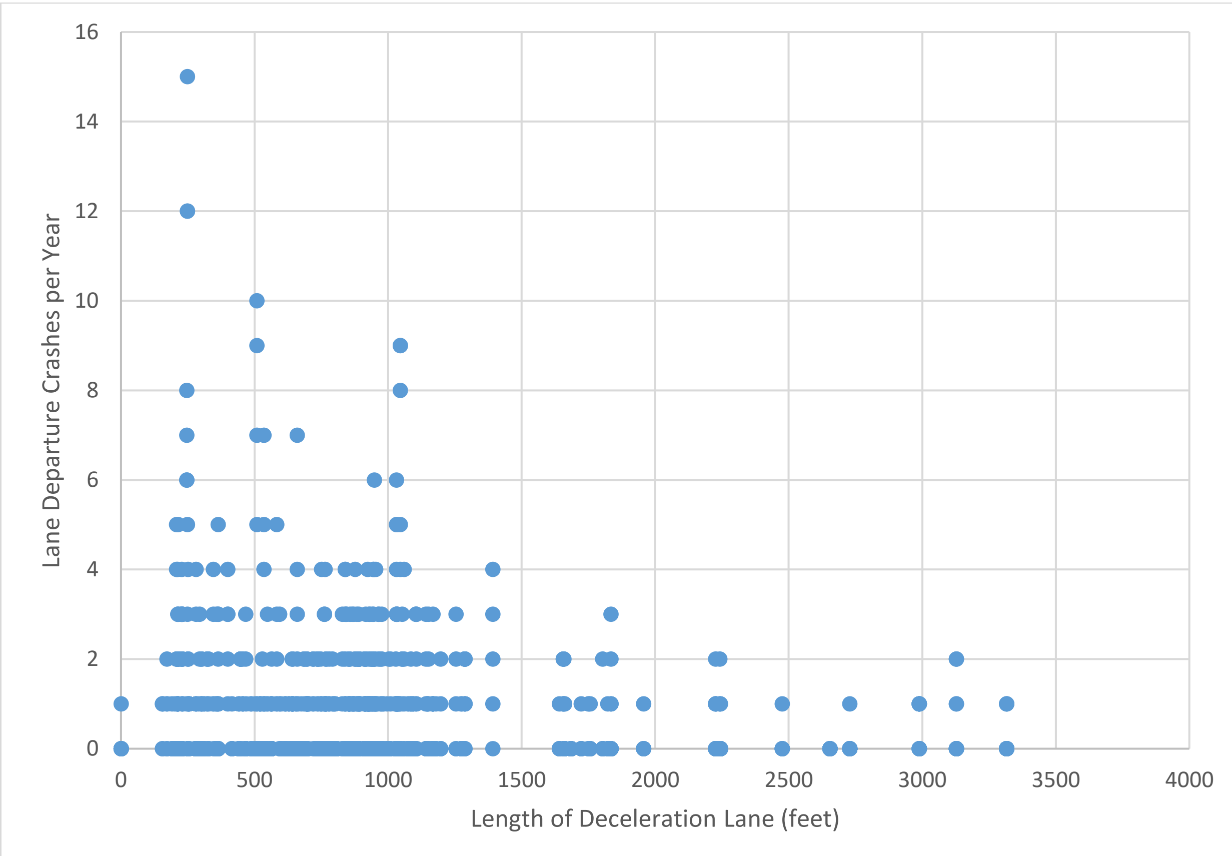


Figure 3.12 Lane Departure Crashes per Year vs. Deceleration Lane Length

Additionally, some variables were removed from the models due to multicollinearity concerns. For example, the curve radius is directly related to ramp advisory speeds as sharper curves (i.e., smaller curve radius) require lower advisory speed. Similarly, exit ramp advisory speeds are used to calculate the speed differential variables, introducing explicit structural correlation between these variables. There was also correlation among other variables such as lane configuration, as tapered type designs are typically associated with shorter deceleration lane lengths. Within the analysis dataset, more than 61 percent of tapered type exit ramps had a deceleration lane length less than the AASHTO recommendation.

Beyond the results presented here, this study also included additional analyses, particularly in relation to different specifications of the speed differential between the mainline and ramp operating speeds. The design speed of each exit ramp was determined based on the measured curve radius assuming a 6 percent superelevation rate based on the AASHTO Green Book (American Association of State Highway and Transportation Officials, 2018). These results were generally consistent with the results present previously. However, a strong relationship was shown between the posted statutory speed limit and the posted advisory speed. Interestingly, this suggests that the advisory speeds do have an influence, and consistency in practices related to the location of the advisory speed signs (e.g., on the deceleration lane versus the ramp) as well as the actual advisory speed are an area of interest for future research.

3.6 Summary

This study examines the safety impact of speed differential between mainline posted speed limit and exit ramp advisory speed with the consideration of several geometry features of the ramps using a random effect negative binomial regression model. Two different crash models (total crashes and lane departure crashes) were estimated based 187 exit ramps with the presence of exit ramp advisory speed signs. The results showed that crashes are expected to increase with the increase in the speed differential. This effect was more pronounced for lane departure crashes. Additionally, crashes are also shown to decrease on ramps where the upstream deceleration lane length was greater than the minimum recommendation as per current design guidance.

The findings from this study provide transportation agencies and traffic safety researchers with important insights regarding the safety of exit ramps with the consideration of higher speed differential. A preliminary study should be conducted first before any future speed limit increase is decided. Factors such as deceleration lane length and speed differential should be one of the criteria that need be examined first. For example, as shown in Figure 3.6, the deceleration lane length recommended by AASHTO Green Book is a function of design speed of the mainline and the average running speed at the ramp controlling feature. If the speed limit is increased, the length of deceleration lane should increase as well.

CHAPTER 4: DRIVER RESPONSE TO A DYNAMIC SPEED FEEDBACK SIGN AT SPEED TRANSITION ZONE ALONG RURAL HIGHWAYS

4.1 Background

Speeding is one of the major causes of traffic fatalities in the United States. In 2019, speeding was responsible for more than 26 percent of traffic fatality based on NHTSA (National Highway Traffic Safety Administration, 2020). Approximately 86 percent of fatal crashes corresponding to speeding occurred on non-interstate roadways, and nearly 41 percent (3,848 out of 9299) were on rural highways. In Michigan, speeding was also one of the major contributing factors that lead to fatal crashes. About 25 percent of fatal crashes in Michigan were due to speeding, which is close to the national rate (National Highway Traffic Safety Administration, 2018).

Speeding on rural highways is one of the critical issues that need to be addressed, particularly when approaching small rural communities located along these highways. Typically, drivers are expected to have an uninterrupted high travel speed when traversing on these highways and passing through such communities. However, it may not be possible due to the need for lower speed limits when passing through these areas (Stamatiadis et al., 2014). In order to warn drivers of oncoming speed reduction areas, suitable speed management strategies must be employed on the approach to the community. Such areas are usually referred to as speed transition zones (Figure 4.1). According to a study from Kentucky, speed transition zone can be defined as an area in which the roadway environment changes (e.g., from rural area to small community) and drivers should adjust their speed accordingly (Stamatiadis et al., 2014).

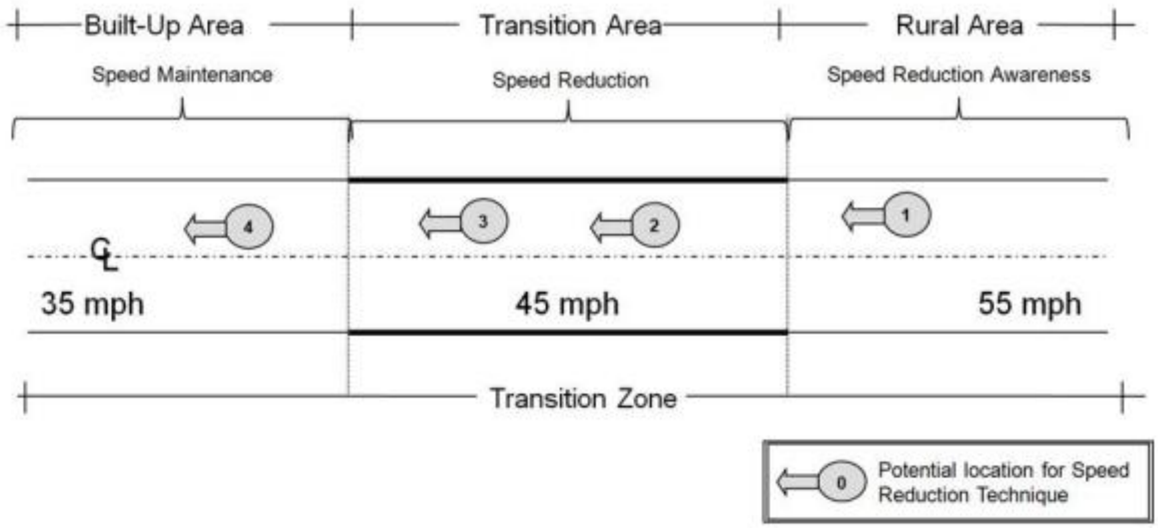


Figure 4.1 Speed Transition Zone Design (Stamatiadis et al., 2014)

To reduce speed before entering a speed limit reduction area, it is essential to effectively communicate to drivers, important information regarding the oncoming reduced speed limit areas. There have been a number of strategies introduced to help manage speeds when approaching these areas, including median islands, road/lane narrowing, road diets, chicanes, transitional speed limits, roundabout, optical speed bars, pavement markings, speed humps, rumble wave surfaces, countdown speed signs, gateways, optical lane narrowing, roadside vegetation, and dynamic speed feedback signs (Stamatiadis et al., 2014; Transportation Research Board, 2011). Figure 4.2 shows some of the examples of speed management strategies. Many of these countermeasures are effective in reducing speeds, especially in low-speed environments. Unfortunately, the effectiveness of these countermeasures on high-speed rural roads is not well established. This may be due to a reluctance in implementing such aggressive speed reduction strategies at speed transition zones on high-speed rural highways (Transportation Research Board, 2011).

