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Quantifying Effectiveness and Impacts of Digital Message Signs on Traffic Flow

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16. Abstract

Digital message signs (DMS) are a vital part of the advanced traveler information systems (ATIS) that disseminate various real-time travel information to the road users, including traffic diversion, travel time, congestion, upcoming roadwork, lane closures, and incidents such as accidents. Other information includes inclement weather, speed regulations, special events, and safety related messages such as seatbelt usage campaigns. Although many state DOT guidelines (including Michigan) closely follow the Federal Highway Administration (FHWA)'s Changeable Message Sign Operation and Messaging Handbook, there exist a number of DMS operational practices that are unique to different states. With a limited budget and resources, it is important for the Michigan Department of Transportation (MDOT) to evaluate its current practices in order to invest only on DMS practices that have proved to be highly effective. Therefore, this research intended to develop a data driven methodology to assess the effectiveness of different DMS, message types and installation location in Michigan. The study also generated results to facilitate better allocation of MDOT's resources by investing in effective sign technologies for traffic improvement, and improve overall DMS operational practices in the state of Michigan.

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EXECUTIVE SUMMARY

Research Introduction and Motivation

Digital Message Signs (DMS) are a vital part of the advanced traveler information systems (ATIS) that disseminate various real-time travel information to the road users. They are digital devices that can display one or more alternative messages. DMS usually display traffic, operational, regulatory, warning, and guidance information. Specific examples of information displayed on DMS include traffic diversion, travel time, congestion, upcoming roadwork, lane closures, incidents such as accidents, inclement weather, speed regulations, special events, and safety related messages such as seatbelt usage campaigns. The Michigan Department of Transportation (MDOT) deployed the first DMS in 1978 on US-131, in Grand Rapids. Currently, MDOT has over 200 DMS (HNTB, 2018) managed and operated by three main MDOT Transportation Operations Centers (TOC), which are the Statewide Transportation Operations Center (STOC), Southeast Michigan Transportation Operations Center (SEMTOC), West Michigan Transportation Operations Center (WMTOC), as well as the Blue Water Bridge Operations Center (BWBOC).

Similar to other state DOTs, MDOT maintains the Digital Message Sign Guidelines manual which provides the general DMS operational guidelines. Although many state DOT guidelines closely follow the Federal Highway Administration (FHWA)'s Changeable Message Sign Operation and Messaging Handbook, there exist a number of DMS operational practices that are unique to these states. Literature shows that there exist several studies which have examined the effectiveness and impacts of DMS on traffic flow in other states to guide their practices. With a limited budget and resources, it is important for MDOT to invest only on DMS that have proven to be highly effective. This called for a more comprehensive DMS evaluation study which covers all DMS sign applications (e.g., real time travel delay information, detour options, queue warning signs, work zone signs, etc.), installation technologies (vertical and longitudinal locations, size, font, color, light intensity) and DMS deployment practices. Therefore, this research had the following specific goals:

1. Developing a data driven methodology to assess the effectiveness of different digital message signs, message types and installation locations.

2. Generating necessary results to allow better allocation of MDOT's resources by investing in effective sign technologies for traffic improvement.
3. Improving digital message sign operational practices in the state of Michigan.

Research approach

To accomplish the objectives of this research, the research team methodically performed several tasks including a literature review which uncovered practices and guidelines used by other states. It also revealed findings from past evaluations conducted in Michigan and elsewhere. The literature review was followed by a comprehensive survey of Michigan roadway users to collect their feedback on the DMS's usefulness and preferences. A series of field case studies were conducted to evaluate specific messages and DMS types, including a laboratory virtual reality (VR) simulation of alternative DMS message phasing designs. The case studies included quantifying and evaluating the impact of weather-related DMS messages on driver speeds; assessing the feasibility of automating the process of displaying messages using Environmental Sensor Station (ESS) data; and an evaluation of the efficacy of selected weather-related messages. Another case study focused on assessing accuracy of travel times displayed on DMS and also identifying factors associated with travel time variations around the state of Michigan. DMSs are used to display travel time of alternative routes to aid motorists on their decision making for route choice. A case study was conducted to quantify the impact of DMS messages on traffic diversion. Construction zones pose challenges to motorists and cause delays. In addition to static signs used to control traffic in work zones, the use of Portable Changeable Message Sign (PCMS) is common. A case study evaluating the benefits of deploying a PCMS to a construction site, was also conducted. Finally, cost-benefit analyses of selected cases were conducted to derive conclusions and recommendations on best and cost-effective practices.

Research Results and Conclusions

Analysis of the survey of more than 900 users of Michigan roadways show that in general, drivers seek different types of trip/route information and use different sources to search for that information after they have started their journey. Traffic conditions and incident information are the type of travel information most often sought by drivers. Drivers also mostly use internet sources (e.g., smartphones) and DMS to search for different types of information. Guiding traffic during incidents and roadwork are the two road conditions during which drivers stated that DMSs are most useful. In addition, understanding DMS content was identified as a significant factor affecting drivers' compliance with DMS messages. This makes perfect sense because if a message is not understood, compliance is impossible. Specific DMS design and operation features and characteristics that need high priority in the effort to facilitate understanding of DMS content include the density of DMS use, message phasing, and clarity of message characters as well as text color. Although survey participants indicated other color preferences for specific conditions, analysis showed that in general the use of yellow color on black background increased visibility of the DMS text. Participants also suggested that increasing clarity of messages with respect to the location of an incident was important to avoid confusion. Furthermore, participants stated that phasing DMS messages made it difficult for them to read both messages in their entirety.

In general, results from case studies conducted in this study indicated that specific DMS messages influence driver behaviors, consistent with survey results. Specifically:

- Assessment of the impact of weather-related message on traffic speeds indicated that the message "ROAD MAY BE SLIPPERY, REDUCE SPEED" resulted in a 5.66 mph reduction in speed by speeding drivers (those approaching the DMS at 80+ mph) just after seeing the message. Similarly, the messages reminding drivers about presence of snow or freezing rain resulted in speed reductions in the segments downstream of the DMS.
- Evaluation of the impact of displaying alternative routes' travel times on motorists' decision making found that the base likelihood of diverting to the alternative route increases by 35% when the alternative route is 1 minute faster than the preferred route. This value was obtained after accounting for drivers' familiarity with the route and traffic volume level. The finding aligns with the survey results, in which drivers stated that they were using the DMS

to seek various information including travel time and they found the information provided by the DMS to be useful.

- Using Portable Changeable Message Sign (PCMS) to inform drivers of lane closure ahead due to construction work improved traffic flow by increasing the percentage of drivers who merge to the open lane early. Specifically, the percent of vehicles merging early increased by 3.18 percent when the PCMS message about lane closure was displayed compared to when it was not displayed. Also, as a result of drivers merging early when the PCMS message was on, there was an average of 5.2 percent reduction in travel time across the work zone compared to when the PCMS message was off.
- The comparison of travel times observed in the field with those displayed on DMS showed that they were reasonably similar, especially when a motorist is driving within the speed limit.
- The analysis of overall travel times displayed on DMS indicated that travel time varies more in urban areas, especially areas with high traffic volume. The results also showed that more travel time variations are observed in daytime since that is when traffic is more dynamic.

A simulation study was conducted using Virtual Reality (VR) technique to investigate the impact of message phasing time and message length on readability and comprehension by motorists. In Michigan, the ATMS defaults to 4 second phase time and 0.3 seconds between phases when DMS messages are displayed in phases. While the results from simulation study may not be conclusive due to the sample size of participants, they highlight important findings, specifically:

- There is association between motorists' speed and the length of the messages displayed in phases on the DMS. Readability of both messages was lower for longer messages compared to relatively shorter message.
- Also, readability of both messages with a phasing time of 4 seconds was lower compared to when the phasing time was 2.5 seconds.

Analysis of the costs and benefits of DMS associated with changes in driver behavior in response to DMS messages observed through case studies was conducted. Among other findings, the results showed that:

- The travel time savings associated with using PCMS in work zone to advise drivers of the upcoming lane closure outweigh the cost. It was also determined that the benefits are a function of the amount of traffic (AADT), distance from the PCMS to the beginning of the work zone, and the percentage of trucks in the traffic mix.
- Using DMS to inform drivers of the hazardous weather condition is a cost-effective way to reduce potential crashes associated with speeding. The benefits can be realized instantly, especially if two or more weather-related crashes associated with speed have been observed at the location.
- Displaying travel times of alternative routes save road users' time. The saving benefits outweigh the cost of installing and operating DMS and are especially pronounced when there is an incident along one of the alternative routes.

Recommendations

The findings from this study are consistent with many previous studies evaluating the effectiveness and impact of DMS in traffic flow. However, a number of findings can lead to adjustments in current MDOT practices to maximize the effectiveness of DMSs. Specifically:

1. When conveying the location of an event (or incident) to drivers using DMS message, street name suffixes (e.g., St, Rd, etc.) should be used to avoid confusing motorists who are unfamiliar with the location. If possible, include the distance to the incident. Almost 50 percent of survey respondents asked about clarity of different messages used to convey the location of an incident stated that a message such as “CONGESTION AFTER MARKET” was unclear compared to a message such as “CONGESTION AFTER MARKET AVE” or “CONGESTION AHEAD 1 MILE.” Page 10 of the November 14, 2019 version of the MDOT Dynamic Message Sign Guidelines could be revised to reflect this.

2. MDOT should consider automating weather-related messages, in addition to travel times. The case study clearly demonstrated that it is possible to automate the display of weather-related messages using Environmental Sensor Stations (ESS) detections. However, further research should be conducted to identify other practical issues such as location of ESS compared to DMS and automation decision process (e.g., decision thresholds). Automation priority should be given to the messages that recommend specific actions to be taken by motorists based on the detected conditions, for example "ROAD MAY BE SLIPPERY, REDUCE SPEED."
3. Survey participants stated having difficulty reading messages when operated in phases. For example, the ability to read both messages from two screens when DMS message phasing is used was the most problematic DMS feature mentioned by drivers. The simulation study confirmed existence of potential issues associated with phasing time and message length and also suggested an issue with phasing duration. There is a need for MDOT to conduct an extensive study to test different phasing designs in the field and laboratory to identify the best designs to implement.

1 Introduction

1.1 Problem statement and research background

The digital message sign (DMS) (also referred as dynamic message signs, variable message sign (VMS) or changeable message sign (CMS)) is a vital part of the advanced traveler information systems (ATIS) that disseminates various real-time travel information to road users. This sign is a digital device that can display one or more alternative messages. The DMS usually displays traffic, operational, regulatory, warning, and guidance information. Specific examples of information displayed on a DMS include traffic diversion, travel time, congestion, upcoming roadwork, lane closures, incidents such as accidents, inclement weather, speed regulations, special events, and safety related messages such as seatbelt usage campaigns (Dudek, 2004; FHWA, 2009). The information provided by a DMS, such as incidents and route alternatives, enhance the even distribution of traffic in the roadway network, thus improving the overall performance of the traffic system and reducing potential traffic delays (AlKheder et al., 2019). The Manual on Uniform Traffic Control Devices (MUTCD), Chapter 2L, stipulates various aspects of DMS, which include the descriptions, applications, legibility, message length and units of information and installation of permanent DMS devices (FHWA, 2009). For specific aspects, the MUTCD refers readers to the Federal Highway Administration (FHWA)'s Changeable Message Sign Operation and Messaging Handbook, which provides DMS operational guidelines (Dudek, 2004). Each state DOT have guidelines that supplement the DMS design and operational practices provided by the FHWA manuals and handbooks. Such guidelines and policies include how each message type should be posted, a list of message types that are prohibited and the procedures on how message types are designed and approved (Roelofs and Schroeder, 2016).

The Michigan Department of Transportation (MDOT) began deploying intelligent transportation systems (ITS) program in the 1960s. One of the components of ITS under Advanced Traveler Information System (ATIS) is DMS. The first DMS in Michigan was deployed in 1978 on US-131, in Grand Rapids. Currently, MDOT maintains over 200 DMS units (HNTB, 2018) managed and operated by three main MDOT Transportation

Operations Centers (TOC), Southeast Michigan Transportation Operations Center (SEMTOC), West Michigan Transportation Operations Center (WMTOC), as well as the Blue Water Bridge Operations Center (BWBOC). Many studies have examined the effectiveness of DMS in other states (e.g., a study by Haghani et al, 2013, in Maryland). In Michigan, however, a study conducted by Oh et al, (2015) to analyze the costs and benefits of Intelligent Transportation Systems (ITS) deployed by the MDOT included some evaluation of the effectiveness of DMS. A user preference survey was conducted to analyze drivers' familiarity, degree of usefulness and trust of different ITS devices. In terms of familiarity, DMS was the most recognized ITS component, with 98.4 percent of respondents stating they recognized this device. The degree of DMS usefulness by message type was also examined, although not all message types were explored. The most helpful DMS message reported by survey respondents was a message giving an advance notice of an incident and recommending an alternative route or detour. Further, 93 percent of survey respondents stated that they trust the information provided by DMS. In terms of DMS effectiveness in altering travel behavior, most of the respondents stated that DMSs helped them to avoid congestion and calm their anxiety as the DMS informed them about reasons for congestion. Overall, the evaluation results showed that the use of DMS in Michigan was rated as very popular, useful and trustworthy to road users. Recently, MDOT concluded another study evaluating the effectiveness of crash fact/safety messages on DMSs (Savolainen et al. (2021)). Among other findings, the study concluded that in general, the type of safety message displayed had minimal impact on driver behavior. Also, the results did not show significant differences with respect to total or nighttime crashes based upon the frequency of pertinent safety messages. It should be noted, however, that the study focused on safety messages only. However, other DMS messages may have impact on traffic flow and consequently crashes.

The deployment of DMS devices remains prevalent in Michigan and other states. Given the limited budget and resources available, it is important for MDOT to invest only on DMS that have proven to be highly effective. This calls for a more comprehensive DMS evaluation study which covers all DMS sign applications (e.g., real time travel delay information, detour options, queue warning signs, work zone signs, etc.), installation technologies (vertical and longitudinal locations, size, font, color, light intensity) and DMS deployment practices. The technology for these DMS devices has been growing over time, prompting the need for updated DMS evaluation studies. In 2016, for example, FHWA completed a study in Michigan which evaluated the MDOT's Weather Responsive Traveler Information (Wx-TINFO) system. The system processes the weather data and provides automated weather alerts and DMS message recommendations to TOC operators (Toth et al., 2016). However, posting of the recommended messages to DMS is mainly accomplished manually. Evaluating the potential for automating such processes is also important because it can save time and improve efficiency. Furthermore, the effectiveness of DMS devices by different geographical areas, (i.e., urban/suburban, and rural) is yet to be investigated in Michigan. The effectiveness of DMS is likely to differ across geographical areas due to the differences in drivers' socioeconomic and demographic characteristics and drivers' travel behavior, as well as traffic patterns.

1.2 Objectives of the study

This research had the following specific goals:

4. Developing a data driven methodology to assess the effectiveness of different digital message signs, message types and installation location.
5. Generating necessary results to allow better allocation of MDOT's resources by investing in effective sign technologies for traffic improvement.
6. Improving digital message sign operational practices in the state of Michigan.

1.3 Research approach

To accomplish the objectives of this project, the research team methodically performed several tasks including a literature review which uncovered practices and guidelines used by other states. It also revealed findings from past evaluations conducted in Michigan and elsewhere. The literature review was followed by a comprehensive survey of Michigan roadway users to solicit their feedback on the DMS usefulness and their preferences. A series of field case studies were conducted to evaluate specific DMS messages and types, including a laboratory virtual reality (VR) simulation of alternative phasing of DMS messages. Finally, cost-benefit analyses of selected cases were conducted to derive conclusions and recommendations on best and cost-effective practices. Figure 1.1 presents the research approach and organization.

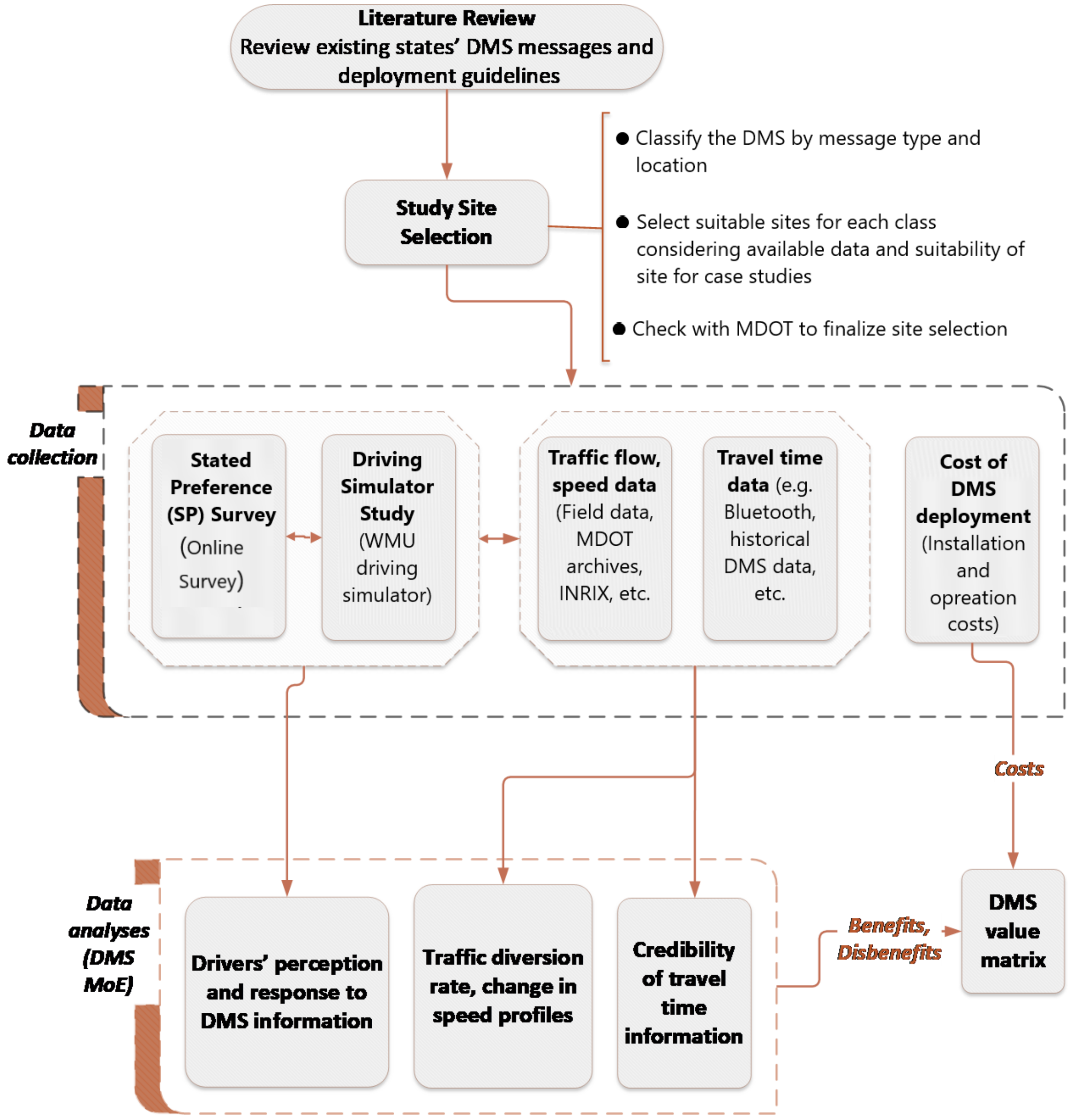


Figure 1.1. Research approach and organization

2 LITERATURE REVIEW

2.1 Introduction

This chapter summarizes the literature review conducted for this study. The review focused on current DMS application guidelines and practices in other states. It also examined previous methods for evaluating effectiveness of DMS. The findings from literature review were considered in subsequent chapters.