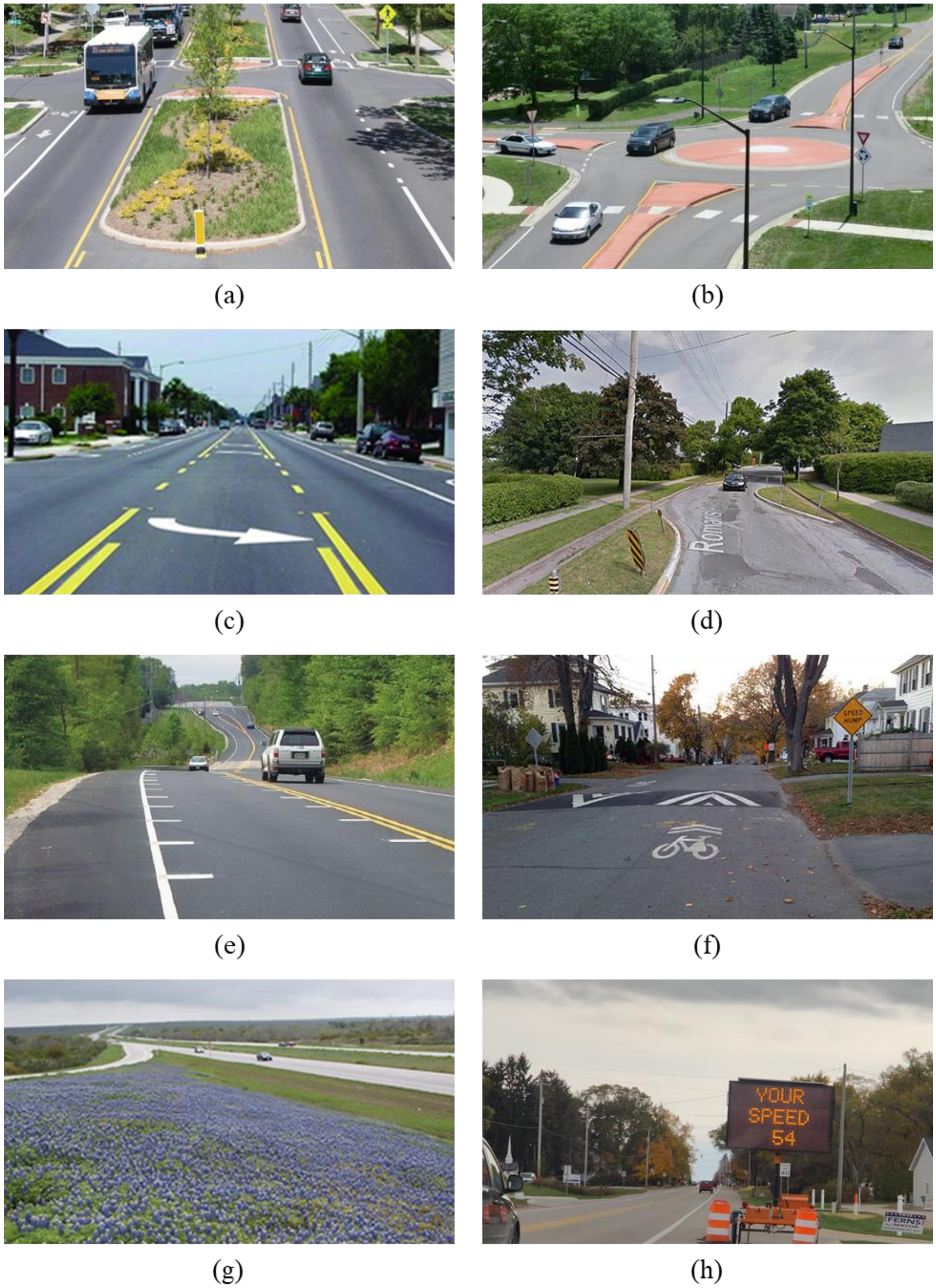


Figure 4.2 Example of Speed Management Strategies, (a) Median Island (FHWA, 2021b); (b) Roundabout (FHWA, 2021c); (c) Road Diet (FHWA, 2017b); (d) Chicane (FHWA, 2019); (e) Optical Speed Bar (FHWA, 2017a); (f) Speed Hump (FHWA, 2019); (g) Roadside Vegetation (Hopwood et al., 2015); (h) Dynamic Speed Feedback Sign

DSFS is a treatment strategy that has shown promising result in reducing vehicle speeds on both low- and high-speed environments. This device uses RADAR to detect vehicle speeds and display them along with speed warning messages such as “SLOW DOWN,” “TOO FAST,” and “SPEED LIMIT XX” on digital display boxes. According to the prior studies, these speed warning messages can be personalized in nature, and they are particularly effective in reducing excessive speeding (Gates et al., 2020; Hallmark, Hawkins, & Knickerbocker, 2015; Mahmud, Motz, et al., 2021). The DSFS has been effective in different roadway settings, such as work zone areas (Garber & Patel, 1994; Mattox et al., 2007), school zone areas (Ullman & Rose, 2005), horizontal curves (Bertini et al., 2006; Hallmark, Hawkins, & Smadi, 2015; Ullman & Rose, 2005), high-speed arterials (Ardeshiri & Jeihani, 2014; Karimpour et al., 2020; Ullman & Rose, 2005), freeway exit ramps (Gates et al., 2020; Mahmud, Motz, et al., 2021), and also on speed transition zones (Cruzado et al., 2009; Hallmark, Hawkins, & Knickerbocker, 2015; Sandburg et al., 2009; Ullman & Rose, 2005). However, the use of this sign as a speed management strategy at speed transition zones along high-speed rural highways is not well established. Thus, the effectiveness of this sign in such environments need to be further explored.

Speed management has become an important topic for the last decade, particularly with the continuation of the speed limit increase on rural highways across the United States. Michigan is one of the states that have increased their maximum regulatory speed limit from 55 to 65 mph on more than 900 miles of two-lane rural highways in the northern part of the state. A recent study from Michigan on speed limit increase has found that the average travel speeds increased by 2.8 to 4.8 mph on rural highway segments that experienced recent speed limit increase (Mahmud, Gupta, et al., 2021). However, the previous study did not consider impacts to travel speeds within speed transition zones on 65-mph rural highways, where the speed limit upon entry to the adjacent rural community typically remained unchanged, thereby creating a greater speed reduction requirement along these highways. Thus, it is important to determine suitable treatments that can safely and effectively help drivers transitioning from a high-speed to low-speed roadway environment.

To that end, this study evaluates the effectiveness of DSFS as a speed management strategy at speed transition zones on high-speed two-lane rural highways in the state of Michigan. The primary objective of this study was to evaluate the effectiveness of the DSFS with different speed limit settings for both the rural highway segments (e.g., 55 vs. 65 mph) and the reduced speed limit area (e.g., 35 vs. 40 vs. 45 mph). This study conducted a before-and-after evaluations that focused on the changes in vehicle speeds at different locations while approaching and entering the reduced speed zone.

4.2 Literature Review and Problem Statements

Previous literature have evaluated the effectiveness of DSFS in reducing speed for different roadway context, including rural highway environments. A study from Iowa found that the average speed decreased by approximately two mph for both passenger cars and heavy vehicles after the installation of DSFS on rural highway curves. Interestingly, these effects retained over the 24 months study period (Hallmark, Hawkins, & Knickerbocker, 2015). Additionally, these effects were also found to be consistent with other studies on horizontal curves (Bertini et al., 2006; Ullman & Rose, 2005). Moreover, a safety-focused study that analyzed 22 horizontal curves from seven different states found that crashes decreased between 5 and 7 percent during the first three years after the installation of DSFS (Hallmark, Qiu, et al., 2015).

In addition to the rural curves, several studies have also assessed the impacts of DSFS on vehicle speeds at speed transition zones along rural highways. A study from Texas evaluated the effects of DSFS on two transition zones, switching from a 55 mph roadway to 45 mph (Ullman & Rose, 2005). The average speed decreased by 2.6 to 3.4 mph after 1-3 weeks of installation. These effects slightly diminished after 2-4 months, where the average speed dropped by 1.4 mph for both sites. This study also found a significant reduction in drivers exceeding the posted speed limits. Another study that investigated a long-term effect of DSFS found substantial reductions in speeds for roadways transitioning from 50-55 mph to 30-45 mph (Sandburg et al., 2009). The average speed decreased by 6 to 7 mph after one week of installation, 3 to 8 mph after two months, 3 to 7 mph after seven months, and 6 to 8 mph after one year. An extended study from Pennsylvania evaluated 12 transition zones on two-lane rural highways, where the roadway environments transitioned from 45-55 mph to 25-40 mph (Cruzado et al., 2009). The average speed was reduced by 6.3 mph during the after period. However, these effects only sustained when the sign was activated. Moreover, a study from Iowa evaluated different types of DSFS at three small rural communities (Hallmark, Hawkins, & Knickerbocker, 2015). A simple speed feedback sign that displayed only drivers' speed at a site transitioning from 55 to 25 mph found a reduction in average speed by 8 mph after one month of installation. A similar setup with additional static sign displaying "YOUR SPEED" message was found to reduce the average speed by 5 mph. Another DSFS, capable of displaying digital messages, was programmed to display vehicle speed when the approach speed was between 26 and 39 mph and display "SLOW DOWN 25" message when the speed was between 40 and 75 mph. The results showed that the average speed was reduced by 5 mph and speeding five mph over the speed limit decreased by 76 percent.