2.2 General criteria in the design of Digital Message Signs

The MUTCD requires uniformity in the design of DMS, which includes shape, color, dimensions, legends, borders, and illumination. DMS message design, which encompasses message content, length, load, and format, has to consider all possible human factors (Campbell et al., 2012). Drivers have a limited amount of time to read the displayed message on the DMS. How much they can read is a function of legibility distance and driving speed. Legibility distance refers to the maximum distance that a driver can first correctly identify letters and words on a sign (FHWA, 2009). It may be influenced by the visual capabilities of the drivers, environmental factors, roadway conditions such as a high percentage of trucks, and road geometry such as the presence of hills. Further, the legibility and visibility of the DMS message are limited to DMS technologies which vary in terms of contrast ratio, luminance, character spacing, and character resolution (Campbell et al., 2012).

The message length needs to be well structured because drivers have limited time to read and comprehend the message as they drive. The MUTCD quantifies the message length as the total number of words displayed on the sign. Message load refers to the units of information presented by words. Typically, a single unit of information contains 1 to 4 words (Dudek, 2006). Every single unit of information must answer an anticipated question from the motorist. Therefore, it is important to find the optimum number of information units based on the driver's visual characteristics and roadway characteristics. Too many units of information may cause a low comprehension rate while fewer units of information may aggravate message ambiguity. Banerjee et al (2019) did a study to determine the optimum number of units of information in DMS that will influence the driver's speeding behavior. The comprehension time was found to be low for fewer units of information. The results showed that participants with age below 55 years slowed down when the unit of information on the DMS was 6-7 while participants in the age group of 26-35 years increased speeds when DMS displayed 2-4 units of information.

2.3 Evaluation of DMS effectiveness

Several studies have explored the effectiveness of DMSs in terms of their design and the way they are operated. The design aspect includes installation details of DMS technologies such as vertical and horizontal location, size, font, color, light intensity, and units of information. Operational factors include proximity of the DMS location relative to the event displayed; when the message is displayed; and message display duration. The most important measure of DMS effectiveness is the travelers' compliance rate to the specific instructions being communicated (displayed) by the DMS. It is challenging to assess this measure quantitatively as it is hard to associate specific driver responses with the DMS information in a complex driving environment. However, various methods have been used to qualitatively and quantitatively estimate the effectiveness of DMS devices. Each study that evaluated the effectiveness of DMS used one or more of the following methods: stated preference survey, driving simulation, analysis of traffic flow, vehicle speeds, or analysis of travel time data. Perception surveys allow drivers to state their expected response to DMS contents. These surveys are used to measure drivers' attitude and perception on usefulness and readability of DMS information. Their perception and responses can then be connected with their socioeconomic and trip characteristics. Surveys are also useful in exploring the effectiveness of various DMS design aspects such as location, text and background color, shape, size, unit of information, among other characteristics. Field studies connect traffic, speed and travel time data to the change in traffic flow resulting from the messages displayed on a DMS. They can also be used to measure the actual percent of traffic diverting to alternative routes in response to messages displayed on a DMS. Field studies have also been used to study reliability of travel times displayed on a DMS. Other studies have used traffic simulation to quantify the effectiveness of a DMS.

2.3.1 DMS evaluation studies using stated preference survey

The survey method is useful in assessing drivers' attitudes, and perceptions of the usefulness and reliability of DMS information. Drivers who consider DMS as a reliable and useful source of information have often been reported to follow the recommended DMS actions (Ma et al, 2014). Benson (1997) assessed the driver's behaviors towards DMS as an effective tool to provide traffic information using seven focus groups and a survey of more than 500 motorists in Washington, D.C. Messages that were highly supported include posting the exact location of accidents, time-tagging traffic information followed by delay time estimates, safety messages, and posting of alternative messages. Time-tagging refers to displaying of the time when a traffic report was first posted on the DMS. This enables the drivers to see how old the information is and judge for themselves about the information accuracy. Three-fifth of the respondent said they would likely take the alternative route recommended by DMS in the case of heavy congestion. In London, a study by Chatterjee et al (2002) investigated the effect of different DMS messages on route choice. A logistic model estimated using stated preference survey results indicated that the location of accident and message characteristics such as content was associated with driver willingness to divert. Overall the drivers thought of DMS as a useful and reliable source of information and therefore support the future investment of DMS.

Socioeconomic characteristics of motorists are one of the contributing factors associated with driver's propensity to divert to an alternative route as recommended by DMS. A study by Kattan et al (2010) found that drivers in the age group of 20–30 years and 30–45 years were less likely to divert to a DMS suggested route while drivers older than 45 years were more likely to divert to a suggested route. In another study, female drivers were more likely to divert to an alternative route compared to male drivers (Ma et al., 2014).

The degree of familiarity with the DMS recommended route and overall network condition is also a key factor in determining the compliance rate (Dia and Panwai, 2007) Drivers who are familiar with alternative routes are more likely to divert to an alternate route recommended by DMS or choosing another route (Kattan et al., 2010; Ma et al., 2014).

Drivers' interest in seeking for pre-trip and en-route information can also impact the likelihood of compliance with DMS message. Kattan et al (2010) found that there was a significant correlation between the propensity of complying with DMS information and the use of traffic information such as TV, radio, etc. Drivers who were keen on listening to other traveler information sources were more likely to comply with the DMS message in terms of route diversions and changes in trip destinations.

Trip characteristics also have been found to influence the propensity to comply with DMS message. A study conducted in Canada found that the trip characteristics such as purpose, time, and length have an impact on diversion behavior. The school /work trips, long-distance trips, and long travel time trips have a negative correlation with the likelihood of route diversion (Choocharukul, 2008; Kattan et al., 2010).

DMS design has been investigated in many studies to capture the perceptions and preferences of drivers towards different DMS designs. A stated survey conducted in Beijing, China, found that the graphical messages on DMS were preferable than the conventional text message (Ma et al., 2014). Wang et al (2007) assessed the effect of using the graphics in DMS by location, color, and frame. They showed that graphical DMS resulted in faster response time from the drivers than the text message and that amber was the most preferable color. The left side of the text was the appropriate location for graphics and the conventional traffic sign frame was the most preferable frame to the graphic frame in the DMS. Similarly, a stated preference survey conducted by Wang et al (2006) revealed the most preferable DMS design was one frame static message (without flashing), and green-amber color combination. Also, familiarity with information wording and context, level of detail, interpreted meaning, previous experience, and trust of DMS information has been reported to affect drivers’ response to DMS message (Sharples et al., 2016).

2.3.2 DMS evaluation studies using traffic simulation

The driving simulation has been used to reveal participants’ preferences and route choices in many studies. The simulated driving environment can provide drivers with virtual driving experience with no risks and allows researchers to control the experiment under different virtual scenarios (Yan and Wu, 2014). For the DMS, several studies have conducted simulation to discern the preferences of participants and stated preference survey to validate participant responses (Roca et al., 2018). The purposes of driving simulation studies were mainly taking account of DMS design and operational effects on traffic.

Lai et al (2010) investigated the influence of DMS design on driver performance under different colors schemes and number of message lines. The study hypothesis was that the effective color coding can potentially be used to represent different classes of DMS information. It was revealed that color and number of lines in the message had a significant effect on the response time of the driver but it did not affect drivers' response accuracy. The faster response was observed for two-color than for one- and three-color schemes. Similarly, a video-based study conducted in Rhode Island, USA, investigated the lines and color formats of DMSs. The study findings indicated that discrete messages display resulted in less response time than sequential messages. Two-lines DMS message took less response time than three lines DMS message (Wang and Cao, 2005). However, with all these promising results, care must be taken to avoid excessive usage of color as it may increase the message comprehension time.

The DMS formats such as multi-combination of color and phasing have been tested in a simulation environment. Responses to such color and phasing design have been investigated based on the gender and age of the participants (Wang et al., 2006; Yang et al., 2005). The results showed amber or green or a green-amber combination was the most favored color schemes. Also, the driving simulation approach has been utilized to understand the effect and preferences of graphic-aided information in the dynamic message signs. Wang et al (2007) highlighted the effect of adding graphics with different color configuration on drivers' response. The study investigated design preferences about DMS such as using a text versus graphics, color, location, type of phasing, and flashing graphics. The driver response was found to be faster on the graphic-aided message rather than other message types, especially for the non-native English-speaking participants. A similar study that was conducted by Yan & Wu (2014) investigated other additional DMSs configurations such as location and the use of graphics on DMS messages. Drivers were more willing to change the route recommended by DMS guidance information delivered by graphics than the text-only format.

Several simulation studies have been conducted to address the effects of the DMS on operational traffic behavior such as driving speed variation and route diversion choice at the work zone. Bham & Leu (2018) conducted a study in speed reduction and variation on work zones to examine the effect of the Portable Changeable Message Sign (PCMS) on the compliance rate for the drivers. The message sign "Prepare to Stop//Traffic Ahead" was the most effective message for reducing vehicle speeds relative to the other messages upstream of the lane closure. In another study, Huang et al (2013) provided DMS design recommendations that minimize the injuries and fatalities related to the work zone. The drivers were found to reduce speed by 11% after passing the DMS. Teenagers and high risk taking drivers tended to drive at a higher speed in work zones. Also, drivers who reported driving more on rural roads had lower compliance in work zones. On the safety aspect, a simulation study by Jeihani et al (2013) found that DMS is a safety device since the drivers didn't reduce their speed significantly to read the DMS content.

Various studies have also investigated the diversion of drivers to assess the reliability, understanding, and usefulness of the DMS using simulation studies. The participants' compliance with DMS message has been investigated based on message content, and position of signs The design, clarity, and reliability have been found to affect the compliance rate of the driver towards the DMS (Dutta et al., 2004; Guattari et al., 2012; Yan and Wu, 2014). Jeihani et al (2017) conducted a study to understand the driver's response to route diversion message displayed on the DMS by integrating driving simulator and network simulation. The study findings revealed a high compliance rate with dynamic message signs in the absence of the route guidance information such as GPS. Compliance was also associated with the reliability of travel time and perceived trustfulness of DMSs by drivers.

2.3.3 DMS evaluation study using field traffic volume and speed data

Various studies have evaluated the effectiveness of dynamic message signs using volume and speed data derived from loop detectors and other sensors. DMS as part of advanced traveler information systems (ATIS) has been used to guide drivers during periods of congestion to improve efficiency of the transportation network, traffic flow, and travel time and on-ramp access to freeways (Xiong et al., 2011).

Gao et al (2011) evaluated the daily origin-destination (OD) demand fluctuation due to dynamic traffic information provided by DMS and other sources of traveler information. It was found that the dynamic traffic information displayed on DMS is less likely to be effective under regular traffic conditions. Major benefits are likely to arise during peak hours and in unusual traffic conditions caused by accidents. The DMS information has been found to increase the traffic flow rate and decrease the duration of congestion.

Yin et al (2012) examined the changes in traffic flow attributed to VMS using loop detector data and incident reports on freeways in Virginia. The diversion propensity was found to increase for longer incidents, lane blockage, and lower speeds on the affected route. In general, the diversion rate was found to relate to instant traffic flow characteristics, traffic demand, and incident characteristics.

Haghani et al (2013) evaluated the potential impact of DMS on traffic flow using data archives from DMS operational data, traffic volume, and speeds from probe-based sensors in Maryland, USA, highways. Bluetooth sensors were deployed onsite to collect field data used to monitor the travel time and traffic diversions. Different message types were evaluated, namely; Danger/Warning (Type 1), Informative/Common Road Conditions (Type 2), and Regulatory/Non-Traffic-Related (Type 3). The study results indicated that drivers reduced speed most often in response to Type 1 messages, followed by Type 2 and Type 3. The average decrease in speed due to message display was 3.13 mph, which occurred in about 17.1% of all the cases that were examined. Overall, the results indicated that the DMS message display is not likely to cause congestion. The study also evaluated the impact of DMS on traffic condition which include traffic diversion. Analyses showed a 5-20 percent increase of traffic diversion rates on alternative routes recommended by DMS.

In another study, Foo et al (2008) analyzed the dynamic impacts of DMS messages on traffic diversion using 3 years of loop detector data, from 2003 to 2005.

Highway 401 in Toronto, Ontario, Canada was used as a case study. The study found an increase in diversion rates ranging from 17.9% to 24.55% attributed to the change of the DMS message. The effectiveness of DMSs in diverting traffic tended to peak shortly after the message changed and stabilized in about 10 min. A similar study was conducted by Xu et al (2011) which modeled drivers' en-route diversion behavior under variable message sign messages using real detected traffic data. The study found that drivers were more sensitive to travel time information than traffic congestion information. Also, drivers were more likely to divert/change routes during peak hours. In response to the queue length, the diversion rate was higher when drivers personally saw the queue than when they obtained the information from VMS.

Edara et al (2014) evaluated the effectiveness of DMS devices in detouring traffic on Missouri's rural corridors. The study observed a significant increase in the flow on the detour route and a decrease in traffic flow in the corresponding route during the freeway closure. Also, the effectiveness of DMS in alerting drivers of the upcoming work zone was assessed. A positive safety effect of using DMS was observed as the average speed on the work zone decreases by 3.65mph and 1.25mph on the two test sites.

Ghosh et al (2018) analyzed the impact of DMS on traffic flow by analyzing incidents that required a driver to take an alternative route or a diversion. The effectiveness of the DMS was measured by the change in traffic flows at the nearby downstream exit points when the DMS was displayed compared to normal days. The traffic flow increased by 14% at the nearby exit points downstream of the DMS location.

2.4 Credibility of DMS messages

The need to convey accurate information to the traveler is very important to ensure the credibility of the message signs. Factors that have been reported to reduce the credibility of DMS include displaying inaccurate, irrelevant, obvious, repetitive, trivial, erroneous, and poorly designed messages (Dudek, 2006). Displaying the same message for a long time may cause drivers to lose interest or ignore the sign information that may likely affect their travel and, in some cases, require them to act. Travel time on DMS requires higher quality and immediate real-time data compared to other traveler information services due to its high visibility and the direct impact it has on drivers' behavior (Center for Advanced Transportation Technology, 2012)

Several studies have evaluated the accuracy of the displayed travel time information displayed on DMSs. Monsere et al (2006) validated the dynamic message sign freeway travel time messages with ground truth geospatial data. The study used probe vehicle data as ground truth data to validate the travel-time estimates displayed on DMS that are derived from inductive loop detector data. The study used DMS travel time information managed by the Oregon Department of Transportation (ODoT). It was found that travel-time estimates derived from inductive loop detector data are reasonably accurate. In instances where the discrepancy was observed it was because of low detector density and poor detector placement.

A similar study conducted by Ban et al (2010) evaluated the DMS travel time estimates against probe vehicle data (ground truth) obtained from FasTrak in the San Francisco Bay Area-California. The accuracy of travel time estimates derived from loop-detector data was found to be better in off-peak periods than in peak periods. Also, the accuracy of travel time estimation was found to depend on the sensor's locations.

Another study conducted by Haghani et al (2013) used Bluetooth sensors instead of probe vehicles as the ground truth data. The case study areas were along the major travel corridor in the Baltimore Metropolitan area in Maryland. The average difference between the displayed time on DMS and true travel times derived from Bluetooth sensors was less than one mile per hour.

Overall, the studies that evaluated the accuracy of travel time displayed on DMS concluded that they are reasonably accurate. Issues such as detector spacing should be further investigated to increase the accuracy and hence the credibility of travel time information to the roadway users.

2.5 Evaluation of DMS benefits

There are various benefits of using DMS such as improved traffic flow as the vehicles approach the incidents, improved use of alternative routes, and safer merging operations in events where the lanes are closed downstream (Minnesota DOT, 2012; Wisconsin

DOT, 2015). The benefits can also be quantified at a network level using aggregate measures such as a change in total system travel time. The agencies need to have effective methods of performing the cost-benefit analysis of DMS deployments to ensure a reasonable and sustainable level of investment (Oh et al., 2015).

Mounce et al (2007) developed a guideline for evaluating dynamic message signs both qualitatively and quantitatively. The framework for evaluation of DMS benefits encompasses mobility, safety, and user satisfaction. The DMS safety benefits can be quantitatively assessed using safety crash history. Further, mobility performance measures such as volume, speed, queue length, and delays can be used to quantify operational DMS benefits. The quantitative metrics can be obtained using historical data or conducting field data collection. On the other hand, the qualitative assessment includes metrics such as the level of service and driver expectation. These metrics can be assessed qualitatively mainly using a different form of surveys such as field intercept study and focus groups. Qualitative metrics include factors such as comfort, convenience, usefulness, timeliness, accuracy, and reliability of DMS information. The qualitative measures pose a practical challenge when estimating the DMS benefits as they cannot easily be assigned a monetary value compared to quantitative metrics such as travel time and crashes.

Tarry (1996) provides examples of performance indicators for DMS as part of the framework for assessing the benefits of ITS. The mobility metrics provided by Mounce et al (2007) such as volume, speed, and queue length can be expounded to cover specific applications of DMS as shown in Table 2.1. For example, by using vehicle volume and speed metrics, impact analysis indicators such as degree of diversion at nodes, reduction of delays, change in total travel times, and reduction in duration of congestion, can be obtained. The indicators established in Tarry’s study can be leveraged in evaluating the impact of DMSs on traffic flow.

Table 2.1. DMS performance indicators (Tarry, 1996)

Evaluation Category	Indicators
Technical Analysis	• Reliability and correctness of information displayed • Appropriateness of plans • Operator interface usability • Sensitivity to errors in inputs • Level of operator intervention needed
Impact Analysis	• Degree of diversion at nodes • Reduction of delays and extent of queuing • Change in travel time on individual routes • Change of total travel times and journey distances in the network • Reduction in the duration of congestion • Reduction in emissions • Drivers response to: a range of information types, travel cost differences on alternative routes, and driver's familiarity with the network • Reduction in traffic diversion through urban areas or on the undesirable routes • Number of accidents
Socioeconomic Analysis	• User cost-benefit analysis of performance network • Impact on non-road users
Legal/Institutional Analysis	• Legal/institutional conflicts
Public Acceptance Analysis	• User attitudes to DMSs • Non-user attitudes to DMSs

A critical assessment of the network impacted by DMSs is important when conducting the cost-benefit analysis of DMS. The total network travel cost has been reported to be a function of network traffic demand, probability of path transformation, DMS location, DMS operational strategy, and the content of traffic guidance information (Chen et al., 2018). The optimal distribution of vehicle flow to an alternative path when the main route is congested is critical in the computation of benefits DMS information (Giglio and Minciardi, 2008). Further, the DMS message inducing drivers to take an alternative route may in-turn decongest the main route. Therefore, the DMS cost-benefit analysis should capture the dynamic aspect of network equilibrium.

Different studies have used either qualitative measure or/and quantitative metrics to evaluate the benefits of DMS on freeways. Edara et al (2014) evaluated the effectiveness of dynamic message sign following the full freeway closure in a rural freeway. The simulation study was conducted to isolate the benefit of DMS from other traveler information systems such as TVs, radio, and newspapers. The cost-benefit analysis considered the sensitivity of the network to different levels of driver's compliance. The cumulative monetary benefit for three days was estimated to range from $2,394 to $65,643 depending on the drivers' compliance rate. In Michigan, a study conducted by Oh et al (2015) analyzed the costs and benefits of Intelligent Transportation Systems (ITS) deployed by the MDOT. Part of the analysis was to evaluate the effectiveness of the DMS. A user preference survey was conducted to analyze the familiarity and degree of usefulness and trustfulness of different ITS devices. In terms of familiarity, DMS was the most recognized ITS component, with 98.4 percent of respondents. The degree of DMS usefulness by message type was also explored. The most helpful DMS message reported by survey respondents was a message giving advance notice of the incident and recommending an alternative route or detour. DMS travel time information was identified as the least helpful. Further, 93 percent of survey respondents stated that they trust the information provided by DMS. In terms of DMS effectiveness in altering travel behavior, most of the respondents stated that DMS helped them to avoid congestion and calm their anxiety as the DMS informed them about reasons for congestion. Overall, the evaluation results showed that the DMS displays in Michigan were very popular, useful, and rated as trustworthy by road users.

2.6 Review of DMS guidelines, operational policies, practices, and procedures

The review of different state guidelines aimed at understanding the operational policies and procedures used by other states. States' guidelines have different operational policies that are either recommended or modified from MUTCD and FHWA Policy Memorandums. Dudek (2006) highlighted several operational policy issues and procedures at both state and regional levels. Such issues include responsibility for the operation of DMS, message display during the periods, displaying upcoming roadwork, limits of DMS influence for incidents, among others. This study gathered two federal guidelines and fifteen state guidelines as listed in Table 2.2.

The review of guideline investigated the following operational policies across the states:

- Prohibited use of Dynamic Message Signs (DMS)
- The use of dynamic elements such as graphics on DMS
- Prioritization of message requests

Table 2.2. List of reviewed guidelines and manuals

	State/Agency	**Guideline**	**Year**
1	Federal	Manual on Uniform Traffic Control Devices (FHWA, 2009)	2009
2	Federal	Changeable Message Sign Operation and Messaging Handbook (Dudek, 2004)	2004
3	Alaska	State of Alaska Permanent Changeable Message Sign (CMS) Policy Guide (Alaska DOT, 2006)	2006
4	California	Changeable Message Sign Guidelines (Wooster and Al-Khalili, 2013)	2013
5	Colorado	Guidelines on Variable Message Signs (VMS) (Colorado DOT, 2017)	2017
6	Connecticut	Remote Control Changeable Message Signs Operation Guide (IBI Group, 2014)	2014
7	Maine	Maine Standard Operating Procedures for use of Changeable Message Sign (CMS) (Maine DOT, 2007)	2007
8	Michigan	Dynamic Message Sign Guidelines (Michigan DOT, 2019)	2019
9	Minnesota	CMS Manual of Practice (Minnesota DOT, 2012)	2012
10	Missouri	910.3 Dynamic Message Signs (DMS) (Missouri DOT, 2019)	2019
11	Montana	Montana Department of Transportation Variable Message Sign Guidelines (Montana DOT, 2013)	2013
12	New Mexico	Dynamic Message Sign (DMS) Operation Manual (New Mexico DOT, 2015)	2015
13	New York	Guidelines for Use of Variable Message Signs (VMS) (New York State Thruway Authority, 2011)	2011
14	North Dakota	NDDOT DMS Guidelines (Advanced Traffic Analysis Center, 2008)	2008
15	Oregon	Guidelines for the Operation of Variable Message Signs on State Highways (Oregon DOT, 2008)	2008
16	Virginia	VDOT Changeable Message Sign (CMS) Policy (Virginia DOT, 2017)	2017
17	Wisconsin	Traffic Engineering, Operations & Safety Manual (Wisconsin DOT, 2015)	2015

2.6.1 Prohibited use of DMS

The information provided on DMS can be from scheduled or unscheduled events that have a significant impact on traffic. The MUTCD prohibits the use of advertising, animation, rapid flashing, dissolving, exploding, scrolling, or other dynamic elements on DMS. A review of the states' guidelines indicated that most states, including Michigan, had a section which lists all prohibited messages and message displaying techniques. The prohibited message displaying techniques include the use of animation, rapid flashing, dissolving, exploding, scrolling, or other dynamic elements on DMS. The prohibited messages where mainly non-traffic related messages. Generally, the following messages were consistently prohibited by each state: advertisements, general/vague and obvious information, public service announcements, date, time, general weather information, conflicting messages, normal recurrent congestions, web-links, email, and phone information. See Appendix 9.1 for more information about the prohibited message and displaying techniques for each reviewed state as stipulated in states' DMS guidelines.

2.6.2 The use of graphics on DMS

Some states, for example, California, Missouri, New Mexico, and Virginia may allow the use of graphics provided that certain conditions are met. The California Changeable Message Sign Guidelines (Wooster and Al-Khalili, 2013) generally prohibits the use of graphic except when the sign has a full matrix technology capable of mimicking the approved MUTCD standard symbols and legends. Further, the full matrix sign should display an exact duplicate of a standard sign or other sign legend using standard symbols, the standard alphabets and letter forms, route shields, and other typical sign legend elements in the appropriate color combinations and with no apparent loss of resolution or recognition. The DMS guidelines for Minnesota (Minnesota DOT, 2012), Missouri (Missouri DOT, 2019), New Mexico (New Mexico DOT, 2015), and Virginia (Virginia DOT, 2017) have similar policies as California on the use of graphics. In addition, the state of Missouri DMS guideline already has a library of available graphics contained in the Advanced Transportation Management System (ATMS) software which may be used for certain messages. The Virginia DMS guideline states that the use of graphics or symbols has shown to improve motorists' comprehension and understanding leading to improved operations and safety (Virginia DOT, 2017). The statement is in agreement with the Federal Highway Administration (FHWA) study on the use of graphics and symbols on dynamic message signs (Ullman et al., 2009). The study identified observed benefits of using graphic display such as improving the ability of drivers to identify available lanes and improving comprehension levels, especially for non-native-language drivers.

The review of state DMS guidelines indicates that the decision on whether to allow the use of graphics is dependent on the DMS technology capable of mimicking approved MUTCD guidelines. Currently, the capabilities of each state's DMS vary significantly based on the age and technology of DMSs (Roelofs and Schroeder, 2016). Some states such as Minnesota, Virginia, and Michigan have started trials with the full-color matrix DMS for text and graphics. The data attained from these trials will help to discern the operational and safety impact associated with the use of graphics in the DMS.

2.6.3 Prioritization of DMS Messages

Michigan DMS guideline prioritizes what message to display on DMS based on the event impact. The priority level is given to high impact events such as full freeway closure, ramp closures, lane closure, and road blocking incidents. The second priority level is given to medium impact events such as congestion/ramp backups, short term work zone, weather conditions. Public service announcements such as weather, safety messages have the least priority. Travel time messages can be posted with any of the higher priority messages. The review of other states’ guidelines about message prioritization follows a similar trend. The messages with high priority are those which have a direct impact on traffic which include incidents as the results of planned (work zones) or unplanned (crash) events. Non-traffic related messages such as public announcements, safety-related messages are given the lowest priority. Appendix 9.2 provides a detailed summary of each state guideline on DMS message prioritization.

2.7 The use of Portable Changeable Message Sign (PCMS)

Portable Changeable Message Sign (PCMS) is made for multiple purposes and so they come in various sizes, power sources, mounting options, and methods of programming. The size of PCMS ranges from small (6 feet wide and 4 feet tall) to large (10 feet wide by

7 feet tall). The size of PCMS depends on the number of characters to be displayed. The technology includes flip disk, LED, fiber optic, and Hybrid. The visibility and the number of moving parts differ among the technologies. The PCMS can be solar-powered, battery-powered, or using the generator as a power source. The method of message programming includes remote programming and onsite programming. Moreover, the PCMS can be mounted on a trailer or truck (FHWA, 2013a).

There are guidelines to be followed in the creation of a PCMS message to be displayed in a work zone. Generally, the message content should state the problem, the location involved, and the recommended action that drivers should employ to avoid or reduce the problem. It is recommended that the message should be brief, informative, and understandable with one or two phases preferably. The message should have a maximum of three lines (with eight characters in each line) per phase. When more than one phase is employed, each phase should be understood alone (FHWA, 2013b). For the message to be effective, drivers should be able to understand it within a short time (Ullman, Dudek and Ullman, 2005).

The effectiveness of PCMS on reducing the speed of drivers has been measured by most of the previous researchers. Zhang, Gambatese and Vahed (2014) evaluated the effect of implementing traffic control devices on highway preservation projects. They considered the speed reduction effect associated with specific signs (identified in the initial traffic control plan) and its combination with other traffic signs compared to the initial traffic control plan of the project. The study included implementation of speed limit signs, PCMS both on rollers and trailers, speed monitoring display, police patrolling, police parked on the side, tubular markers, and drums on both sides. The findings suggested that a combination of temporary speed limit signs, PCMS on both roller and trailer, and radar speed monitoring display had a significant speed reduction on drivers.

Li, Bai and Firman (2010) performed a study on the effectiveness of the PCMS in speed reduction of drivers in rural work zone areas. They investigated the effectiveness of PCMS in three scenarios which are PCMS on, PCMS switched off but still visible and PCMS removed from the road and out of sight. Results suggested that PCMS was highly significant in reducing the speed of drivers when switched on compared to when it was off and out of sight. Furthermore, their findings suggest that the presence of PCMS had significant speed reduction whether on (by 4.7 mph over a distance of 500 feet) or off (3.3 mph over a distance of 500 feet) compared to when it was out of sight. A similar study was done by Bai, Finger and Li, (2010) on the drivers' responses to temporary signage which involved PCMS whether on or off compared to the temporary traffic sign. Results showed that a visible PCMS whether on or off is more effective in reducing speed in a two-lane work zone in the rural area.

When used to control traffic congestion in work zones, two traffic merging techniques have been proposed. The early merge strategy instructs drivers to merge early from the closed lane prior the point where they will be forced to merge. This strategy is said to work best in low-traffic volume roads to avoid congestion. The second strategy is the late merge (zipper merge) where drivers are instructed to remain in their respective lanes until the point of merging. This enables the utilization of the lanes to the full potential and smooth flow of traffic without the need to change lanes frequently. The late lane merge works best in high traffic volume and low average speed in congestion. The merging strategy employed can be static or dynamic depending on the signs used (Algomaiah and Li, 2021). The static early merge which uses static signs is like the traditional merge where drivers are warned approximately 1 mile in advance, and they tend to merge before the taper. In the typical traffic control, the traditional merge works well until congestion occurs. When congestion occurs, the capacity of the work zone is exceeded, and queues extend past the warning signs (Pesti *et al.*, 1999). The use of messages on PCMS in the two recently introduced merging strategies has been done by multiple researchers. Grillo, Datta and Hartner (2008) used several PCMSs in implementing the dynamic late merging in work zones which improved the flow of travel and the percentage of vehicles that merged near or at the taper location. Harb *et al.*, (2009) also suggested the use of simplified dynamic lane merging systems which employed the use of PCMS in the short-term work zone. Their findings suggest that the early merging rate was higher in the dynamic early merge system compared to the late merge system. This showed that the drivers were complying with the messages displayed on the PCMS.

3 DATA COLLECTION

This chapter introduces data collected by the research team, which included Microwave Vehicle Detector Sensor (MVDS), Continuous Counting Station (CCS), archived probe vehicle travel time, DMS operational messages, weather records from Environmental Sensor Stations (ESS), surveys, field travel time (using Bluetooth (BT) sensors), and simulation data (using Virtual Reality (VR) simulation). The MVDS, CCS, probe vehicle, and DMS operation data were acquired from MDOT while the Bluetooth sensor data, survey data, and simulation data were collected directly from the field or laboratory experiment. This chapter focuses mainly on data collection, preprocessing steps, and assessment of the availability and usability of the data.

3.1 DMS operational data

DMS operational data was one of the essential datasets used in this research. The data is tied directly to the overall objective of the research which was to evaluate the impact of DMS messages on the traffic flow. The research team requested MDOT to provide the DMS operational data for the year 2019. The data received included the list of 277 DMS units and their metadata such as the DMS name, DMS type by size, status – whether the DMS is operational, and location information (longitude and latitude). Table 3.1 shows the distribution of DMS by type.

Table 3.1. Distribution of DMS by type

DMS type	Frequency	Percent
Large	202	72.9%
Controller	41	14.8%
27X95	12	4.3%
27x100	5	1.8%
27x105	5	1.8%
Small	4	1.4%
27x108	2	0.7%
18X125	1	0.4%
27x60	1	0.4%
32x36	1	0.4%
Support	1	0.4%
No info	2	0.7%

The majority of the DMS were categorized as large (73%) followed by other smaller sizes. The DMS size was part of the important criteria used in the later analysis of site selection and cost-benefit analysis. The DMS location information was crucial as it enabled the researchers to spatially integrate the DMS metadata with other forms of data. The DMS location was mapped using ArcGIS and integrated with other GIS layers such as the MDOT region layer, Michigan road layer, county layer, among others. Figure 3.1 shows the spatial distribution of DMS across Michigan counties and Traffic Operation Centers (TOC). It can be observed from Figure 3.1 that most of the DMS are located in Southeast TOC followed by West Michigan TOC, as expected.

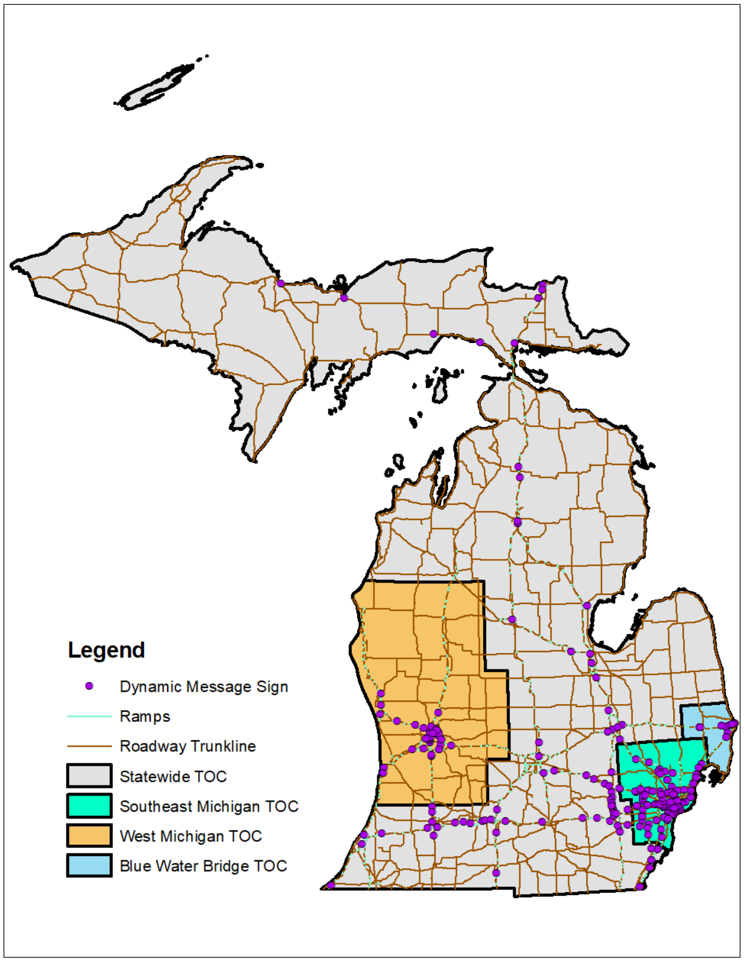
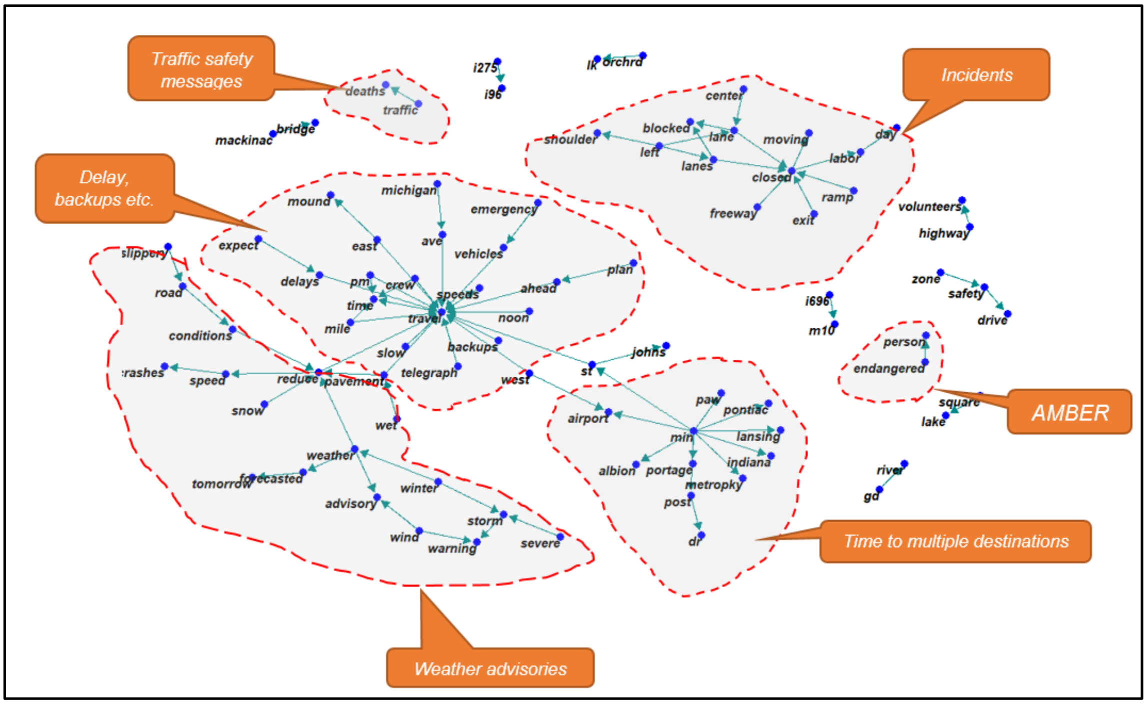


Figure 3.1. Distribution of DMS in Michigan by MDOT TOCs

Processing of the DMS operational data included converting DMS messages from coded format to human-readable format and categorizing the messages into various groups which conform with the Michigan Digital Message Sign Guidelines. Since the DMS message file did not have an attribute that categorized the messages by type, an effort was made to categorize the messages using text mining approach. The text mining approach was used to extract the keywords that were used in each of the messages. The keywords were then used to form clusters of word networks. Each cluster represented a particular group of messages. Figure 3.2 shows the clusters of the word network. From the word cluster, one could observe various keywords that were used to form various message types.