The findings from previous studies have shown that DSFS are capable in reducing vehicle speed upon entering reduced speed limit areas. However, research has been limited as to the effectiveness of the sign on speed transitioning from speed limits exceeding 55 mph. This is particularly important since many rural highways in northern Michigan have recently experienced speed limit increase from 55 to 65 mph, making speed control a particular concern. To that end, further research is warranted on the effectiveness of DSFS at speed transition zones with upstream speed limit exceeding 55 mph.

4.2 Data Collection Process

This study utilized a before-and-after field evaluation at five different speed transition zones in northern Michigan. These areas are located along two different two-lane rural highways passing through four small rural communities. The following subsections explain different aspects of this assessment, including a summary information of the test sign, detailed explanation on the site characteristics, procedure of speed data collection, and process of data reduction.

4.2.1 Test Sign and Messaging Strategy

The type of DSFS used in this study was a portable changeable message sign (PCMS) as shown in Figure 4.3. This sign is compliant with the MUTCD guideline and aligns with the Draft Special Provision for DSFS by the MDOT. The sign has a light-emitting diode (LED) feedback display that measures 138 in. by 75 in. It has the capability to display up to three lines of alphanumeric characters, with a maximum of eight 14 in. tall characters per line. The sign is integrated with RADAR detection system, embedded at the bottom of the message sign board. The RADAR unit utilizes the microwave K-band to detect vehicle speed and it has an average detection range of 1,000 ft. and an accuracy of ±1 mph for speed less than 40 mph and ±2 mph for speeds greater than 40 mph.

Figure 4.3 Dynamic Speed Feedback Sign for Field Evaluation in Hale, Michigan

For the purpose of this study, the DSFS was programmed in such that the speed of an approaching vehicle will be displayed in the format of “YOUR SPEED XX”, alternating with a warning message on the reduced posted speed limit information at one-second interval in the format of “REDUCED SPEED XX MPH” (Figure 4.3). In this study, the sign was positioned beyond the shoulder to provide sufficient lateral buffer from the travel way.

4.2.2 Study Sites

This study analyzed the effectiveness of DSFS as a countermeasure to reduce vehicle speed at five different speed transition zones located on two-lane rural highways in the northern part of Michigan. The sites were selected based on the suggestions from MDOT due to the reports on speeding-related issues by the locals. These speed transition zones were located on two separate rural highways; three of them were on M-65 with an upstream speed limit of 65 mph, and the remaining two locations were on US-23 with a rural speed limit of 55 mph. The reduced speed limits ranged between 35 and 45 mph. For sites with upstream speed limit of 65 mph, these sites transition into 35-45 mph roadways, while for 55 mph upstream speed limit sites, the speed limit reduces to 45 mph upon entering small communities. Table 4.1 displays details of each of the five speed transition zone locations.

Table 4.1 Site Characteristics

Site No	Location & Direction	Upstream Speed Limit (mph)	Speed Limit at the Transition Zone (mph)	Downstream Speed Limit Sign to DSFS (ft.)	Downstream Speed Limit Sign to Advance Warning Sign (ft.)
1	Whittemore-NB	65	35	283	1,229
2	Whittemore-SB	65	40	352	585
3	Hale-SB	65	45	296	679
4	Oscoda-NB	55	45	299	628
5	Tawas-SB	55	45	400 & 625	1,008

MUTCD-compliant W3-5 advanced warning signs as shown in Figure 4.4 were present at all five sites. However, the location of the advance warning signs with respect to the reduced speed limit signs varied from site-to-site, as shown in Table 4.1. For example, the W3-5 signs at sites 1 and 5 were positioned at approximately double the distance from the speed limit sign as the W3-5 signs at sites 2, 3, and 4. It should be noted that the nearest 55 or 65 mph posted speed limit sign was more than 2 miles upstream of the speed transition zone at each site.

Figure 4.4 Reduced Speed Limit Ahead Sign, W3-5 (FHWA, 2009)

The DSFS was installed between the W3-5 sign and the posted speed limit sign at each site. For sites 1 through 4, the DSFS was installed between 283 and 352 ft. upstream of the reduced posted speed limit sign. However, a driveway at site 5 required the DSFS to be positioned further upstream, and it was decided to subsequently test the sign at two different upstream locations (400 ft. and 625 ft.) at this site.

4.2.3 Speed Data Collection

The speed data were collected in two phases at each study site: 1) under the existing site conditions (i.e., without the DSFS), and 2) after the installation of the DSFS. For site 5, data were collected with the presence of DSFS at two different locations. Data were collected during weekdays under clear weather conditions in late fall 2020 and late spring 2021. To address any novelty effect associated with the DSFS, the after-period data were collected no earlier than one week after installing the DSFS. The same setups (e.g., the placement of the signs, the positions of data collector vehicles, etc.) were used for both before and after data collection.

Vehicle speeds were continuously tracked for vehicles approaching and entering the reduced speed limit area at each site with and without the presence of DSFS. The speed data were collected using a series of two handheld LIDAR guns (i.e., typically used by law enforcement) operated by well-trained data collectors from within different vehicles parked beyond the shoulder or in a driveway. Data were collected from the same location for both study periods. The LIDAR guns were ProLaser III manufactured by Kustom Signals Inc., which can detect vehicular speed and distance at a maximum range of 6,000 ft. with an accuracy of ±1 mph at three times per second. From a practical sense, each LIDAR gun is typically only utilized over a range of 1,200 ft. due to geometry constraints and encroachment of other vehicles.

The upstream LIDAR collector was positioned between 1,810 and 2,280 ft. upstream of the reduced speed limit sign, while the downstream data collector was positioned between 640 and 1,025 ft. upstream of the reduced speed limit sign. These locations were selected to be away from any of the critical traffic control devices (i.e., DSFS, W3-5, speed limit sign, etc.) to minimize the influence of the data collection vehicle on driver behavior (e.g., drivers might notice the LIDAR held by the technician, which might influence their travel speed). The upstream LIDAR technician would track each vehicle for at least 100 ft. beyond the position of downstream data collector, at which the downstream data collector would continue the tracking of each subject vehicle over the remaining course of the roadway segment to slightly beyond the reduced speed limit sign. The data collectors communicated through cellular communications to ensure a smooth "hand-off" of the LIDAR speed tracking as each subject vehicle passed through the speed transition zone. In doing so, the upstream data collectors would communicate the information each subject vehicle (e.g., vehicle type and color) to the downstream technician. In order to separate driver response to the DSFS, only freely flowing vehicles were recorded. Figure 4.5 illustrates the data collection setup that includes the positions of data collectors (i.e., upstream and downstream LIDAR), locations of advance warning sign, DSFS, and reduced posted speed limit.

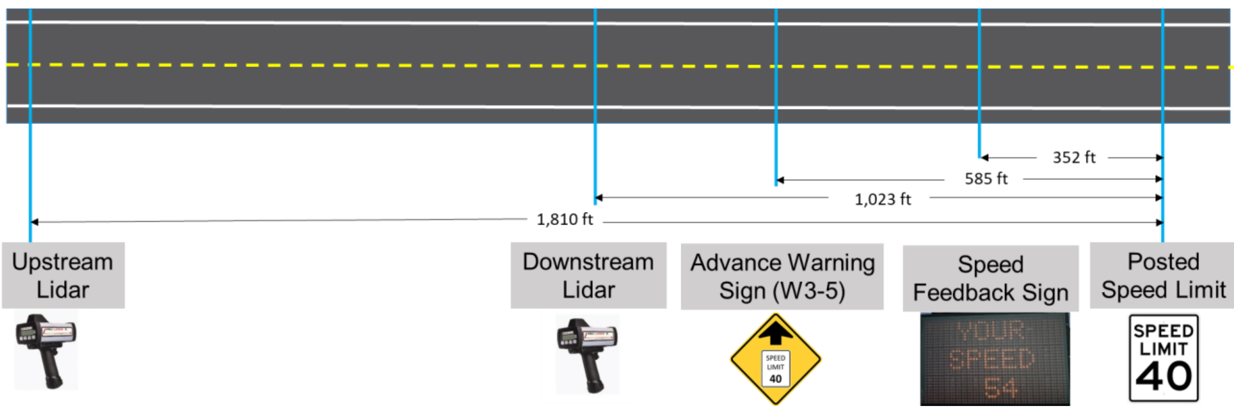


Figure 4.5 Typical Data Collection Setup for Speed Tracking

The LIDAR guns were connected to Windows XP laptops via data transfer cables to record all information coming from the LIDAR in real-time using proprietary software. The information included vehicle speed, timestamp, and vehicle distance for each measurement. Once the LIDAR tracking was completed for each subject vehicle, the same remarks were entered by both data collectors that include the type and color of the vehicle, as well as any additional comments. Subsequently, this information were used to combine the two datasets into one coherent format to obtain a complete speed profile for each subject vehicle. One of the advantages of collecting speed data using LIDAR tracking method over cameras or pneumatic tubes is the type of data obtained, where LIDAR provides continuous measurements of speed for the entire targeted segments, as opposed to spot-speeds at fixed points.

4.2.4 Data Processing

After the completion of speed data collection from the field, datasets from both upstream and downstream data collectors were combined based on the vehicle sequence, type, and color. Additional remarks added were used to flag and remove vehicles that did not match between the files. These events occasionally occurred due to several reasons including incomplete speed profile due to technical issue or view blocked by other vehicles, vehicle entering/exiting a driveway, presence of other vehicle on the shoulder, etc. Figure 4.6 shows a sample of joined raw speed data between upstream and downstream data files.

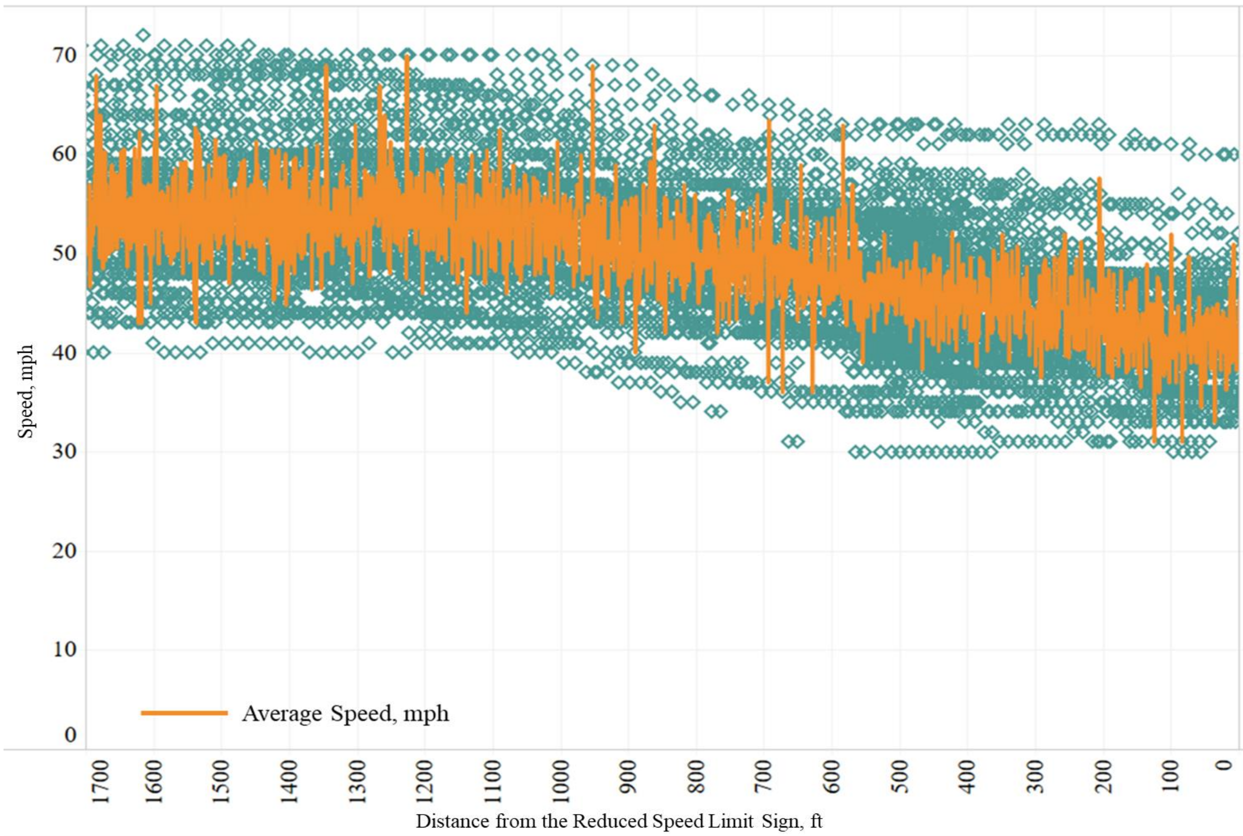


Figure 4.6 Raw LIDAR Data

Since the distances between the positions of data collectors and various traffic control devices were known, this study converted all distances to be relative to the reduced posted speed limit sign (i.e., the start of the speed reduction zone). However, the LIDAR guns used in this study were not able to obtain the speed data at the same locations along the roadway for every vehicle. Subsequently, data conversion to a series of spot speeds using interpolation technique was performed in order to analyze the data at specific reference points. This data were linearly interpolated for every foot based on the known adjacent speeds. Consequently, the interpolated speeds were selected at every 50 ft interval starting from the reduced posted speed limit sign as shown in Figure 4.7. By reducing the data in this manner, it provides a robust array of spot speeds and allows a comparison of the speed profiles between before and after installing the DSFS. This also allows changes in speeds at various distances from the start of the speed reduction zone to be calculated.

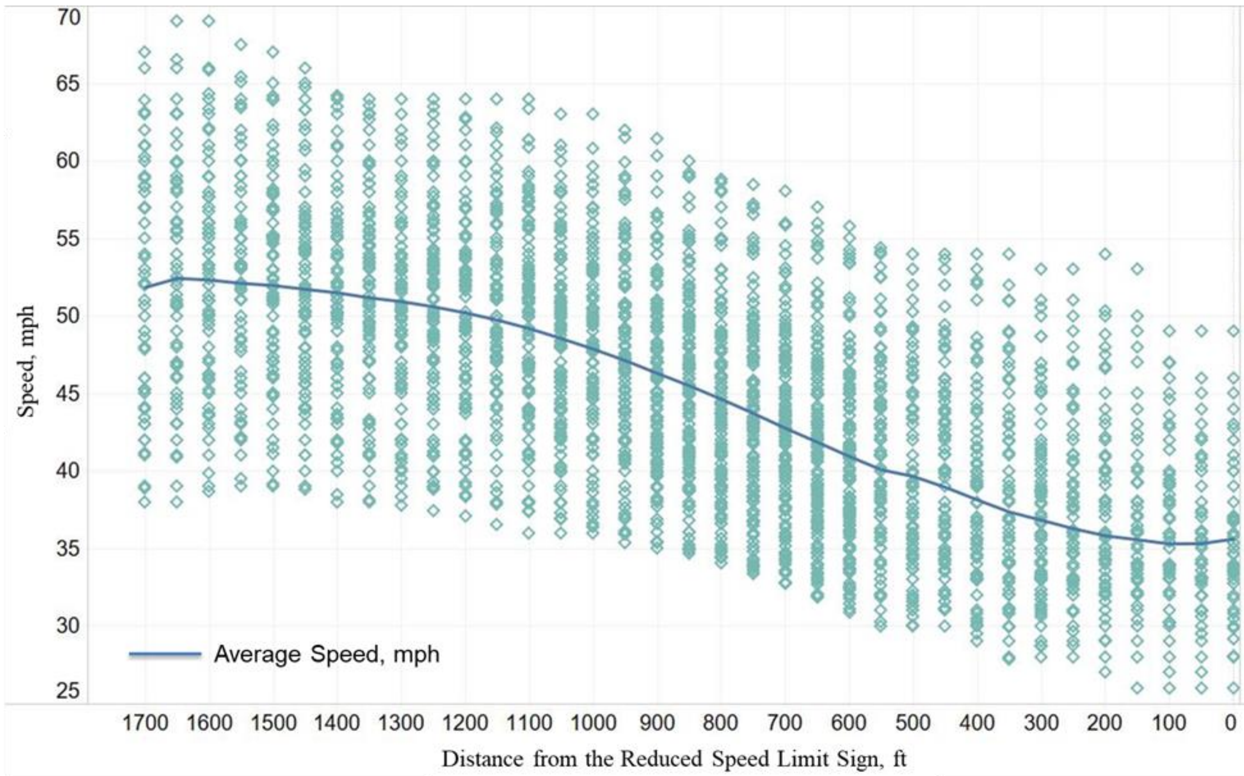


Figure 4.7 LIDAR Data Interpolated at 50 ft. Increment

The data collected before and after the installation of the DSFS were combined for each site separately. After processing the data, the descriptive statistics (i.e., mean, standard deviation, etc.) were compared, and simple graphical representations (i.e., scatterplot, line graphs, frequency distribution) were plotted independently for each site, as the reduced speed limit and the advance warning sign positions were different among the five sites. Passenger cars and heavy vehicles were coded separately. Preliminary models suggested only marginal differences in DSFS effectiveness between passenger cars and heavy vehicles and further analysis of vehicle-specific DSFS effects was not performed.

4.3 Statistical Methods

To determine the effectiveness of DSFS in reducing speeds, the entire speed profiles before and after the installation of the DSFS were analyzed. Two primary analyses were conducted using multiple linear regression or binary logistic regression, depending on the nature of the dependent variable. The dependent variables for these analyses included:

- Speeds while traversing through the transition zone, and
- Probability of vehicle exceeding the reduced speed limit.

When analyzing the speed data, the speed measurements were binned at 50 ft. increments on the approach to the transition zone, beginning with the furthest upstream point (between 1,700 and 1,850 ft depending on the site), and continuing to the posted speed limit sign. The before-period speed at the furthest upstream point at each location was treated as the base condition in the models. The speed data in other distance categories (and separated between the before and after the installation of DSFS) were coded with separate binary variables and analyzed against the base condition to determine the effects of the DSFS incrementally on the approach to the speed reduction zone. To streamline the analysis and simplify interpretation of the results, the incremental speed measurements were categorized into different regions, as follows: upstream of the transition zone, at the approximate detection limit of the DSFS RADAR, at the DSFS itself, and at the speed limit sign posted at the start of the reduced speed limit zone.

Multiple linear regression model was used when analyzing the vehicular speed data. A general form of the models is shown in Equation 4.1:

$$Y_i = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k + \varepsilon_i \quad (4.1)$$

where Y_i is the measured speed at any point for vehicle i, X_1 to X_k are the independent variables affecting the target variables (e.g., vehicle type and vehicle position along the road), β_0 is the intercept term, β_1 to β_k are the estimated regression coefficients for each independent variable, and ε_i is a normally distributed error term with variance σ^2.

The probability of vehicles exceeding the posted speed limit at the reduced speed limit sign was analyzed using binary logistic regression analysis. The binary logistic regression model has the form of:

$$Y_i = logit(P_i) = ln\left(\frac{P_i}{1-P_i}\right) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k \quad (4.2)$$

where the response variable, Y_i, is the logistic transformation of the probability of speed over the reduced speed limit. This probability is denoted as P_i. Similar to the linear regression model, X_1 to X_k are independent variables, β_0 is an intercept, β_1 to β_k are estimated regression coefficients for each independent variable.