Traffic safety messages

Incidents

Delay, backups etc.

AMBER

Time to multiple destinations

Weather advisories

Figure 3.2. A cluster of words used in DMS messages

The final message types derived from the 2019 DMS operational data were:

- Work zone-related messages (lane and/or roadway closures, Traffic detours)
- Incident-related message (lane blockage due to accident, broken vehicle, etc.)
- Congestion related message (traffic pattern changes)
- Weather-related messages (Weather impacts and advisories on roadway conditions)
- Real-time travel times messages

- Amber Alerts
- Safety-related messages (General Safety Information, PSAs etc.)

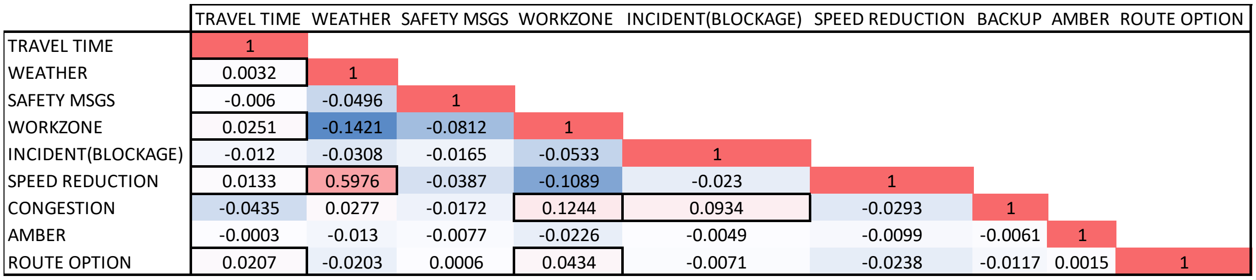
Table 3.2 shows examples of DMS messages for each type.

Table 3.2. Examples of DMS message types

Category	**Message Example**
Weather	SNOW ADVISORY PLAN FOR 2X LONGER PM COMMUTE TIME VIA I-75 NORTH M-8 5 MI 10 MIN I-696 10 MI 18 MIN
Incident	LEFT LANE BLOCKED AHEAD USE CAUTION TRAVEL TIME TO US-127 S 7 MI 7 MIN M-52 25 MI 23 MIN
Weather	SLIPPERY ROAD CONDITIONS REDUCE TRAVEL SPEEDS TRAVEL TIME TO I-75 11 MI 11 MIN I-675 18 MI 18 MIN
Congestion	SLOW TRAFFIC UNTIL FULLER AVE TRAVEL TIME TO LEONARD 5 MI 12 MIN WALKER 13 MI 19 MIN
Safety	ICE AND SNOW DON'T CAUSE CRASHES DRIVING TOO FAST FOR CONDITIONS CAUSES CRASHES
Amber	WRONG WAY DRIVER REPORTED IN AREA USE EXTREME CAUTION

It should be noted that the MDOT Digital Message Sign Guidelines allow for the message to be concatenated and displayed in phases. So, it is common practice in Michigan to find a travel time message concatenated with other message types depending on the situation. A correlation matrix was created to see which message types are frequently concatenated together as shown in Table 3.3. The correlation ranges from -1 to 1 with the values of -1 and 1 indicating a perfect correlation. From Table 3.3, it can be observed that it is a common practice for travel time to be concatenated with the weather, incident, work zone, and route option, among others. The weather-related messages tend to be concatenated with the message instructing road users to reduce speed while the congestion messages tend to be concatenated with work zone and incident messages.

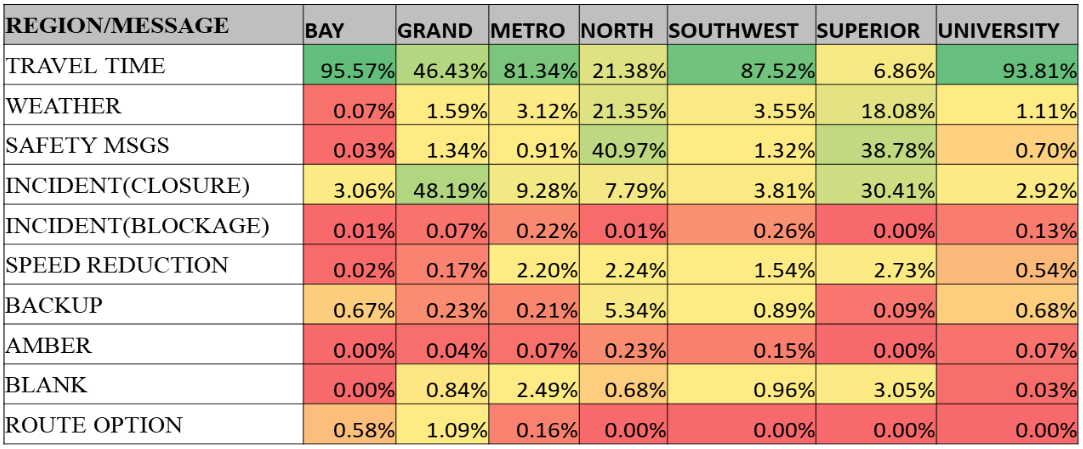
Table 3.3. Example of the correlation matrix for some of the message types to indicate co-occurrences



	TRAVEL TIME	WEATHER	SAFETY MSGS	WORKZONE	INCIDENT(BLOCKAGE)	SPEED REDUCTION	BACKUP	AMBER	ROUTE OPTION
TRAVEL TIME	1								
WEATHER	0.0032	1							
SAFETY MSGS	-0.006	-0.0496	1						
WORKZONE	0.0251	-0.1421	-0.0812	1					
INCIDENT(BLOCKAGE)	-0.012	-0.0308	-0.0165	-0.0533	1				
SPEED REDUCTION	0.0133	0.5976	-0.0387	-0.1089	-0.023	1			
CONGESTION	-0.0435	0.0277	-0.0172	0.1244	0.0934	-0.0293	1		
AMBER	-0.0003	-0.013	-0.0077	-0.0226	-0.0049	-0.0099	-0.0061	1	
ROUTE OPTION	0.0207	-0.0203	0.0006	0.0434	-0.0071	-0.0238	-0.0117	0.0015	1

The message types were also grouped by MDOT regions to get a general overview of which types of messages are displayed mostly in each region. This was useful in the later analysis whereby the results informed the research team on what type of messages to evaluate. Table 3.4 shows the frequency of use of each DMS message by percent. The percent sums up to 100 for each region. The frequency of use was extracted directly from the raw DMS operational data files. Each timestamp for a given message was considered one count. From Table 3.4, it can be seen that the travel time message was predominantly displayed in Bay, Metro, Southwest, and University while, as expected, weather and safety-related messages were predominant in North and Superior regions.

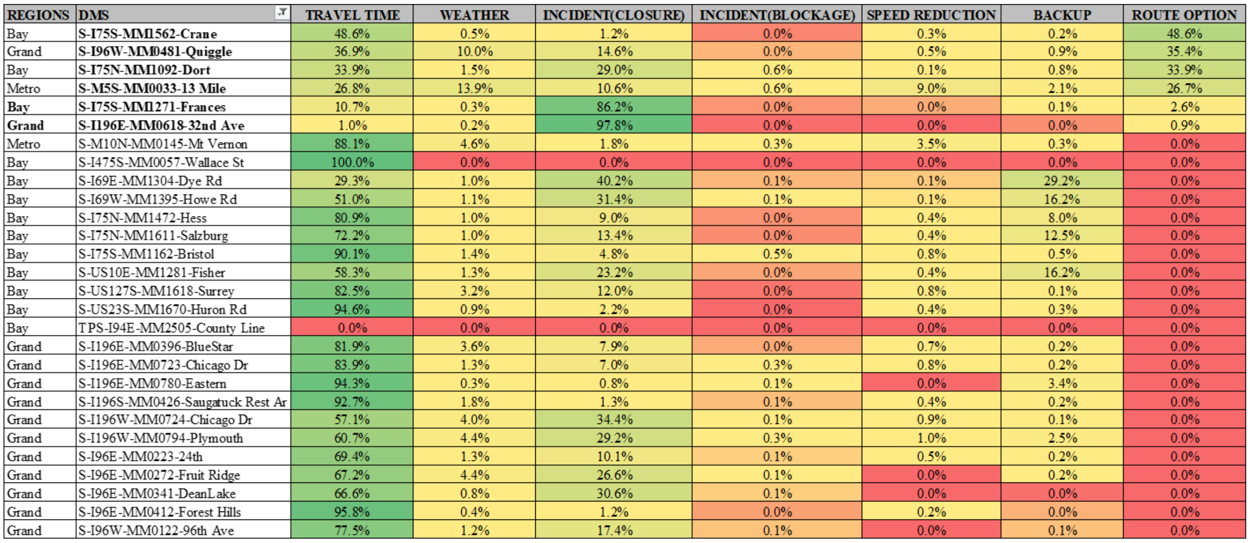
Table 3.4. Message utilization by MDOT region



REGION/MESSAGE	BAY	GRAND	METRO	NORTH	SOUTHWEST	SUPERIOR	UNIVERSITY
TRAVEL TIME	95.57%	46.43%	81.34%	21.38%	87.52%	6.86%	93.81%
WEATHER	0.07%	1.59%	3.12%	21.35%	3.55%	18.08%	1.11%
SAFETY MSGS	0.03%	1.34%	0.91%	40.97%	1.32%	38.78%	0.70%
INCIDENT(CLOSURE)	3.06%	48.19%	9.28%	7.79%	3.81%	30.41%	2.92%
INCIDENT(BLOCKAGE)	0.01%	0.07%	0.22%	0.01%	0.26%	0.00%	0.13%
SPEED REDUCTION	0.02%	0.17%	2.20%	2.24%	1.54%	2.73%	0.54%
BACKUP	0.67%	0.23%	0.21%	5.34%	0.89%	0.09%	0.68%
AMBER	0.00%	0.04%	0.07%	0.23%	0.15%	0.00%	0.07%
BLANK	0.00%	0.84%	2.49%	0.68%	0.96%	3.05%	0.03%
ROUTE OPTION	0.58%	1.09%	0.16%	0.00%	0.00%	0.00%	0.00%

The message utilization table was expanded to display the specific DMS within a given region as shown in Table 3.5. This assisted in the selection of sites for field data collection to evaluate the effectiveness of the specific message type. For example, in Table 3.5, DMS named S-I75S-MM1562-Crane, S-I96W-MM0481-Quiggle, S-I75N-MM1092-Dort, S-M5S-MM0033-13 Mile, and S-I75S-MM1271-Frances were potential sites for evaluating the effectiveness of route option study. All were utilized to display route option messages at relatively higher percentages ranging from 26.7% to 48.6%. Similarly, the potential sites for other types of messages were selected for further investigation.

Table 3.5. Percent of DMS utilization by message type



REGIONS	DMS	TRAVEL TIME	WEATHER	INCIDENT(CLOSURE)	INCIDENT(BLOCKAGE)	SPEED REDUCTION	BACKUP	ROUTE OPTION
Bay	**S-I75S-MM1562-Crane**	48.6%	0.5%	1.2%	0.0%	0.3%	0.2%	48.6%
Grand	**S-I96W-MM0481-Quiggle**	36.9%	10.0%	14.6%	0.0%	0.5%	0.9%	35.4%
Bay	**S-I75N-MM1092-Dort**	33.9%	1.5%	29.0%	0.6%	0.1%	0.8%	33.9%
Metro	**S-M5S-MM0033-13 Mile**	26.8%	13.9%	10.6%	0.6%	9.0%	2.1%	26.7%
Bay	**S-I75S-MM1271-Frances**	10.7%	0.3%	86.2%	0.0%	0.0%	0.1%	2.6%
Grand	**S-I196E-MM0618-32nd Ave**	1.0%	0.2%	97.8%	0.0%	0.0%	0.0%	0.9%
Metro	S-M10N-MM0145-Mt Vernon	88.1%	4.6%	1.8%	0.3%	3.5%	0.3%	0.0%
Bay	S-I475S-MM0057-Wallace St	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Bay	S-I69E-MM1304-Dye Rd	29.3%	1.0%	40.2%	0.1%	0.1%	29.2%	0.0%
Bay	S-I69W-MM1395-Howe Rd	51.0%	1.1%	31.4%	0.1%	0.1%	16.2%	0.0%
Bay	S-I75N-MM1472-Hess	80.9%	1.0%	9.0%	0.0%	0.4%	8.0%	0.0%
Bay	S-I75N-MM1611-Salzburg	72.2%	1.0%	13.4%	0.0%	0.4%	12.5%	0.0%
Bay	S-I75S-MM1162-Bristol	90.1%	1.4%	4.8%	0.5%	0.8%	0.5%	0.0%
Bay	S-US10E-MM1281-Fisher	58.3%	1.3%	23.2%	0.0%	0.4%	16.2%	0.0%
Bay	S-US127S-MM1618-Surrey	82.5%	3.2%	12.0%	0.0%	0.8%	0.1%	0.0%
Bay	S-US23S-MM1670-Huron Rd	94.6%	0.9%	2.2%	0.0%	0.4%	0.3%	0.0%
Bay	TPS-I94E-MM2505-County Line	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Grand	S-I196E-MM0396-BlueStar	81.9%	3.6%	7.9%	0.0%	0.7%	0.2%	0.0%
Grand	S-I196E-MM0723-Chicago Dr	83.9%	1.3%	7.0%	0.3%	0.8%	0.2%	0.0%
Grand	S-I196E-MM0780-Eastern	94.3%	0.3%	0.8%	0.1%	0.0%	3.4%	0.0%
Grand	S-I196S-MM0426-Saugatuck Rest Ar	92.7%	1.8%	1.3%	0.1%	0.4%	0.2%	0.0%
Grand	S-I196W-MM0724-Chicago Dr	57.1%	4.0%	34.4%	0.1%	0.9%	0.1%	0.0%
Grand	S-I196W-MM0794-Plymouth	60.7%	4.4%	29.2%	0.3%	1.0%	2.5%	0.0%
Grand	S-I96E-MM0223-24th	69.4%	1.3%	10.1%	0.1%	0.5%	0.2%	0.0%
Grand	S-I96E-MM0272-Fruit Ridge	67.2%	4.4%	26.6%	0.1%	0.0%	0.2%	0.0%
Grand	S-I96E-MM0341-DeanLake	66.6%	0.8%	30.6%	0.1%	0.0%	0.0%	0.0%
Grand	S-I96E-MM0412-Forest Hills	95.8%	0.4%	1.2%	0.0%	0.2%	0.0%	0.0%
Grand	S-I96W-MM0122-96th Ave	77.5%	1.2%	17.4%	0.1%	0.0%	0.1%	0.0%

3.2 Continuous Count Station (CCS) data

Traffic volume and speed were variables of interest in this research. Traffic volume was required to determine the number of road users at a particular instance of interest. Moreover, the traffic volume was also necessary to objectively explain the drivers' behaviors such as speed reduction. Traffic counts can be obtained either manually or automatically by using sensors, including Continuous Counting Stations (CCS) and Microwave Vehicle Detector Sensors (MVDS). Since MDOT maintains a number of CCSs throughout state routes, the research team explored the usability of this data in the study. CCSs are permanent traffic counting stations that collect vehicle volume continuously throughout the year. Some CCSs collect not only the traffic volume but also the vehicle speed, classification, and weight.

The 2019 file consisted of 131 CCSs distributed across the Michigan TOCs. Table 3.6 summarizes the CCSs in Michigan by identifying those within and not within the vicinity of a DMSs. The CCSs considered to be within the vicinity of a DMS were those within a 2-mile buffer from the DMS. Table 3.6 shows that more than half of all CCSs in Michigan were in the Statewide TOC. Despite a majority of CCSs being in this region, only 15% were within the vicinity of the DMS. Moreover, about a quarter (24%) of the CCS were installed in the Southeast Michigan TOC with about three-quarters (74%) of these CCS within the DMS vicinity. The West Michigan TOC has 14% of the CCS in Michigan and out of those, 33% are within the DMS vicinity. There were only 2 CCS in Blue Water Bridge TOC which is 1% out of the CCS in Michigan. Out of the two CCS in Blue Water Bridge TOC, only one was within the DMS vicinity. Generally, only 32% (42) of the CCS were within the vicinity of DMSs in Michigan.

Table 3.6. Distribution of CCS by traffic operation center

TOC	**NOT in vicinity of DMS**	**In vicinity of DMS**	**Total**	**% of CCS in the TOC**	**% of CCS in vicinity of DMS**
Blue Water Bridge TOC	1	1	2	1%	50%
Southeast Michigan TOC	8	23	31	24%	74%
Statewide TOC	68	12	80	61%	15%
West Michigan TOC	12	6	18	14%	33%
Grand Total	**89**	**42**	**131**	**100**	**32%**

By considering other factors, only 16 CCSs out of the 42 CCS were selected as suitable to for analysis. For these 16 CCSs, the research team requested their data from MDOT at an aggregation level of at most 5minutes. However, MDOT could only retrieve data that was at an aggregation level of one hour. This aggregation level could not be used in the analysis since a lot of traffic variations are expected to happen within one hour. This limited the use of CCS data in many analyses but it was still useful in validating other data collected using other methodologies, where appropriate. For example, the

CCS data was used as ground truth data to assess the accuracy of Microwave Vehicle Detection System (MVDS) data. In addition, it was used as an aggregate measure of traffic exposure in calibrating the model in the traffic diversion study (see Chapter 5).

3.3 Microwave Vehicle Detection System (MVDS) data

The microwave vehicle detection system is used by MDOT for collecting traffic data such as volume, occupancy, and speed data. The MVDS uses microwave radar signals that are designed to detect vehicles and collect traffic information. In Michigan, MVDS have been deployed massively especially in metropolitan areas. To determine the MVDS which could be used in the analysis, those within the proximity of the DMS (2-mile buffer) were identified. Unlike the CCS where only 32% were within the DMS vicinity, about three-quarters (74%) of the installed MVDS in Michigan are within the vicinity of the DMS. To further prove the suitability of MVDS, it was crucial to also assess their availability as well as their accuracy.

3.3.1 MVDS data availability

The MVDS data were available in 655 locations out of a total of 911 locations. The data contained traffic volume and the corresponding timestamp at an interval of one minute. These MVDS data which were provided at a minute level were aggregated to an hourly level to check the availability of the MVDS data throughout the year. Generally, the MVDS data availability was not high. It was observed only 74% of the MVDS were near the DMSs and hence their traffic data could be used in this study. The analysis of data availability for MVDSs within the vicinity of DMS indicated that none of the MVDS had 100% of the data available throughout the year (Figure 3.3). This limitation on the MVDS data availability led to relying mostly on field data collected manually by the research team using Bluetooth sensors and video cameras.

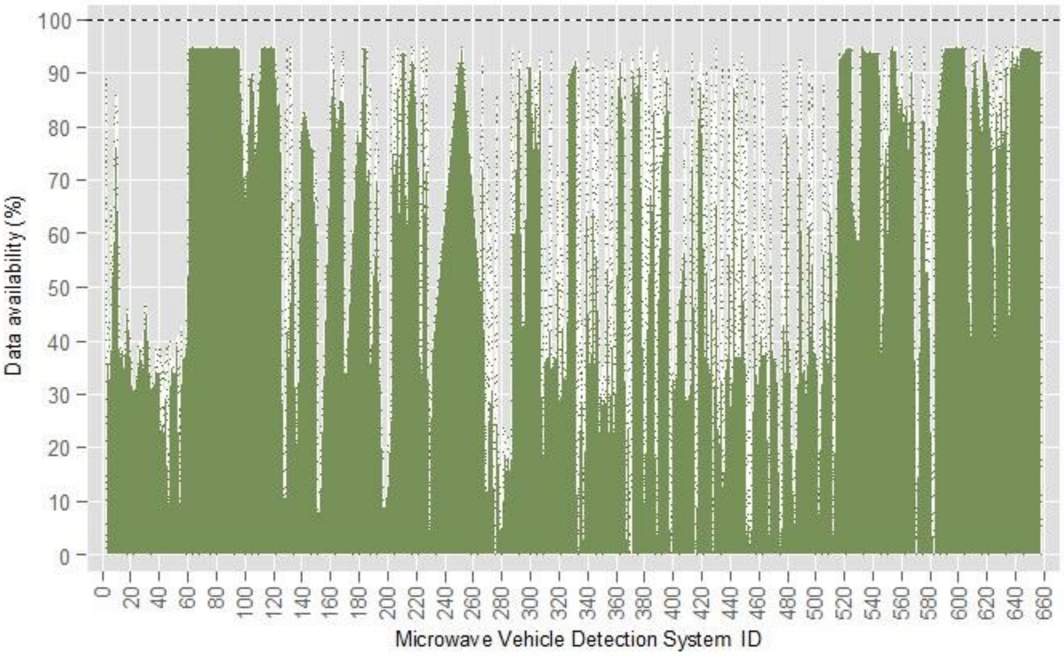


Figure 3.3. MVDS data availability at hourly level within 2-mile buffer of DMS

3.3.2 MVDS Data Validation

The usability of the MVDS data also depended on its accuracy. Past research conducted in Michigan showed that approximately thirty percent of the observed MVDS had accurate traffic volume and sixty percent of accurate speed data (Oh et al., 2018). To further assess usability of the available MVDS data from specific locations (i.e., those in the vicinity of DMS), data validation was performed. Comparison of the MVDS traffic volume data from two potentially usable sites to the nearby CCS sites was performed using the CCS data as the ground truth data. For similar dates and times, the MVDS volume and the CCS volume were plotted for both the northbound and southbound (Figure 3.4). Since the two sites had the CCS near the MVDS, it was expected that the volumes would be the same and the linear relationship (red line) would coincide with the expected (blue line) in Figure 3.4. The two volumes were found not to be equal since the fitted line did not coincide with the expected line. From both sites, the plot showed that the MVDS volume was much higher compared to the respective CCS volume.

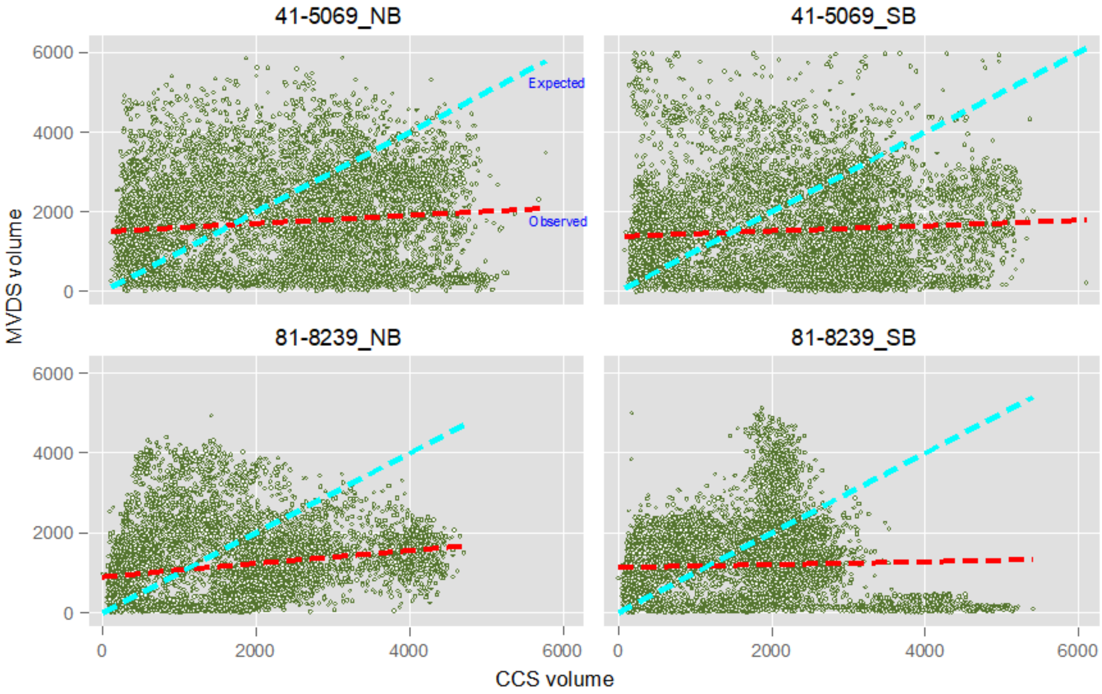


Figure 3.4. Comparison between CCS volume and MVDS volume

With these findings, it was noted that most of the MVDS data was not available and that which was available could not be reliable. Therefore, where the use of MVDS data was necessary, validation by comparing with manual counts was performed before using them in the analysis.

3.4 Environmental Sensor Stations data

Environmental Sensor Station (ESS) is a system that is made up of a network of environmental sensors. These stations consist of multiple types of sensors that measure various real-time atmospheric parameters, including air and road surface temperatures, barometric pressure, wind, salt concentrations on the road surface, frost depth, and dew point. Multiple ESSs have been employed in Michigan to monitor the atmospheric and road surface conditions. This enables MDOT to better manage the weather conditions and provide better travel information to the motorists. In this study, one ESS located in Grand Region was used to evaluate the feasibility of automating weather-related messages on a DMS located in the proximity of the ESS. Details of this case study are provided in Chapter 5.

3.5 Bluetooth Sensor and Video Camera data

The Bluetooth sensors detected the Bluetooth Media Access Control (MAC) addresses/fingerprints which are emitted from smart devices such as smartphones, tablets, wearable devices, and vehicular embedded systems. The MAC address does not change, and it is unique for each device which enabled tracking of a particular MAC address or fingerprint over time. The raw log data extracted from the sensors contained the timestamps for each MAC address. These Bluetooth sensors were mounted at MVDS poles or DMSs poles. In locations where MVDS or DMS poles were not conveniently available, MDOT a wooden pole was installed on the site (Figure 3.5). The detection range of each Bluetooth sensor is about 328 ft (100 m). Because of the large radius of detection, multiple timestamps could be registered for a single MAC address (Figure 3.6). Therefore, these timestamps were averaged to obtain one timestamp which is closer to the sensor location.

(a) Wooden pole (b) MVDS pole

Figure 3.5. Installation of Bluetooth sensors and camera

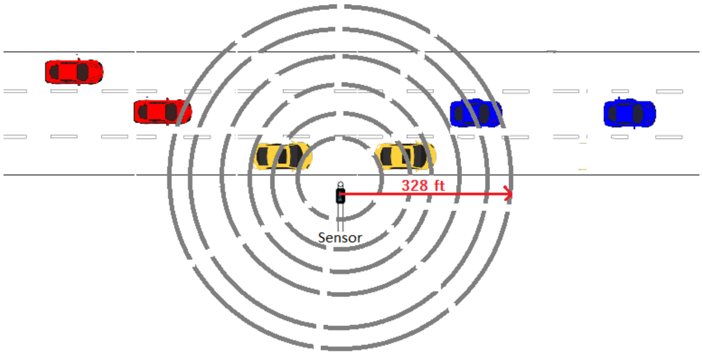


Figure 3.6. The detection range of the Bluetooth sensors

A thorough procedure was then established to process the raw timestamp data from two or more Bluetooth sensors to obtain the travel time and convert it into speed profiles where needed. To obtain the travel time between two sensors, the averaged detections with a similar fingerprint from the two sensor locations were matched. Since each detection has its respective timestamp, the difference in time between the two timestamps is the estimated travel time. The vehicle speed between the two sensors was calculated dividing the distance by the time difference between the two sensor locations. The analysis of the field studies employed the data (travel time or speeds) within the interquartile range to remove the outliers, a procedure which is documented thoroughly in the case study chapter.

Similarly, the traffic volume data was extracted from the video cameras. Where traffic volume data was required, video cameras were installed in the sites in a way that the drivers didn't know that they were being recorded. The counts were done manually using counting software at a one-minute interval. In the absence of CCS data, manual counts extracted from the video camera were also used as ground truth to check the accuracy of the MVDS volume before being used in the analysis.

3.6 Archived speed data

Speed data from Probe Data Analytics (PDA) RITIS provided by INRIX was used for certain analyses where Bluetooth data were not available. INRIX has multiple data sources which include traffic sensors, probe vehicles and INRIX Smart Dust Network. Speed information can be deduced from the traffic sensors such as radar sensors and induction loop sensors employed on the roadway. Also, INRIX has a large amount of probe vehicles with GPS devices to tell the location and speed of the vehicles in a roadway. INRIX has agreement with several fleet to get from them the speed and location data anonymously. On the other hand, INRIX Smart Dust Network averages the data from probe vehicles, traffic sensors and other real time traffic information to calculate speeds occurring in a particular segment at a certain degree of accuracy (Sharma et al., 2017).

3.7 Survey data

Another important aspect that was covered in this study was the determination of public perception of the effectiveness of the DMS. An online survey was administered through a link posted on Michigan “Mi Drive” and MDOT's Facebook page, where participants were encouraged to participate in the survey. The survey was done in two phases: Phase 1 was administered during summer time in 2020 from 06/11/2020 to 09/11/2020. Phase 2 was administered during winter time for the period starting from 02/05/2021 to 02/23/2021. The survey questions covered the respondent’s demographic information, trip characteristics, and driver’s perception of the DMS design and messages. In addition to that, the respondents were given one open-ended question to air out their views with regard to the DMS. Chapter 4 documents the survey data, analysis and results.

3.8 Simulation data

One of the main issues highlighted by survey respondents was their difficulty reading DMS messages when displayed in phases (see Chapter 4). Therefore, this study investigated the DMS phasing time by simulating the actual DMS environment. This study evaluated two phasing times (2.5 seconds and 4 seconds) and two messages with different lengths. Using the simulator, the vehicle trajectory and other parameters such as lane positioning and eye gazing were recorded. On the other hand, the survey questionnaire was used to record the demographic characteristics of the driver (such as age, gender and driving experience) as well as their feedback on the phasing scenarios tested.

4 Survey of Michigan Drivers on the Effectiveness of Digital Message Signs (DMS)

4.1 Introduction

This chapter covers an online survey designed to study the effectiveness of Digital Messaging Signs (DMS). The survey was administered online by inviting participants through a link posted on the Michigan Department of Transportation (MDOT)'s construction and traffic information website (Mi Drive) and Facebook page. The survey was designed to address the following specific objectives:

- Collect public perceptions on the effectiveness of DMS.
- Identify and study different factors associated with drivers' perception of their compliance with different messages displayed on DMS under different road and traffic conditions.

4.2 Survey Design and Administration

The original research plan included both an intercept and an online survey. However, the restrictions related to the COVID-19 pandemic made it impossible to conduct intercept surveys, and therefore only the online survey option was used. The survey was administered in two phases: Phase 1 in the summer of 2020 from 06/11/2020 to 09/11/2020, and Phase 2 in the winter of 2021 from 02/05/2021 to 02/23/2021. In general, the survey questions encompassed the following categories:

- *Demographic information*: These questions obtained information on the characteristics of survey respondents, such as their postal code, gender, age, and driving experience.
- *Trip characteristics*: These questions captured data on the type of vehicle typically driven by drivers, the type(s) of trip/route information that drivers usually sought after starting their trip (e.g., travel time, direction, and weather), and the source of trip/route information used after they have started their journey (e.g., DMS, radio, and smartphones).
- *Driver's perception of the design features and characteristics of DMS displays*: These questions captured information on driver's opinions concerning the design

features and general characteristics of DMS displays such as text color, location of DMS, etc. Other questions focused on driver perceptions on clarity of displayed messages, readability of the messages, the usefulness of DMS under different road and traffic conditions, drivers' likelihood to comply with different DMS messages under different road and traffic conditions, and DMS design and operation features and characteristics (e.g., text colors).

- *General opinions*: An opportunity for the respondent to make comments not captured by the surveyed questions.

The detailed survey questionnaire can be found in Appendix 9.3.

4.3 Survey Analysis Methods

Survey data were analyzed in two ways: (1) descriptive statistics and (2) hypothesis testing and modeling.

4.3.1 Descriptive statistics

Data collected from both survey phases (summer 2020 and winter 2021) were combined in this analysis which generated two main types of results: the number of drivers that answered each question and the percentage distribution of answers across each rating for each question. In each question analyzed, drivers were asked to provide their opinion using a 5-point Likert Scale. A graphical presentation of the percentage distribution by response (rating) was provided to visualize the results. In addition, a weighted average of the ratings for each question was determined. A weighted average is a single number that represents the overall survey rating for each question. It is a function of the number of people that chose a specific rating, the corresponding rating, and the total number of people who responded to that particular question. Mathematically, it can be shown as follows:

$$W_{avg} = \frac{(5 * n_5) + (4 * n_4) + (3 * n_3) + (2 * n_2) + (1 * n_1)}{n_1 + n_2 + n_3 + n_4 + n_5} \qquad 4.1$$

where numbers 1 through 5 are the Likert Scale ratings of importance and n_1 through n_5 are the corresponding number of responses for each Likert Scale rating.

4.3.2 Hypothesis testing and modeling

Hypothesis testing and modeling approaches were conducted to make statistical inferences and draw conclusions. The hypothesis testing specifically provided a statistical conclusion on whether drivers' responses differed by gender, age, or season (summer vs. winter). An ordered logistic regression analysis was conducted to identify factors influencing drivers' compliance with actions recommended on DMS messages. The following sections describe specific tests and modeling approaches.

a. Chi-square test

To investigate whether there exists a statistical dependency of drivers' opinions with demographic factors (age and gender), a chi-square test (χ^2) was used. A chi-square test, also known as the Pearson's chi-square test, is used to determine any statistically significant association between two variables being tested. It uses a contingency table's observed and expected frequencies to test any statistically significant difference between the two variables. Under the null hypothesis, the chi-square test states that; there is no statistically significant difference between the observed and the expected frequencies of categories of the contingency table (i.e., there is no association between the two variables being tested). The chi-squared test is given by:

$$\chi^2 = \sum \frac{\left(O_{ij} - E_{ij}\right)^2}{E_{ij}} \qquad 4.2$$

Where χ^2 is the Pearson's chi-square statistic.

O_{ij} is the observed frequency on row i and column j of the contingency table.

E_{ij} is the expected frequency on row i and column j of the contingency table.

b. Mann-Whitney U test

As pointed earlier, the survey was conducted in two phases: during the summer and winter seasons, to determine whether there are differences in responding between the summer and winter months. The Mann-Whitney U (MWU) test was conducted to test whether seasons influenced drivers' choices and opinions. The MWU test is a non-parametric test used to compare the differences between two groups by comparing the means of the ratings. One important assumption for using the MWU test is that the responses are at least ordinal. Since the survey data analyzed was ordinal, the MWU test was deemed suitable. The test is a two-sided test with the following hypothesis:

- The null hypothesis (H_0): The two populations are equal
- The alternative hypothesis (H_1): The two populations are not equal

The test statistics for the MWU test are denoted by U and are the smaller of the two values, U_1 and U_2. The test is defined as follows:

$$U_1 = n_1 n_2 + \frac{n_1(n_1 + 1)}{2} - R_1 \qquad 4.3$$

$$U_2 = n_1 n_2 + \frac{n_2(n_2 + 1)}{2} - R_2 \qquad 4.4$$

Where; n_1 and n_2 are the total observations from group 1 and group 2, respectively.