4.4 Results and Discussions

4.4.1 Effect of DSFS on Transition Zone Speeds

The results of linear regression models for vehicle speeds approaching each speed transition zone are shown in Table 4.2, and are reflected graphically in Figure 4.8. Note, although the DSFS was tested in two positions at Site 5, to provide consistency with the other test sites, only the results from the 400 ft. upstream position are included in Table 4.2. The effects of the DSFS position at this site will be presented and discussed later. The change in speed at different locations while approaching the speed reduction zone for any site can be estimated directly from the table. For example, compared to the speed at the upstream of transition zone without DSFS, speed at advance warning sign were lower by 0.94 mph without DSFS and 4.75 mph with the DSFS at site 1. The same measures for site 2 was 5.18 mph and 8.6 mph without and with DSFS, respectively.

Table 4.2 Linear Regression Results for Transition Zone Speeds, by Site and DSFS Presence

Variable	DSFS Present?	Site 1: 65 mph to 35 mph (N=9,620)		Site 2: 65 mph to 40 mph (N=9,036)		Site 3: 65 mph to 45 mph (N=10,728)		Site 4: 55 mph to 45 mph (N=10,286)		Site 5: 55 mph to 45 mph (N=17,100)	
		Est.	*p*-Value	Est.	*p*-Value	Est.	*p*-Value	Est.	*p*-Value	Est.	*p*-Value
Intercept		55.48	<0.01	55.17	<0.01	59.61	<0.01	56.17	<0.01	56.60	<0.01
Passenger vehicle		Baseline									
Heavy vehicle		-3.82	<0.01	-1.21	<0.01	-1.36	<0.01	1.14	<0.01	-1.55	<0.01
Upstream of transition zone	No	Baseline									
	Yes	-2.16	<0.01	-0.32	0.67	-2.37	<0.01	0.58	0.26	-0.82	0.09
At DSFS RADAR detection limit	No	-0.55	0.34	-2.20	<0.01	-1.49	0.34	-0.13	0.75	0.44	0.24
	Yes	-3.94	<0.01	-3.03	<0.01	-4.67	<0.01	0.11	0.79	-0.88	0.02
At advance warning sign	No	-0.94	0.20	-5.18	<0.01	-4.82	<0.01	-0.90	0.07	-0.02	0.96
	Yes	-4.75	<0.01	-8.60	<0.01	-9.46	<0.01	-1.78	<0.01	-3.44	<0.01
At DSFS	No	-10.90	<0.01	-6.62	<0.01	-6.58	<0.01	-2.66	<0.01	-1.00	<0.01
	Yes	-18.66	<0.01	-11.27	<0.01	-12.16	<0.01	-5.83	<0.01	-6.34	<0.01
At speed limit sign	No	-13.29	<0.01	-8.91	<0.01	-8.45	<0.01	-3.80	<0.01	-2.41	<0.01
	Yes	-19.53	<0.01	-13.19	<0.01	-13.65	<0.01	-7.40	<0.01	-8.04	<0.01

Note: Est. = estimate coefficient

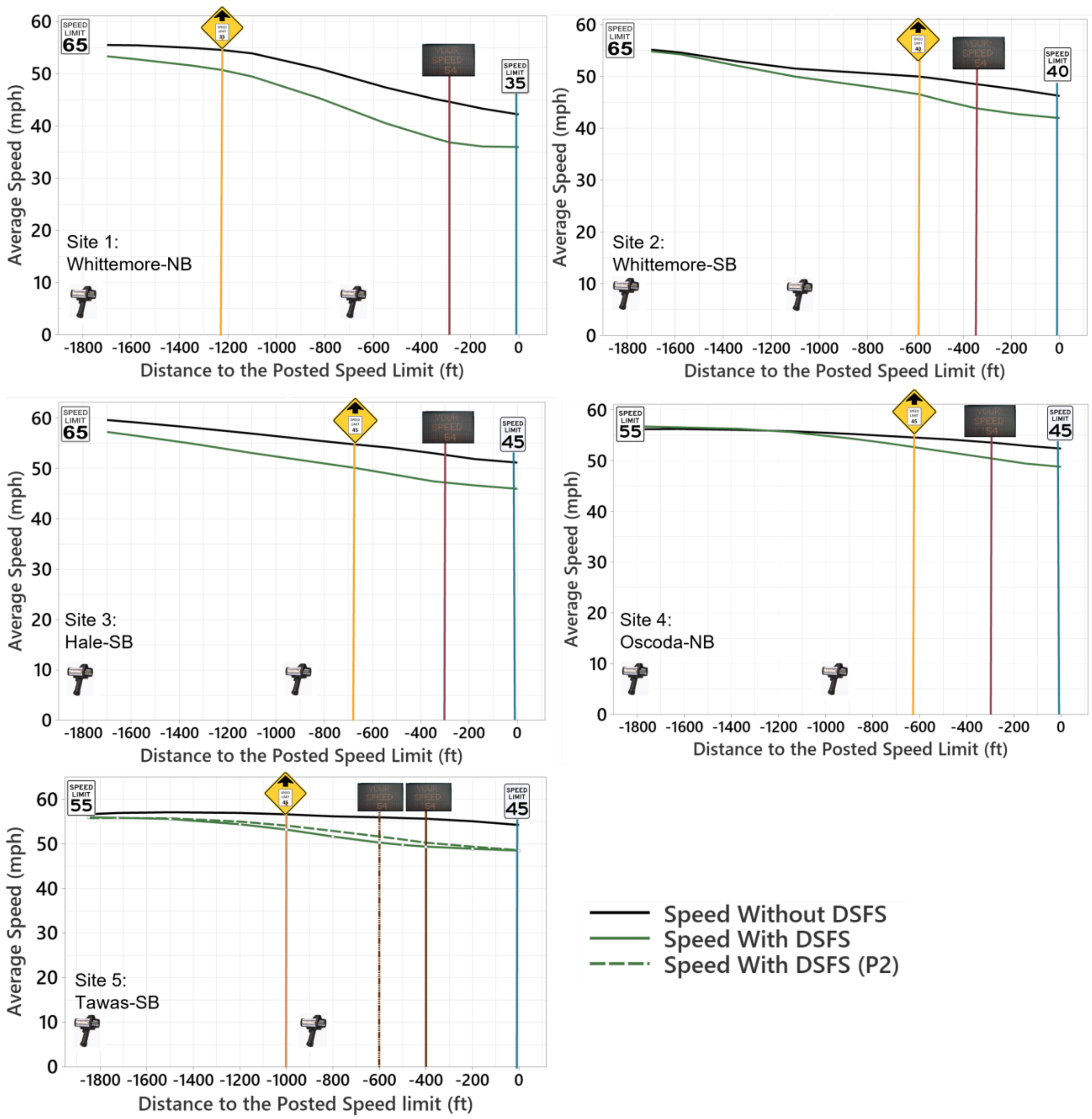


Figure 4.8 Transition Zone Vehicle Speed Profile, by Site and DSFS Presence

The results displayed in Table 4.2 suggest that the DSFS had a significant effect on vehicle speeds throughout the speed transition zone. The magnitude of the DSFS effects can be interpreted by taking the difference between the DSFS parameter estimates (i.e., “Yes” minus “No”) at each speed measurement location. For example, the effect of DSFS at the speed limit sign for site 1 is 6.24 mph (19.53 minus 13.29). According to Figure 4.8, three out of five locations (site 1, site 3, and site 5) saw early effect of DSFS where the vehicle speeds started to reduce at the furthest upstream of the data collection point. Note that, this point was between 1,700 and 1,850 ft from the posted speed limit sign. This finding was not unexpected since the DSFS was already visible to motorists at this point.

Based on the magnitude of the estimate coefficients of the categorical variables (i.e., speed at certain locations along the road), the effect of DSFS on the speed reductions became greater as drivers continued approaching to the community. When drivers entered the RADAR detection range of the DSFS, the average speed decreased with the presence of DSFS at four out of five locations. The DSFS-related speed reductions were between 0.8 mph and 3.4 mph, on average, at these sites.

Figure 4.9 shows the magnitude of speed reductions at three different locations (at advance warning sign, at DSFS, and at reduced speed limit sign) while approaching the rural communities. The effect of DSFS was more pronounced when vehicles reached the DSFS itself. The speed reductions were between 3.2 mph and 7.8 mph, on average, across all five sites with the presence of DSFS. This speed reduction effect was generally sustained through the remainder of the transition zone through to the speed limit sign posted at the start of the reduced speed limit zone, at which point the speed data collection ceased. At this point, vehicular speeds ranged from 3.6 to 6.2 mph lower, on average, across the five sites when the DSFS was present.