R_1 and R_2 are the sums of ranks for group 1 and group 2, respectively

c. *Logistic regression*

The major purpose of this study was to determine the effectiveness of DMS from the driver’s point of view. One way to measure the effectiveness of DMS is by assessing the compliance of drivers to the messages displayed on the DMS. Another way to assess the effectiveness is to survey drivers’ ratings of the likelihood that various factors would influence their compliance with actions recommended by DMS messages. Because the dependent variable (the rating provided by survey respondents) that explains the likelihood of drivers to comply with recommended actions on DMS messages were ordinal, the logistic regression was used (Long and Cheng, 2004; McCullagh 1980). The general equation for the logistic regression is given by:

$$y^* = x\beta + \varepsilon \qquad 4.5$$

Where, y^* is the dependent variable, *x* is the vector of independent variables, and ε is the error term. Since y^* is a categorical variable, the categories of responses can be expressed as:

$$y = \begin{cases} 0, & if\ y^* < \mu_1, \\ 1, & if\ \mu_1 < y^* \leq \mu_2 \\ 2, & if\ \mu_2 < y^* \leq \mu_3 \\ & . \\ & . \\ & . \\ N, & if\ \mu_N < y^* \end{cases} \qquad 4.6$$

Where µ is the cutoff point of the observed categories, and N is the total number of cutoff points given by the total number of categories minus one.

4.4 Results from General Analysis of Survey Data

The general analyses conducted included the overall analysis, the association of age and gender with drivers' responses, and the impact of season on perceptions towards DMSs.

4.4.1 Overall analysis

The overall analysis provided two specific results: percentage distribution of responses by rating and the weighted average of the responses. It utilized data collected during the entire survey period. A total of 929 individuals responded to the survey (719 responses in summer and 210 in winter). Table 4.1 is the summary of survey responses by different participant characteristics.

Table 4.1: Descriptive statistics of survey respondents

Age	**Gender**			**Driver type**			**Driving experience**		
	Male	Female	Other	Passenger Car Drivers	Truck Drivers	Motorcycle	15 years and less	More than 15 yrs	Unknown
16 - 20 yrs	10	0	2	12	0	0	12	0	0
21 - 24 yrs	18	7	1	26	0	0	26	0	0
25 - 40 yrs	118	40	8	155	11	0	60	106	0
41 - 59 yrs	213	120	6	326	13	0	24	315	0
60 - 64 yrs	93	74	6	164	9	0	0	173	0
65 yrs and Older	96	31	7	130	4	0	0	133	1
Other	22	12	45	67	3	9	2	49	28
Total	**570**	**284**	**75**	**880**	**40**	**9**	**124**	**776**	**29**
Grand Total	**929**			**929**			**929**		

The overall analysis provides a general overview and insight into the drivers' perception of the effectiveness of DMS displays (messages). The analysis included descriptive statistics that provided the distribution of responses for each question. Each question had five options from which drivers had to choose. In each question, a distribution of what percentage of drivers chose each option is provided in a colored graphical presentation. Each color represents one specific answer choice/option.

Furthermore, the weighted average results are presented in a bar graph. The weighted average analysis is used to compare the preferences among different choices. Below are the overall results for each survey question analyzed.

a. *How frequently do you seek and/or use the following trip and route information (if available) after starting the journey?*

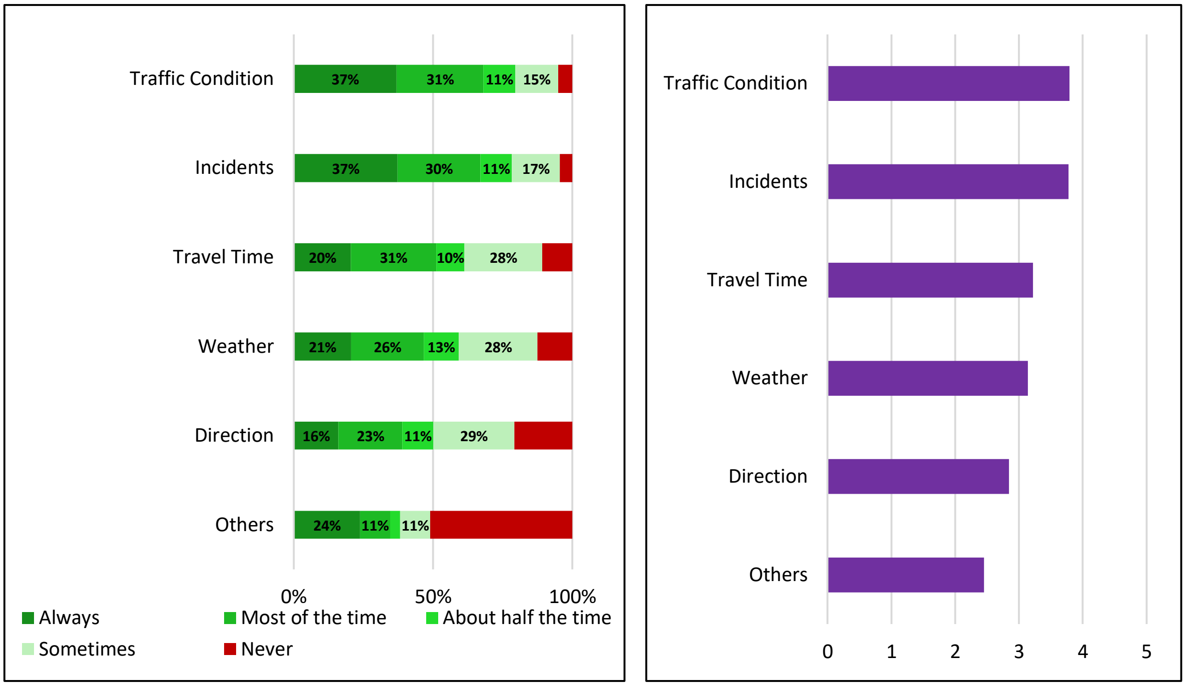
This question analyzed the type of trip/route information drivers seek after starting the journey and how frequently they seek them. It was important to specifically ask for types of trip/route information sought after they started their journey because DMSs are mainly used by drivers while driving in freeways after starting their trip. Survey respondents were asked to specify the frequency of seeking each of the following five types of trip/route information:

- **Travel time:** Before starting a trip, one might know how long their trip would take. This question specifically aimed at assessing whether travel time is important information that drivers are interested in even after starting their journey. The degree of interest is indicated by how frequently drivers said they would seek such information.
- **Direction:** Drivers usually know where they are going, but it is also true that there are drivers unfamiliar with the route, especially for long-distance travel. In such cases, drivers might only know the origin and destination of their trip and expect to obtain more directions from different sources as the trip progresses. In addition, there could be some circumstances (e.g., construction) that might dictate changes to the normal route (detours). Such conditions require the driver to either be familiar with the new route (detour) or search for direction information to the new

route. This question was specifically designed to determine how frequently drivers seek route direction information after starting the journey.

- **Weather condition:** Weather condition is another type of trip/route information that drivers seek after starting the journey. Understanding how important this information is to drivers would provide a basis for further investigation on how the presence or absence of such information can impact the usefulness of DMS displays.
- **Traffic condition:** In general, this question investigated the importance of traffic condition information to drivers. Just as with other types of trip/route information, DMS displays might increase the accessibility of this information to drivers.
- **Incident information:** Drivers were asked to rank how frequently they seek incident information after starting their journey. In addition, drivers were allowed to state other types of trip/route information they seek after they had started their journey.

A total of 908 individuals responded to this question. Figure 4.1a and 4.1b show the distribution of responses and the weighted average for each type of trip/route information sought, respectively. Traffic conditions and incidents were the most frequent among all trip/route information drivers always seek. About 37 percent of drivers reported always seeking traffic condition information and incident information while driving. The weighted average analysis shows that while traffic condition information ranked as the information sought most frequently, direction information was ranked the least of all (Figure 4.1b). That is to say, if the agency is to prioritize types of trip/route information to display on DMS based on drivers' opinion, then the priority should follow the following order: traffic conditions, incident information, travel time information, weather-related information, and direction. Survey respondents also listed other types of travel information, including amber alerts, service area location (e.g., rest areas, food, and gas), future road construction, and closures.



4.1a: Descriptive statistics

4.1b: Weighted average

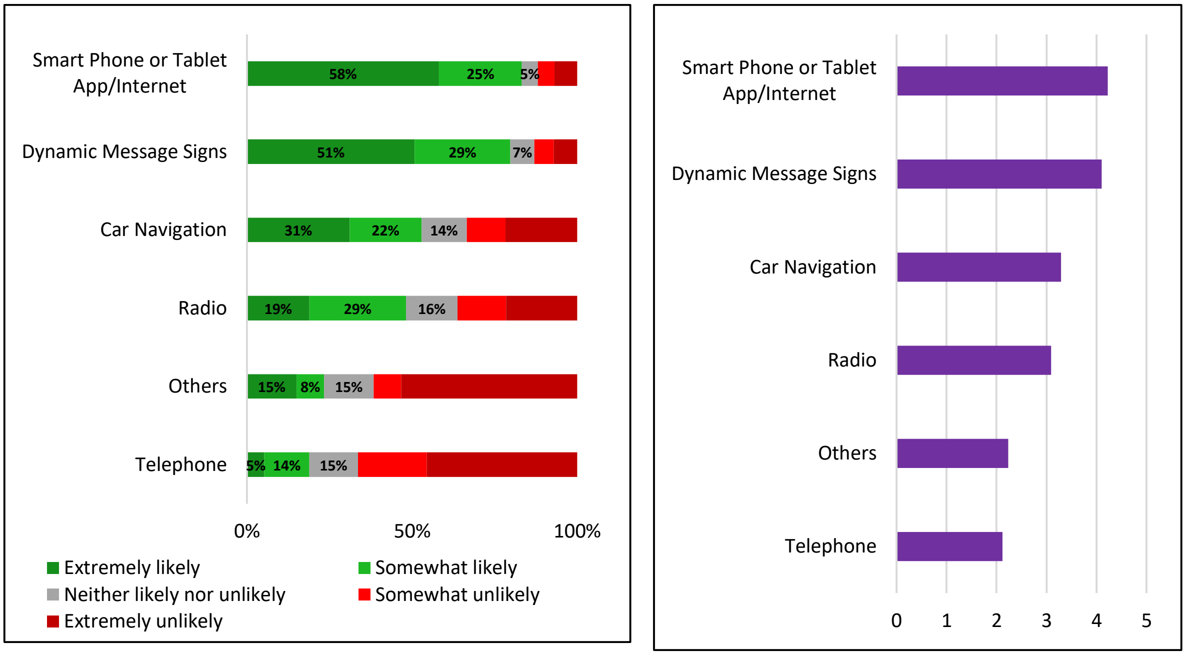
Figure 4.1: Type of trip and route information drivers seek after starting the journey

b. *Which source(s) would you likely use (if available) for trip and route information after starting the journey?*

This question investigated the sources of information (the means/ways) drivers use to search for route/trip information after starting their journey and how frequently they use them. Understanding the type and frequency of each source of information used by drivers is important in determining how drivers prioritize each source. Five alternative sources of information were provided to drivers: Digital Messaging Signs (DMS displays), internet sources (such as smartphones, tablets, etc.), car navigation systems (e.g., GPS), telephone, and radio. Aggregating types of information drivers seek, and the sources of information they use would assist in determining what type of information should be displayed on DMS to improve DMS usability. Drivers were also asked to provide a list of any other sources of information they were likely to use.

A total of 898 responses were analyzed. Drivers indicated that they were most likely to use internet sources (e.g., smartphones), closely followed by DMS displays.

Specifically, about 58 percent of drivers were extremely likely to search trip/route information from internet devices, followed by 51 percent who said they were extremely likely to use DMS as a source of trip/route information. The telephone (i.e., calling someone they know) was the least likely source of information used by drivers. Only about 5 percent of drivers are extremely likely to use telephones as the source of trip/route information (Figure 4.2a). Figure 4.2b is the weighted average for each source type that drivers reported using. Results show that among all types of sources of information, drivers are most likely to use internet devices to search for route information after starting the journey. DMS is the close second on the list of sources that drivers are likely to use. Other types of sources of information in the order of their likelihood of being used are car navigation (e.g., GPS), radio, telephone, and others. For the “others” category, drivers reported using sources of route information such as Mi Drive, old-fashioned maps, and directions from people (stop and ask people).



4.2a: Descriptive statistics

4.2b: Weighted average

Figure 4.2: Source drivers use for trip/route information after starting the journey

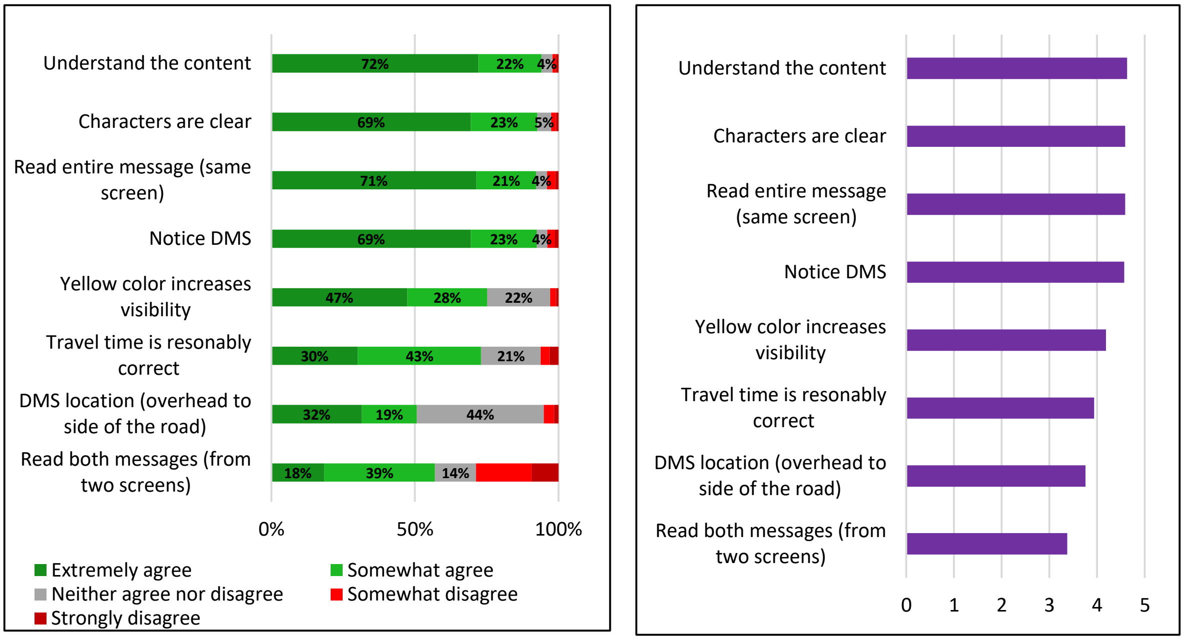
The results show that even though DMS is not at the top of the list, it is a very popular source of information. Internet sources rank the highest probably due to their reliability and easy accessibility compared to DMS, which are few and have fixed locations. The findings suggest that DMSs are still useful to motorists.

c. *Please, indicate how much you agree with the following statements about DMS signs while driving in Michigan.*

These statements specifically focused on the different characteristics and features of DMS displays in Michigan, including: the density (number) of DMS displays, the reliability of the information provided, the general understanding of the messages displayed, the readability of the messages displayed, the color used in characters, and DMS mounting locations. Drivers were asked to rate how much they agree with different statements related to DMS while driving on Michigan roads. For the statements that drivers did not agree with, they were asked to explain why they didn't agree. Respondents were asked to rate how much they agreed with the following statements:

- I often notice one or more DMS on a trip.
- When a DMS message is too long to fit on one screen, it is usually split and displayed into two subsequent screens (two phases). I usually can read both messages.
- If the DMS message does not require splitting and is displayed on one screen, I usually can read the entire message.
- I usually understand DMS content.
- The characters in the DMS are usually clear.
- Yellow color increase visibility.
- I prefer the overhead location for the DMS rather than at the side of the road.
- The travel time information of the DMS is reasonably accurate.

A total of 898 responses were analyzed, out of which 71 percent extremely agreed with the statement that they could read the entire message when displayed on a single screen. That is to say, when the message is fully displayed on a single screen, drivers find it easy to read the entire message. Only 18 percent of drivers extremely agreed that they could read both messages when the message was split between two phases on the DMS display. Other distributions of answers and the weighted average for each of the DMS features and characteristics are presented in Figure 4.3. Results show that more than 50 percent of drivers reported agreeing with different DMS design and operation features and characteristics. Ability to read two messages when each message is displayed for too long seemed to be the most problematic DMS design feature, especially when this compounded with high speed. This observation suggests the need for MDOT to review of the current message phasing guidelines.



4.3a: Descriptive statistics

4.3b: Weighted average

Figure 4.3: Drivers opinion on DMS design and operation features and characteristics

Some of the exact wording of the comments on the ability to read both messages when displayed in phases are:

- *"At a distance, I see the sign says one thing, and then when I get closer, it says something else. I usually pass the sign before it changes back to the first message."*
- *"Depending on the road being traveled on the speed limit is between 55 and 70 MPH, taking your eyes off of the road long enough to read two messages on a roadside sign is far too long and dangerous."*
- *"Often traffic is heavy and I am reluctant to take my eyes off the road to read a 2 screen message from the DMS"*

- *“The timing between the two screens is too long.”*
- *“By the time I notice there's something other than travel times, don't always have time to react and read multiple messages.”*
- *“Not enough time to read. And trucks are usually in the way”*
- *“On screen-times are too long. Usually I can read one screen, but have usually driven past the DMS before I am able to read the second screen.”*

Examples of reasons that drivers gave for disagreeing with other statements include:

<u>For “I usually notice one or more DMS on travel.”</u>

- *“DMS is a rarity except when in a large inner city. I have only seen a handful in my 40 years of driving but would like to see more.”*
- *“The route I travel most often does not have a sign”*

<u>For “If the DMS message does not require splitting and is displayed on one screen, I usually can read the entire message.”</u>

- *“Depending on sun direction, normally I can only read 1 to 2 lines. Never 3”*
- *“I can usually read the entire message, but my complaint is that the message is trivial or irrelevant and is a waste of taxpayer money. And distracting for no value-added.”*
- *“If it's during daylight hours you can't see until really close and most times can't read all the message”*
- *“Some messages are long and have statistics. They are not easy to comprehend quickly and sometimes take a second read which is not good.”*

<u>For “I usually understand DMS content.”</u>

- *“Focus on traffic or immediate issues ahead of you...and not on statewide safety messages... how can you understand it when it is 15 words long.”*
- *“You don't put it on very well.”*
- *“Some content doesn't make sense. And is easier to listen to local radio instead.”*
- *“Sometimes the message doesn't make sense, abbreviations sometimes cause confusion.”*

- *“Sometimes I feel the landmarks it uses don't fit into where I'm driving to so I don't know how to use it.”*

<u>For “The characters in the DMS are usually clear.”</u>

- *“They are not clear. Dim and fuzzy would be the best description.”*
- *“This is a problem when they are either too bright or too many words on one screen.”*
- *“Letters too small and need clarity.”*
- *“At times the light is too dim to read when the sun shines in the sign. Lettering too small.”*
- *“Use less words and larger font for aging drivers.”*
- *“They aren't. They are too out of focus in daylight, and too bright at night.”*

<u>For “Yellow color increases visibility.”</u>

- “*I prefer different colors for different occasions. Road closed: red, construction yellow, icy road: blue, direction and travel time in green... something like this, a color-coded format.”*
- *“I think white is easier to read than yellow.”*
- *“It’s actually more challenging for me to read. You increased the visibility of your trucks with green lights because yellow wasn’t visible enough, and I feel the signs should be the same. A brighter green color would be better to see against a black background.”*
- *“Simply a poor choice. Please take driving into the sun into consideration.”*
- *“Yellow letter against the grey background and a sunny day makes them less eye-appealing a/o ease to read.”*
- *“It fades out in bright sunlight.”*
- *“During late hours, the yellow is not bright enough to see clearly.”*

<u>For “I prefer the overhead location for the DMS rather than at the side of the road.”</u>

- *“I'm more comfortable with reading messages on the side of the road, it is more common”*

- *"Overhead is often blocked if following tall vehicles."*
- *"You are forced to acknowledge the sign as you have to drive underneath."*
- *"In my area, most of the signs are usually at the side of the road so that is what I am used to. It also seems the signs on the side of the road are usually bigger and easier to read."*
- *"I've not often encountered an overhead DMS and think on the side of the road works fine and you could theoretically see from that perspective for a longer amount of time."*

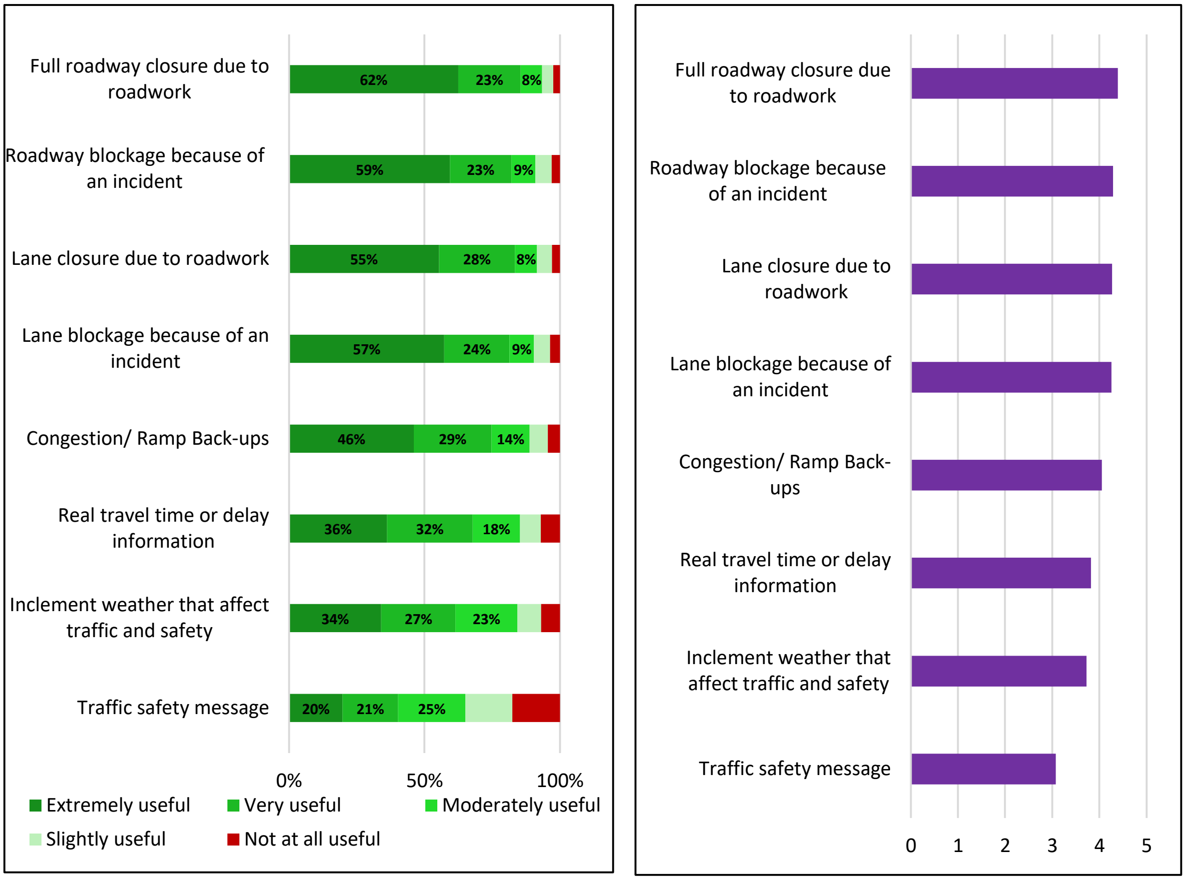
For "The travel time information of the DMS is reasonably accurate."

- *"It usually takes me twice as longer to get through that congestion than what is stated on the sign."*
- *"Typically, the time listed is much slower than what the actual drive time is (i.e., 46 miles doesn't take 42 minutes on 70mph road)."*
- *"Updates typically lag behind the actual road conditions."*
- *"I often find the travel times given are slower than what it actually takes. What says will take 12 minutes usually ends up being only 8-10, etc."*
- *"Isn't updated frequently enough. During heavy traffic times, they are rarely accurate."*
- *"It seems the times are based on posted speed limits rather than actual traffic flow."*
- *"The travel time indicated on the signs is nothing more than a challenge for divers to "beat the time." Unless there are traffic delays there shouldn't be a time indication on these signs as it's is pretty well known it's going to take "15 mins to travel 17 miles" under normal conditions."*

d. *In your opinion, how useful are the DMS in guiding traffic in the following events in the Michigan roadway?*

Drivers were asked to provide their opinion on the usefulness of DMS in guiding traffic under different road and traffic conditions (scenarios). Scenarios investigated were: congestion/ramp back-ups, lane closure due to roadwork, full roadway closure due to roadwork, lane blockage because of an incident, roadway closure because of an incident, inclement weather that affects traffic, real travel time or delay information display and display of traffic safety message. This question was designed to determine which scenarios drivers find DMS information most useful. Understanding specific scenarios that drivers think traffic operation can be improved through the use of DMS will in turn influence drivers’ use and compliance with DMS messages. When a message containing important information to drivers is displayed at a location, time, and road condition expected, drivers' chances of complying with the message recommendations might be high.

A total of 910 responses were analyzed, of which 62 percent said that DMSs are extremely useful in guiding their response to a full road closure due to roadwork. On the other hand, 18 percent of drivers said they are not useful for traffic safety messages (e.g., reduce speed on wet pavement). This observation was surprising because one would expect DMS to be useful in providing traffic safety messages. However, this might raise the question of whether the driving population understands the purpose of traffic messages or whether safety messages are too obvious and, therefore, DMS are not effectively used when they display such messages. Figure 4.4a and Figure 4.4b show the distribution of responses and the weighted average, respectively, for each suggested scenario. In general, more than 50 percent of drivers said that DMS were useful in each of the given road conditions and scenarios. The weighted averages show that DMS usefulness was highest during full road closure because of roadwork. Other scenarios in the order of their usefulness were: roadway blockage because of an incident, lane closure due to due to roadwork, lane blockage because of an incident, during congestion/ramp backups, real travel time, or delay information, inclement weather that affect traffic and traffic safety messages. Understanding drivers’ feedback on when the DMSs are deemed useful is crucial in prioritizing road and traffic conditions to display on the DMS.



4.4a: Descriptive statistics

4.4b: Weighted average

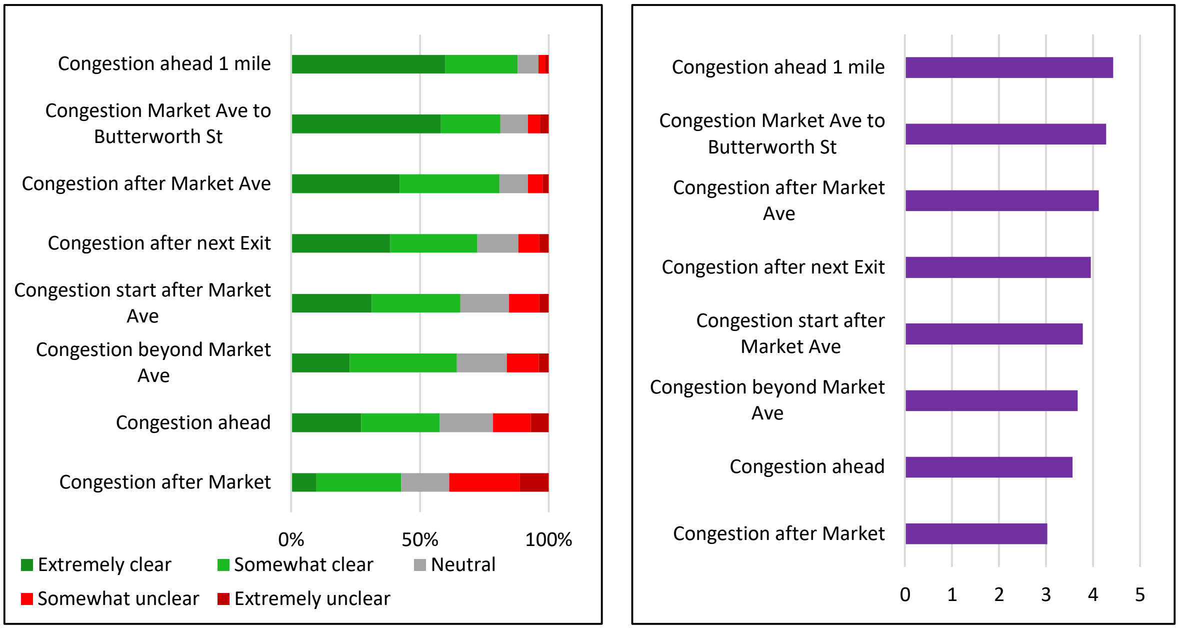
Figure 4.4: Usefulness of DMS in guiding traffic during different road conditions and scenarios

e. *How clear are the following DMS messages in conveying the location of congestion?*

The purpose of this question was to determine the best way to convey the location of the event (or incident) being communicated to drivers using DMS. Clarity of a DMS message is a prerequisite for comprehension and eventually compliance and perceived usefulness. While commuters may easily understand the location referred to in the message, drivers unfamiliar with the location require a very clear message. Therefore, this question specifically provided drivers with eight (8) alternative messages communicating the location of congestion on the roadway section. Figure 4.5 is a drawing provided to drivers to show the location of the congestion (highlighted blue), the direction of travel (red arrow), and the DMS where the message would be displayed (red circle). Drivers were asked to choose how each alternative message clearly conveyed the congestion location. The given messages were: CONGESTION AFTER MARKET; CONGESTION AFTER MARKET AVE; CONGESTION AHEAD; CONGESTION START AFTER MARKET AVE; CONGESTION AHEAD 1 MILE; CONGESTION BEYOND MARKET AVE; CONGESTION AFTER NEXT EXIT; CONGESTION MARKET AVE TO BUTTERWORTH ST.

Figure 4.5: Typical example to show the congestion location (Image Source: Google)

Figure 4.6 presents the distribution of responses and the weighted average for each type of message selected. About 60 percent of drivers stated that the message "CONGESTION AHEAD 1 MILE" was extremely clear, and the other 28 percent of respondents thought it was somewhat clear. On the contrary, 11 percent of drivers stated that the message "CONGESTION AFTER MARKET" was extremely unclear, and another 27 percent of respondents said it was somewhat unclear. The observed contrast shows that the message is clearer when it explains the event (congestion) and provides the distance (location) to the event (1 mile). The weighted average analysis can rank all the alternative messages by their clarity as perceived by the drivers. The list of the messages in the decreasing order of their clarity is as follows: "CONGESTION AHEAD 1 MILE", "CONGESTION MARKET AVE TO BUTTERWORTH ST", "CONGESTION AFTER MARKET AVE", "CONGESTION AFTER EXIT", "CONGESTION START AFTER MARKET AVE", "CONGESTION BEYOND MARKET AVE", "CONGESTION AHEAD" and "CONGESTION AFTER MARKET."



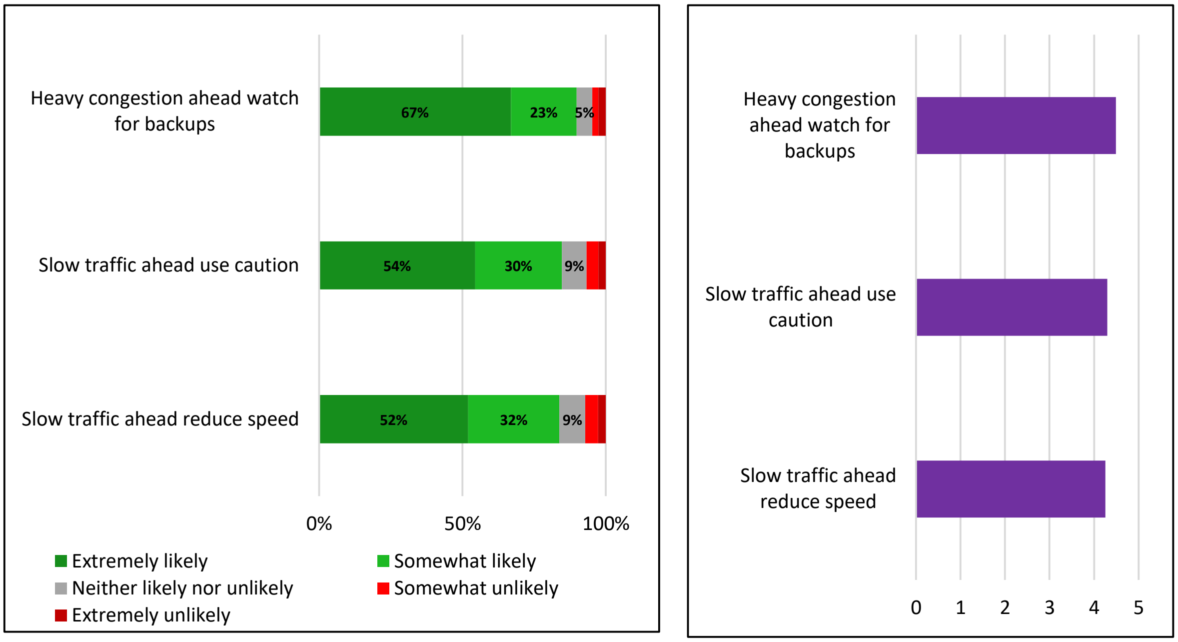
4.6a: Descriptive statistics 4.6b: Weighted average

Figure 4.6: Drivers' opinion on the clarity of DMS message in conveying location of an event

f. How likely would you take recommended actions during congestion/ramp back-ups

This question provided drivers with messages that recommended specific actions during different congestion/ramp backup traffic conditions. Drivers were asked to rate how likely they would take the recommended actions displayed on DMS during congestion/ramp back-up conditions. A total of 902 responses were analyzed. In general, drivers were likely to comply with three tested recommended actions during congestion/ramp backups. Specifically, the survey found that 67 percent of drivers reported were extremely likely to comply with the "HEAVY CONGESTION AHEAD WATCH FOR BACKUPS" message. Furthermore, 54 percent and 52 percent of respondents were extremely likely to comply with "SLOW TRAFFIC AHEAD USE CAUTION" and "SLOW TRAFFIC AHEAD REDUCE SPEED" messages, respectively. These results signify the importance of displaying timely and clear congestion messages on DMS. Congestion can result from several causes such as incidents, roadwork, etc.

Earlier, this survey revealed that drivers frequently search for traffic conditions and incidents more than other trip/route information types. The survey also showed that drivers consider DMS to guide traffic during congestion, incidents, and roadwork. Therefore, the finding that drivers are extremely likely to comply with congestion-related recommended actions is not surprising. Figure 4.7 is the descriptive statistics and weighted average of the compliance rating for each of the selected recommended actions during congestion/ramp back-ups.



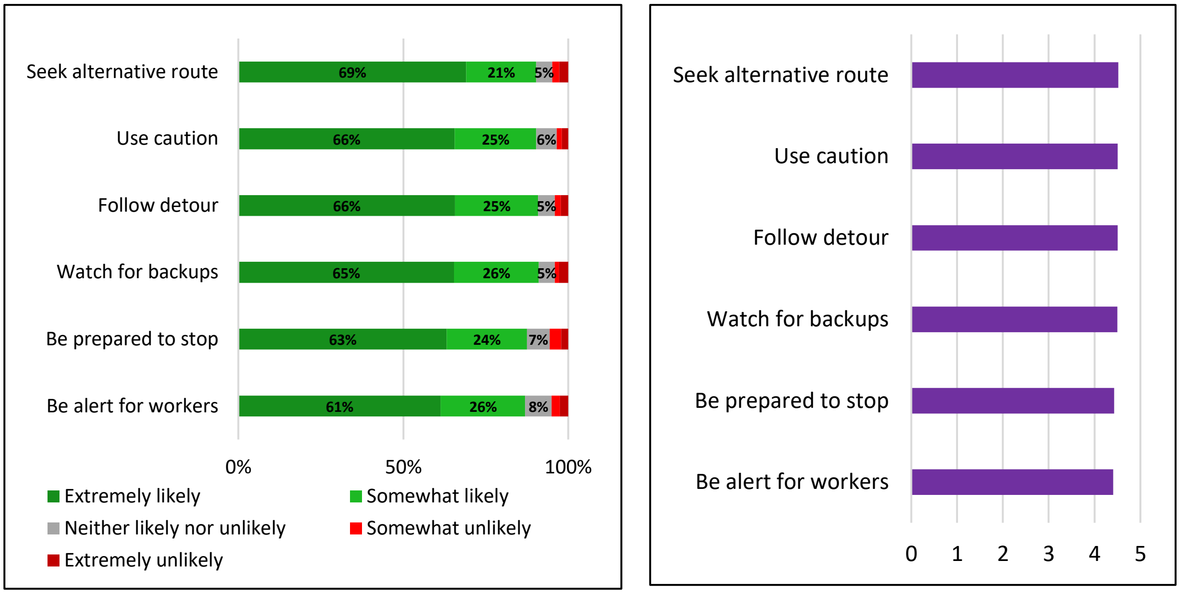
4.7a: Descriptive statistics

4.7b: Weighted average

Figure 4.7: Drivers’ compliance with DMS messages during congestion/ramp back-ups

g. *How likely would you take recommended actions during lane closure due to roadwork*

As in the previous question, drivers were also asked to state their likelihood to comply with DMS messages displayed to guide traffic during lane closure due to roadwork. A total of 907 responses were analyzed, of which more than 60 percent were extremely likely to comply with the recommended actions. The descriptive statistics and weighted average analysis of each of the sample messages revealed that, in general, drivers are likely to comply with DMS messages displayed during lane closure as a result of roadwork (Figure 4.8).