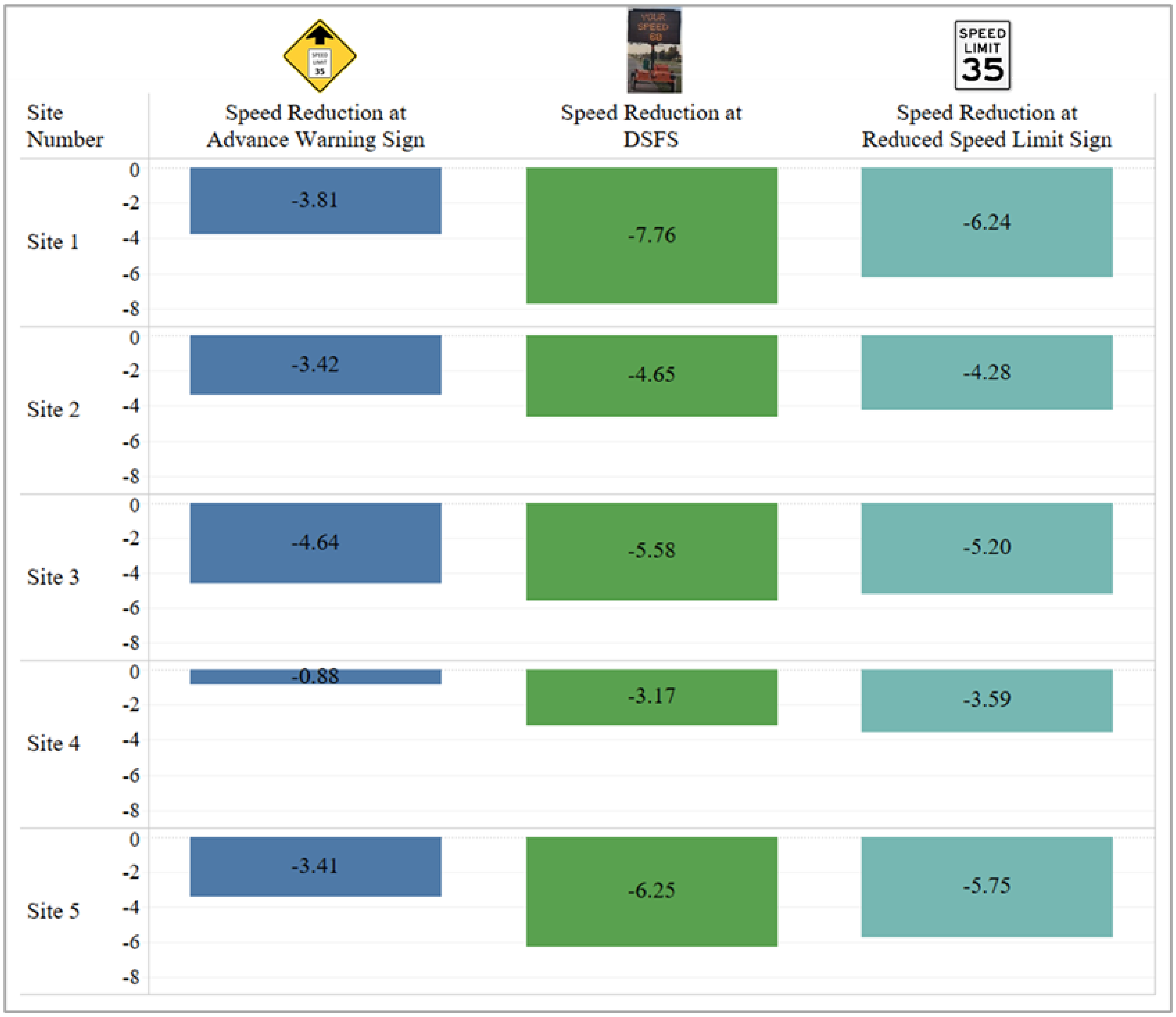


Figure 4.9 Speed Reductions at Different Critical Locations

Although the DSFS was shown to be effective at each of the five speed transition zones, the strongest DSFS speed reduction effects were observed at the location with the greatest speed limit reduction (site 1; 65 mph to 35 mph). However, beyond this, there were no apparent trends between the upstream or downstream speed limit and the speed reduction effectiveness of the DSFS. The DSFS consistently showed the weakest effect at Site 4, which was a 55 to 45 mph location. This was perhaps due to the transition zone site being located in a slightly more urbanized environment (e.g., greater density of commercial property and driveways) compared to the other four sites.

Site 5 provided the additional opportunity to assess the effect of the position of the DSFS with respect to the speed reduction zone. At this site, the DSFS was tested at 625 ft and 400 ft upstream of the speed limit sign. The results of this analysis are presented in Table 4.3. Again, the DSFS effects may be directly interpreted by taking the differences between the DSFS parameter estimates at each speed measurement location. The intercept term represents the average speed of passenger vehicle at the furthest upstream of data collection point when DSFS is not present at the site. On average, the upstream speed is approximately equal to the posted speed limit of 55 mph.

Table 4.3 Linear Regression Results for Transition Zone Speeds with Respect to DSFS Location (Site 5)

Variable	DSFS Presence and Location	Estimate	*p*-Value
Intercept		56.60	<0.01
Passenger vehicle		Baseline	
Heavy vehicle		-1.55	<0.01
Upstream of site	No DSFS	Baseline	
	DSFS at 625 ft	0.69	0.16
	DSFS at 400 ft	-0.82	0.09
At DSFS RADAR detection limit	No DSFS	0.44	0.24
	DSFS at 625 ft	-1.05	<0.01
	DSFS at 400 ft	-0.88	0.02
At 600 ft upstream of speed limit sign	No DSFS	-0.69	<0.01
	DSFS at 625 ft	-6.35	<0.01
	DSFS at 400 ft	-4.96	<0.01
At 400 ft upstream of speed limit sign	No DSFS	-1.00	<0.01
	DSFS at 625 ft	-7.25	<0.01
	DSFS at 400 ft	-6.34	<0.01
At speed limit sign	No DSFS	-2.41	<0.01
	DSFS at 625 ft	-8.15	<0.01
	DSFS at 400 ft	-8.04	<0.01

As expected, the DSFS had a significant effect on vehicle speeds throughout the transition zone for both DSFS installation locations. Not surprisingly, the speed reductions began further upstream when the DSFS was positioned further upstream, which is also clearly reflected in Figure 4.8. At 600 ft. upstream of the posted speed limit sign, the DSFS had an approximately 1.4 mph greater effect on motorist speeds when installed at the further upstream location. However, any speed reduction differences between the two sign locations diminished as vehicles approached the speed reduction zone, becoming negligible at the speed limit sign entering the community.

4.4.2 Effect of DSFS on Speed Limit Compliance

Table 4.4 shows the results of binary logistic regression analysis for vehicles exceeding the speed limit at the speed limit sign posted at the start of the reduced speed limit zone. Five different models were developed separately based on the five sites. Similar predictor variables were tested for four of the five sites (site 5 had two different setups of the DSFS). When interpreting the model results, positive estimate indicates that drivers are more likely to exceed the speed limit at the speed limit sign. Conversely, negative estimate is indicating that drivers are less likely to go beyond the speed limit. Figure 4.10 shows the percentage of vehicles exceeding the speed limit, in addition to exceeding 5 and 10 mph over the speed limit

Table 4.4 Binary Logistic Regression Results for Exceeding the Posted Speed Limit

Site 1 – Dependent Variable: Exceeding Posted Speed Limit of 35 mph				
Variable	Estimate	SE	*p*-Value	Elasticity
Intercept	-4.47	1.58	<0.01	0.01
Upstream speed	0.13	0.03	<0.01	1.14
Passenger vehicle	Baseline			
Heavy vehicle	0.32	0.66	0.63	1.38
No DSFS	Baseline			
DSFS present	-2.57	0.37	<0.01	0.08
Site 2 – Dependent Variable: Exceeding Posted Speed Limit of 40 mph				
Variable	Estimate	SE	*p*-Value	Elasticity
Intercept	-7.17	1.66	<0.01	0.00
Upstream speed	0.17	0.03	<0.01	1.19
Passenger vehicle	Baseline			
Heavy vehicle	-0.99	0.52	0.06	0.37
No DSFS	Baseline			
DSFS present	-1.60	0.36	<0.01	0.20
Site 3 – Dependent Variable: Exceeding Posted Speed Limit of 45 mph				
Variable	Estimate	SE	*p*-Value	Elasticity
Intercept	-12.19	2.05	<0.01	0.00
Upstream speed	0.25	0.04	<0.01	1.28
Passenger vehicle	Baseline			
Heavy vehicle	0.54	0.63	0.39	1.71
No DSFS	Baseline			
DSFS present	-2.58	0.36	<0.01	0.08
Site 4 – Dependent Variable: Exceeding Posted Speed Limit of 45 mph				
Variable	Estimate	SE	*p*-Value	Elasticity
Intercept	-11.25	2.75	<0.01	0.00
Upstream speed	0.25	0.05	<0.01	1.29
Passenger vehicle	Baseline			
Heavy vehicle	-0.21	0.64	0.74	0.81
No DSFS	Baseline			
DSFS present	-1.55	0.41	<0.01	0.21
Site 5 – Dependent Variable: Exceeding Posted Speed Limit of 45 mph				
Variable	Estimate	SE	*p*-Value	Elasticity
Intercept	-12.10	2.12	<0.01	0.00
Upstream speed	0.28	0.04	<0.01	1.32
Passenger vehicle	Baseline			
Heavy vehicle	-0.98	0.45	0.03	0.38
No DSFS	Baseline			
DSFS present (P1)	-2.33	0.44	<0.01	0.10
DSFS present (P2)	-1.98	0.45	<0.01	0.14

Note: P1 = 625 ft. upstream of the speed limit sign; P2 = 400 ft. upstream of the speed limit sign; SE = standard error

As expected, drivers were less likely to exceed the speed limit at start of the reduced speed limit area point when the DSFS was present. Interpretation of the parameter estimates from the binary logistic regression model suggests that drivers were 78.8 to 92.4 percent less likely to exceed the speed limit at the start of the reduced speed limit, depending on the location. Similar to the linear regression models for transition zone speeds, the DSFS was found to be most effective where the speed limit reduction was greatest (i.e., site 1: 65 mph to 35 mph). Further, the DSFS was also slightly more effective when positioned at the further upstream location (i.e., 625 ft) at site 5. Interestingly, examination of Figure 4.10 suggests that speed limit compliance was lowest at the two 55 to 45 mph speed reduction zone sites, with and without the DSFS.

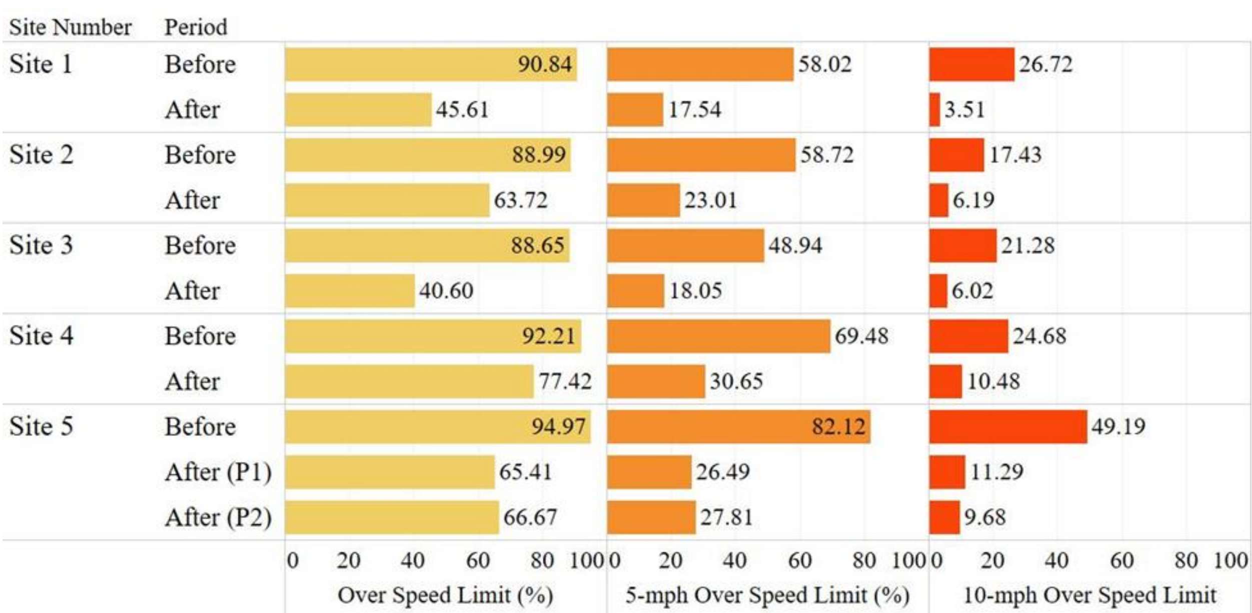


Figure 4.10 Percentage of Vehicles Exceeding the Speed Limit, 5 mph Over the Speed Limit, and 10 mph Over the Speed Limit

4.5 Summary

This study evaluates the short-term effectiveness of DSFS as a speed reductions strategy on high-speed rural highways transitioning into rural communities. Five different speed models using linear fixed effect regression were developed based on five locations where speed data were collected. Additionally, separate models were estimated for vehicle exceeding the posted speed limit at the start of the speed reduction zone using binary logistic regression.

The findings from the study revealed that the installation of DSFS in such settings reduced drivers' speed significantly regardless of the characteristics of the locations. Additionally, the model results showed that drivers were less likely to speed at the start of speed reduction zone when the DSFS was present. Lastly, this study documented the range for the installation of DSFS to obtain the most effective results in reducing vehicle speeds. It is recommended that the sign should be installed at a range of 250 ft. to 650 ft. upstream of the posted speed limit. The efforts put forth in this study may help transportation agencies to tackle down any speeding issues, particularly when entering speed reduction zones.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

In, general, this study investigated the effects of different traffic control devices on traffic safety and operation: 1) traffic crashes in relation to the frequency of safety messages displayed on DMS, 2) crash frequency associated with the exit ramp advisory speed reduction, and 3) DSFS as a speed reduction strategy at speed transition zone. The findings documented in previous chapters provide useful information for transportation agencies and traffic safety researchers.

5.1 Examining Trends in Traffic Crashes as they relate to the Display of Safety Messages on Dynamic Message Sign

5.1.1 Conclusions

The use of DMS to display safety messages has become increasingly popular, particularly during periods when the signs are not needed for other purposes (e.g., travel time information). In Michigan, safety messages are displayed 17 percent of the time (61 days per year) on average across all DMS in the state. Despite their widespread use, evaluations as to potential impacts on driver behavior and the resultant impacts on traffic crashes have been very limited. This study sought to examine whether the frequency and type of safety messages that were displayed showed any measurable relationship with traffic crashes.

The results from this study did not show any meaningful differences in terms of total crashes. However, it is important to restate that this analysis considered all types of safety messages. Nighttime crashes decreased marginally as the frequency of alcohol and impaired driving messages increased. This relationship tended to vary significantly from segment to segment (as reflected by the standard deviation of this parameter), which is a possible reflection of important unobserved characteristics of these roadways and the surrounding environment.

The most pronounced effects were related to speed-related crashes where statistically significant reductions were observed. A one-percent increase in the frequency with which safety messages were displayed was associated with a 1.5-percent decrease in crashes. This result was also found to vary from segment to segment. This may be due to unobserved factors such as the frequency of targeted speed enforcement. Additional research is warranted in this area, particularly since this study coincided with speed limit increases that occurred throughout rural areas of Michigan.

Beyond the results presented in this study, additional analyses were conducted with other subsets of crashes (e.g., distracted driving), at other levels of detail (e.g., daily and weekly crashes), and with alternate model specifications (e.g., with upstream segments, with alternate specifications for message frequency and type). However, these analyses did not provide any additional insights as to the nature of the relationship between the use of safety messages and the occurrence of traffic crashes.

It should be noted that designing a study to effectively ascertain safety impacts of DMS messages is quite challenging for several reasons. First, it is unclear how many of the drivers read, understood, and ultimately retained these messages. This is particularly true when trying to ascertain the impacts of messages that may have been displayed a limited number of times. Secondly, there are a variety of confounds that are difficult to control for. This includes the dense spacing of DMS in urban environments, variation in the manner in which messages are deployed across different areas of the state, and issues with respect to the underlying DMS message data. Extensive quality assurance efforts were required in order to effectively leverage the output from MDOT’s historical message inventory.

5.1.2 Recommendations and Future Research

Much of the prior research in this area has focused on feedback from drivers as to the efficacy of different types of messages, including the specific behaviors and issues that are targeted, as well as in the form of the actual messages with respect to tone, creativity, etc. The evidence from this study suggests a potential disconnect between these stated preferences and actual driving behavior. Many of the messages that are used are also very general in nature (e.g., number of fatalities to date). Recent research suggests that displaying messages that address specific issues, such as distracted driving or seatbelt use, yield better comprehension than general safety messages (Shealy et al., 2020). It has also been suggested that safety messages that are locally curated perform better than general safety messages (Elvik et al., 2009). For example, several MDOT regions have used local statistics and other messaging strategies that are more likely to resonate with the local population.

Given the increasing use of DMS for safety messaging, this has been a high-interest area nationally, which has led to extensive discussions regarding the use of DMS for such purposes. To this end, on January 4, 2021, the FHWA issued a Memorandum clarifying the use of DMS through Official Ruling No. 2(09)-174 (I) – Uses of and Nonstandard Syntax on Changeable Message Signs (Kehrli, 2021). As per this memo, the two principal uses of CMS are for real-time traffic control messages (e.g., non-recurring congestion, incidents, work zones, or similar conditions) and travel time messages. It is noted that any other uses, to the extent allowable, are considered secondary in nature. This includes traffic safety campaign messages in addition to several other use cases. In such cases, it is suggested that when displaying safety messages, the messages should be of limited duration (not continuous and frequent), plan message display in tandem with national safety initiatives, and display messages relevant to the roadway type (Kehrli, 2021).

This memorandum further clarifies that “The primary purpose of CMS is for the display of traffic operational, regulatory, warning, and guidance information. Other messages allowed by the MUTCD include traffic safety campaigns (by contrast with active warning messages of downstream conditions)...” Of particular relevance to this study, the memorandum states “The use of CMS to help promote traffic safety is becoming increasingly popular among States and transportation agencies. It is recognized that CMS can be an effective means of further propagating traffic safety campaign messages directly to the motoring public in a cost-effective manner. However, to ensure safety and effectiveness as a traffic control device, it is expected that CMS will be used judiciously for the display of safety messages, and that those messages will be derived from larger safety campaigns that rely on other media as their principal means of communicating the campaign message.”

Ultimately, the findings from this study largely reinforce the FHWA memorandum (Kehrli, 2021). Similarly, the results are also consistent with proposed amendments for the next edition of the MUTCD. The proposed language that would have the most substantive impact on the use of safety messages notes that “Traffic safety campaign messages shall not be displayed on CMS unless they are part of an active, coordinated safety campaign that uses other media forms as the primary means of outreach.” Subsequent guidance is proposed, stating “Traffic safety campaigns using CMS should include coordinated enforcement efforts where penalties or enforcement type warnings are part of the message displayed on the CMS.”

To this end, additional research is warranted as to potential immediate impacts on driving behavior. For example, if safety messages do have an impact, it is likely to be greatest during the periods shortly after the driver has viewed the DMS. Consequently, field studies that measure real-time response to safety messages represent the most promising means to discerning whether any causal relationship exists. Among behaviors that may be influenced, those with a potential enforcement component are likely to be strong candidates. For example, cell phone use by drivers, non-use of seatbelts, and speeding would seem to be the most promising behaviors to target as a part of such studies.

Finally, while the results of this study are generally consistent with the recommendations of the FHWA, public feedback suggests that a substantive portion of drivers find value in safety messages. While travel and weather advisory information should take precedence, there is a reasonable argument for displaying safety messages, particularly at locations where these higher priority messages are very infrequent.

5.2 Safety Evaluation of Freeway Exit Ramps with Advisory Speed Reduction

5.2.1 Conclusions

In recent years, many states have increased their freeway speed limits, including Michigan where speed limits were increased to 75 mph during 2017. Despite these increases, evaluations on the safety impact of speed differential between the mainline speed limit and the exit ramp advisory speed have been very limited. This study investigates whether the speed differential had any effects on the traffic crashes, considering several ramp characteristics. A total of 187 freeway exit ramps in Michigan were evaluated based on five years of crash data from 2014-2016 and 2018-2019.

As for the primary factor of interest, the difference between the mainline speed limit and the advisory speed of the exit ramp was found to exhibit a strong relationship with crash risk. This was true of total crashes and, particularly lane departure crashes. The lane departure crashes are expected to increase by 29.4 percent on exit ramps with speed differential of 40 to 45 mph as compared lower speed differential. The crash risk was found to be much higher on exit ramps with speed differential between 50 and 55 mph as compared to the baseline (65.9 percent more crashes). Additionally, the effect of speed differential was more pronounced on exit ramps with higher traffic volumes. Interestingly, the mainline speed limit itself was not found to exhibit a consistent relationship However, it should be noted that only 16 percent of the final sample included the higher 75 mph mainline limit.

5.2.2 Recommendations and Future Research

The findings from this study provide important insights to transportation agencies and traffic safety researchers on the safety impacts of higher speed differential at freeway exit ramps. Understanding the relationships between speed selection and crash risk at freeway exit ramps is essential given continuing discussions on speed limit policies across the U.S. When speed limits are increased on freeway, the speed differential at exit ramps would also increase. Thus, thorough investigations must be done (e.g., deceleration lane length must be sufficient after the speed limit increase as the length depends on the mainline speed) when considering speed limit policy impacts particularly at the interchange influence area before any decision is made.

There are several strategies that could be implemented based on the results to improve the safety performance of exit ramps. Greater deceleration lane lengths are shown to be associated with fewer crashes, particularly when the ramp length is greater than the minimum recommendations as per the AASHTO Green Book (American Association of State Highway and Transportation Officials, 2018). Drivers may require additional space on the deceleration lane to maneuver into the curve safely and comfortably. Widening the shoulder may also improve traffic safety, allowing drivers to have extra space in case of an emergency when traversing the ramp. Additionally, various experimental implementation of signs such as advance advisory exit speed sign, and dynamic speed feedback signs at ramp approach have also shown positive results in reducing speed of vehicles onto ramps (Ma et al., 2019; Mahmud, Motz, et al., 2021).

To this end, further research is warranted to better understand the implication on both safety and operational standpoint of higher speed differential between the mainline and the exit ramp. For example, the effect of speed differential does not only affect the safety performance of the exit ramp, but also on the speed change lane, as well as the mainline segments adjacent to the speed change lane. Consequently, additional data such real-time speed of the mainline segments as well as the crash data on both speed change lane and the mainline (i.e., both need to analyze separately) are needed to evaluate this effect. Research as to the crash risk near entrance ramps in consideration of speed differential represents another opportunity area for future research.

5.3 Driver Response to a Dynamic Speed Feedback Sign at Speed Transition Zone along Rural Highway

5.3.1 Conclusions

Speed management has become an increasingly important topic over the prior decade as speed limits on rural highways have continued to increase across the U.S. This is particularly the case in Michigan, where speed limits were increased from 55 to 65 mph on more than 900 miles of two-lane rural highways in 2017, and research has shown increases in travel speeds along these segments (Mahmud, Motz, et al., 2021). Considering this, it is important to identify countermeasures that can safely and effectively help drivers with the transition from a high-speed to low-speed road environment. While the findings from previous studies have shown that DSFS are appropriate speed reduction countermeasures at speed transition zones, no prior research evaluated transitions from speed limits of 65 mph.

To address these issues, research was conducted to evaluate the effectiveness of a dynamic speed feedback sign as a speed reduction strategy on high-speed rural highways transitioning into rural communities. A primary objective of this research was to assess the effectiveness of the DSFS across various speed limits, considering both the rural highway segment (e.g., 55 vs. 65 mph) and upon entry to the community (e.g., 35 vs. 40, vs. 45 mph). A before-and-after observational study was conducted at five different speed transition zones on two-lane rural highways in northern Michigan. The DSFS was programmed to display the approaching vehicle's speed (measured by RADAR) and alternated with speed limit information. The DSFS display was mounted on a PCMS and positioned on the shoulder in upstream of the reduced speed limit area at each site.

Vehicle speeds were continuously tracked for a sample of vehicles approaching and entering the speed reduction zone at each location before and after installation of the DSFS. The speed data were collected using a sequence of two handheld LIDAR guns operated by technicians from within separate vehicles parked just beyond the shoulder or in a driveway. This LIDAR speed tracking method allowed for the speed reduction effects of the DSFS to be assessed at various points along the speed transition zone.

The results of this evaluation suggest that the DSFS had a significant effect on vehicle speeds throughout the speed transition zone, and this effect was consistent across the five test locations. The speed reductions generally began when the DSFS came into the motorists' view, and the speed reduction effect of the DSFS increased as motorists approached the community. The DSFS had the greatest effect on speeds when vehicles reached the DSFS itself, where speeds were 3.2 to 7.8 mph lower, on average, when the DSFS was present across the five sites. This speed reduction effect was generally sustained through the remainder of the transition zone, continuing to the speed limit sign posted at the start of the reduced speed limit zone entering the community. At this point, vehicular speeds ranged from 3.6 to 6.2 mph lower, on average, across the five sites when the DSFS was present. In terms of speed limit compliance, as expected, drivers were 78.8 to 92.4 percent less likely, on average, to exceed the speed limit when the DSFS was present.

There was limited evidence to suggest that the DSFS provided a greater speed reduction benefit as the differential between the upstream and downstream speed limit increased, although this effect was only supported by the results from a single site. Considering the effect of DSFS location with respect to the reduced speed limit zone, not surprisingly, the speed reductions began further upstream when the DSFS was positioned further upstream. However, this effect diminished as vehicles approached the speed reduction zone, becoming negligible at the speed limit sign entering the community.

5.3.2 Recommendations and Future Research

Collectively, the findings from this research suggest that a DSFS is an effective speed reduction strategy when used in speed transition zones on rural highways, and the continued use of such devices in this context is recommended. The sign should be placed in advance of the speed transition zone between the advance notification sign (e.g., W3-5 from Figure 4.4) and the posted speed limit sign, to allow sufficient time to react and adjust speed accordingly. However, this study caution against placing the DSFS at too great a distance upstream, as drivers may be more likely to disregard warning message that are delivered prematurely (Gates et al., 2020; Mahmud, Motz, et al., 2021). In this context, installing the DSFS at a range of 250 to 650 ft. upstream of the posted reduced speed limit is recommended.

This evaluation was limited to temporary installations of a PCMS-mounted DSFS. Future research should assess the effects of smaller roadside post-mounted DSFS in these contexts, and include a temporal assessment to determine whether the sign loses effectiveness over time. Prior studies have demonstrated the use of the smaller signs (15-inch or 18-inch display) to be effective in speed reduction in other contexts such as interchange ramps and rural highway curves (Gates et al., 2020; Mahmud, Gupta, et al., 2021). To that end, future evaluations should also assess the amount of time that the portable DSFS, such as those utilized in this study, should be left on site before moving elsewhere.

APPENDIX

R-code for identifying safety messages from the MDOT DMS database:

Note 1: Data sent by the Michigan Department of Transportation were in multiple files for each year. These files were imported into R to combine them into one big dataset. This is for 2014 data.

```
file2014_1_1 <- read.csv(file.choose())
file2014_1_2 <- read.csv(file.choose())
file2014_1_3 <- read.csv(file.choose())
file2014_1_4 <- read.csv(file.choose())
file2014_2_1 <- read.csv(file.choose())
file2014_2_2 <- read.csv(file.choose())
file2014_2_3 <- read.csv(file.choose())
file2014_3_1 <- read.csv(file.choose())
file2014_3_2 <- read.csv(file.choose())
file2014_3_3 <- read.csv(file.choose())
```

Note 2: Combine all files mentioned above into one dataset.

```
Data_2014 <- rbind(file2014_1_1, file2014_1_2, file2014_1_3, file2014_1_4, file2014_2_1,
file2014_2_2, file2014_2_3, file2014_3_1, file2014_3_2, file2014_3_3)
```

Note 3: Arrange data based on device ID and sent date (the date when messages were sent to be displayed on DMS).

```
Data_2014_arrange_by_devid <- arrange(Data_2014, DEVICE_ID, SENT_DATE.in.number)
```

Note 4: To get the duration of each message that was displayed

```
DATA_2014_DUR <- as.data.frame(Data_2014_arrage_by_devid$SENT_DATE.in.number[-1]-
Data_2014_arrange_by_devid$SENT_DATE.in.number[-
length(Data_2014_arrange_by_devid$SENT_DATE.in.number)])
```

Note 5: To create a new data frame just for the duration information

```
pre_final_2014<- rbind(DATA_2014_DUR, c(0))
```

Note 6: Combine two data frames (the original combined data and the duration information) into one final dataset

```
Final_2014_durwise<- cbind(Data_2014_arrange_by_devid, pre_final_2014)
```

Note 7: This line of code is to search each message in the final dataset if they contain any of the keywords listed in the quotation mark. If it does, it will return TRUE in the 'keywords' column, otherwise FALSE.

```
Final_2014_durwise$keywords <- grepl("CRASH | CRASH AHEAD | WRONG WAY | PED |
ACCIDENT | WORK CREW | YOUNG | IMPAIRED | SEAT BELT | LIGHT | LEAVING LANE
| DEATH | CRASHES | BUZZ | SIGNAL | WORK ZONE SAFETY | TREAD | MOVE OVER |
MOTORCYCLE | DRINK | ICE | PHONE | TAILGATE | DRUNK | SCHOOL | TICKET | FINE
| SPEEDING | SOBER | BUCKLE | TEXT | DEER | CYCLIST | HEADLIGHT | WORK ZONE",
Final_2014_durwise$MESSAGE)
```

Note 8: To obtain the dataset that only contain safety messages

```
only_keywords_2014 <- Final_2014_durwise[!(Final_2014_durwise$keywords=="FALSE"), ]
```

Note 9: Export the final dataset that contains only safety messages

```
write.csv(only_keywords_2014, file = "modified keywords2014")
```

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REFERENCES

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