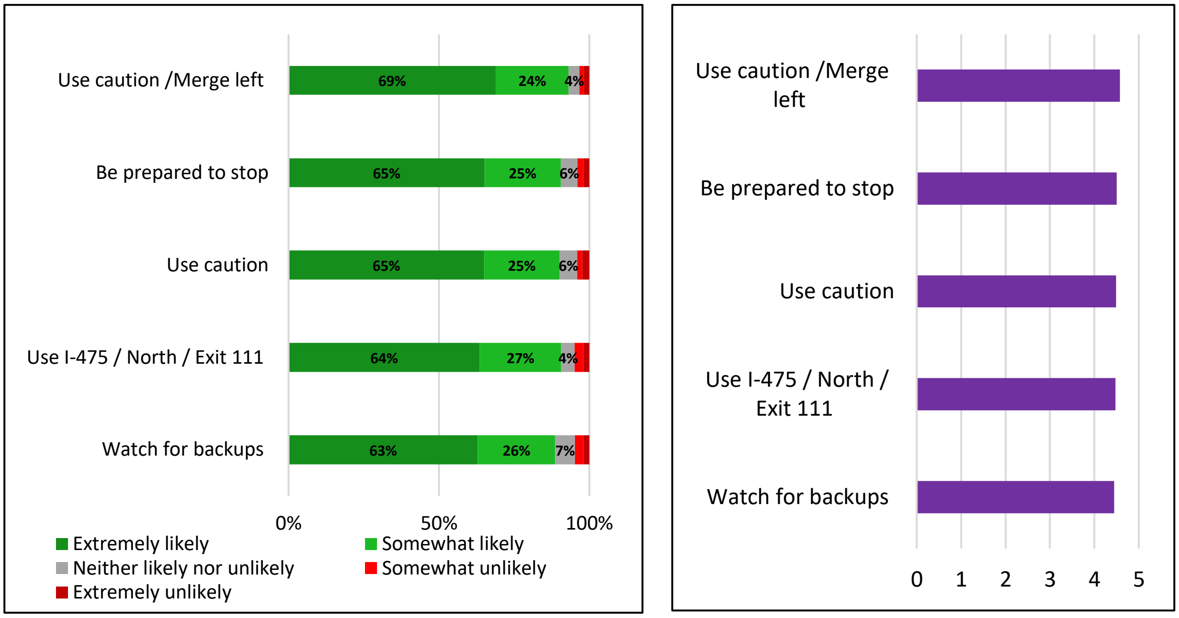
4.8a: Descriptive statistics

4.8b: Weighted average

Figure 4.8: Drivers' compliance with DMS messages during lane closure due to roadwork

h. How likely would you take recommended actions during lane blockage because of incident

Lane blockage because of an incident was another road condition type analyzed. Drivers were provided with different possible messages displayed on DMS to guide traffic during a lane blockage. Drivers were again asked to rate their likelihood of complying with the given recommended action. Five recommended actions were provided, and drivers' likelihood to comply was analyzed. A total of 903 drivers responded and provided their opinion. In general, more than 60 percent said they were extremely likely to take each of the recommended actions (Figure 4.9a). The weighted average of each recommended action analyzed shows that drivers were equally like to comply with DMS messages displayed during lane blockage because of an incident (Figure 4.9b). These results emphasize the importance of DMS messages during lane blockage as it was previously shown that drivers seek incident information frequently and found DMS to be useful in guiding traffic during an incident.



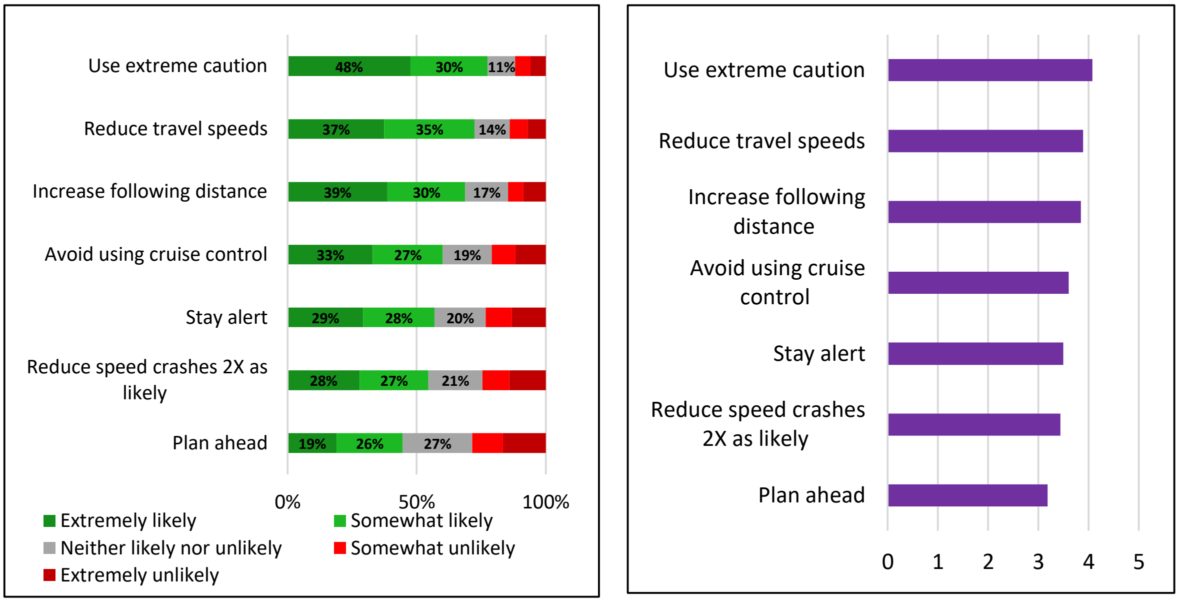
4.9a: Descriptive statistics

4.9b: Weighted average

Figure 4.9: Drivers' compliance with DMS messages during lane blockage because of incident

i. *How likely would you take recommended actions during inclement weather that affects traffic and safety*

The likelihood of drivers to comply with DMS messages displayed during inclement weather was also investigated. Drivers were presented with different messages and were required to report how likely they would take the recommended actions (Figure 4.10). Figure 4.10a is the percentage distribution of responses for each type of recommended action. Results show a different degree of compliance with inclement weather-related DMS messages depending on the actual message displayed. Out of 904 responses analyzed, about 48 percent of drivers were extremely likely to comply with the recommended action "USE EXTREME CAUTION," while only 19 percent said they were extremely likely to comply with the recommended action. "PLAN AHEAD." While 27 percent were neither likely nor unlikely, 29 percent were either somewhat unlikely or extremely unlikely to comply with the recommended action “PLAN AHEAD.” Other distributions are as provided in Figure 4.10a. The weighted average analysis revealed that drivers were most likely to comply with the recommended action “USE EXTREME CAUTION” (Figure 4.10b). Other messages in the order of decreasing the likelihood of drivers’ compliance were; “REDUCE TRAVEL SPEED”, “INCREASE FOLLOWING DISTANCE”, “AVOID USING CRUISE CONTROL”, “STAY ALERT”, “REDUCE SPEED CRASHES 2X AS LIKELY”, and “PLAN AHEAD.”



4.10a: Descriptive statistics

4.10b: Weighted average

Figure 4.10: Drivers’ compliance with DMS messages during inclement weather that affects traffic and safety

4.4.2 Association of age and drivers’ responses

A chi-square test was conducted to test whether there exist any significant association between age and drivers’ responses. Survey participants were divided into three main groups: younger drivers (aged between 16 years to 24 years), middle-age drivers (aged between 24 -59 years), and older drivers (aged 60 years and older). Results show a significant association between age and drivers’ responses on the sources of information they use to search for trip/route information after starting the journey. Specifically, there was a significant association between age and the following sources of information:

internet sources and telephones. That is to say, differences in the drivers' responses on their likelihood to use the mentioned sources of trip/route information could be influenced by their differences in age. For example, younger, middle-aged, and older drivers were 89 percent, 88 percent, and 75 percent respectively, likely to use the internet as a source of trip/route information. There was also a significant association between age and drivers' perception of their compliance with DMS messages for certain recommended actions during different road conditions. For example, younger, middle-aged, and older drivers were 89 percent, 90 percent, and 94 percent, respectively, likely to comply with DMS recommended action "WATCH FOR BACKUPS." The association of age and the response to each survey question are presented in Table 4.2. A detailed analysis of how age significantly influenced drivers' responses to other questions is presented in Appendix 9.4. In addition, a detailed analysis of how age influenced the likelihood of drivers' compliance with different messages is presented in Section 4.5 of this report.

Table 4.2: The association of age with drivers' responses

Response/Category	**Chi-Square**	***p*-value**
Types of trip/route information drivers sought before start of their journey		
Travel time	6.564	0.584
Direction	12.074	0.148
Weather	8.625	0.375
Traffic condition	8.625	0.375
Incident	4.687	0.791
Source of information drivers used to search for trip/route information		
DMS	5.840	0.665
Internet sources	27.295	0.001**
Car navigation	8.084	0.425
Radio	10.988	0.202
Telephone	15.442	0.051*
DMS design and operation features and characteristics		
Density	4.770	0.782
Reading both messages	6.742	0.565
Reading entire message	6.003	0.647
Understanding content	7.695	0.464
Clear characters	8.940	0.347
Yellow color increases visibility	10.335	0.242
DMS location	5.448	0.709
Travel time is correct	7.224	0.513
Usefulness of DMS in guiding traffic during different road conditions and scenarios		
Congestion and ramp back-ups	7.801	0.453
Lane closure due to roadwork	9.849	0.276
Full road closure due to roadwork	10.238	0.249

Response/Category	**Chi-Square**	***p*-value**
Roadway blockage because of an incident	4.215	0.837
Lane blockage because of an incident	3.080	0.929
Inclement weather that affects traffic and safety	9.456	0.305
Real travel time or delay information	3.387	0.908
Traffic safety messages	10.388	0.239
Compliance with recommended actions during congestion/ramp backups		
Heavy congestion ahead watch for backups	13.209	0.105
Slow traffic ahead use caution	20.319	0.009**
Slow traffic ahead reduce speed	29.097	0.000**
Compliance with recommended actions during lane closure due to roadwork		
Watch for backups	26.504	0.001**
Seek alternative route	7.698	0.464
Follow detour	7.610	0.473
Use caution	24.197	0.002**
Be prepared to stop	18.791	0.016**
Be alert for workers	15.240	0.055*
Compliance with recommended actions during lane blockage because of incident		
Use I-475/North/Exit 111	11.437	0.178
Use caution/Merge left	13.450	0.097*
Use caution	15.157	0.056*
Watch for backups	23.127	0.003**
Be prepared to stop	17.784	0.023**
Compliance with recommended actions during inclement weather that affects traffic		
Plan ahead	11.678	0.166
Reduce travel speeds	4.718	0.787
Use extreme caution	3.248	0.918
Increase following distance	5.767	0.673
Avoid using cruise control	13.197	0.105
Stay alert	15.379	0.052*
Reduce speed crashes 2x as likely	12.240	0.141

Note: ** indicates a significant association at the 95 percent level of confidence
* indicates a significant association at the 90 percent level of confidence

4.4.3 Association of gender and drivers' responses

A chi-square test was also conducted to assess the association between gender and each driver's responses. We found an association between gender and some responses that drivers provided, including: types of trip/route information sought, sources used to search for trip/route information, DMS characteristics and features, the usefulness of DMS, and drivers' compliance with DMS messages. For example, regarding the types of information sought, gender was associated significantly with traffic conditions and incidents. That is to say, the differences in survey responses on how frequently they search for such trip/route information could be influenced by their differences in gender, among other factors. The analysis of how gender impacted drivers' responses is summarized in Appendix 9.5.

Interestingly, a significant association was observed between gender and DMS messages for each sample of recommended actions listed. That suggests gender could play a role in drivers' likelihood to comply with different DMS messages. The association of gender and each of the survey questions asked is presented in Table 4.3. In addition, a detailed analysis of how gender, when controlling for other factors, influenced drivers' compliance with DMS messages is provided in Section 4.5 of this report.

Table 4.3: The association of gender with drivers' responses

Response/Category	**Chi-Square**	***p*-value**
Types of trip/route information drivers sought before start of their journey		
Travel time	5.787	0.216
Direction	4.526	0.339
Weather	4.474	0.346
Traffic condition	7.819	0.098*
Incident	16.723	0.002**
Source of information drivers used to search for trip/route information		
DMS	8.531	0.074*
Internet sources	4.748	0.314
Car navigation	6.093	0.192
Radio	3.099	0.541
Telephone	27.607	0.000**
DMS design and operation features and characteristics		
Density	2.981	0.561
Reading both messages	10.201	0.037**
Reading entire message	6.691	0.153
Understanding content	1.819	0.769
Clear characters	7.387	0.117
Yellow color increases visibility	7.418	0.115
DMS location	1.609	0.807
Travel time is correct	2.172	0.704
Usefulness of DMS in guiding traffic during different road conditions and scenarios		
Congestion and ramp back-ups	11.531	0.021**
Lane closure due to roadwork	14.740	0.005**
Full road closure due to roadwork	12.279	0.015**
Roadway blockage because of an incident	5.290	0.259
Lane blockage because of an incident	8.104	0.088*
Inclement weather that affects traffic and safety	21.039	0.000**
Real travel time or delay information	11.234	0.024**
Traffic safety messages	39.132	0.000**
Compliance with recommended actions during congestion/ramp backups		
Heavy congestion ahead watch for backups	20.808	0.000**

Response/Category	**Chi-Square**	***p*-value**
Slow traffic ahead use caution	51.513	0.000**
Slow traffic ahead reduce speed	45.006	0.000**
Compliance with recommended actions during lane closure due to roadwork		
Watch for backups	17.069	0.002**
Seek alternative route	12.204	0.016**
Follow detour	16.380	0.003**
Use caution	14.971	0.005**
Be prepared to stop	32.696	0.000**
Be alert for workers	31.019	0.000**
Compliance with recommended actions during lane blockage because of incident		
Use I-475/North/Exit 111	14.792	0.005**
Use caution/Merge left	21.324	0.000**
Use caution	29.168	0.000**
Watch for backups	28.692	0.000**
Be prepared to stop	15.829	0.003**
Compliance with recommended actions during inclement weather that affects traffic		
Plan ahead	21.563	0.000**
Reduce travel speeds	65.515	0.000**
Use extreme caution	33.823	0.000**
Increase following distance	45.898	0.000**
Avoid using cruise control	52.284	0.000**
Stay alert	28.967	0.000**
Reduce speed crashes 2x as likely	33.202	0.000**

Note: ** indicates a significant association at the 95 percent level of confidence
* indicates a significant association at the 90 percent level of confidence

4.4.4 Analysis of the impact of season on drivers' responses

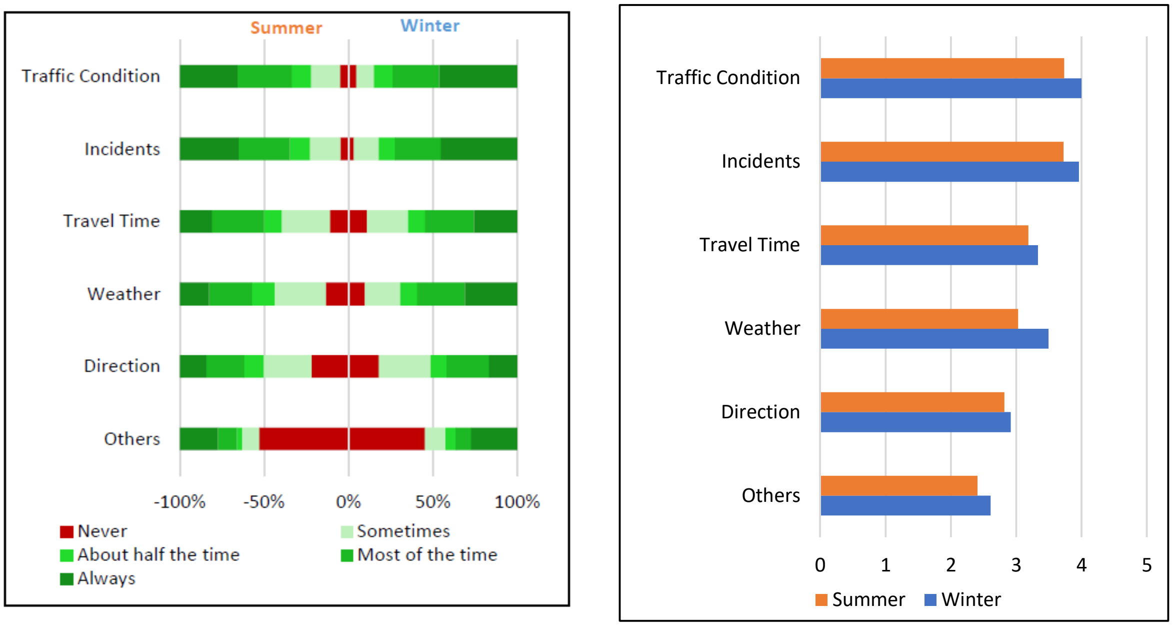
This section documents an analysis of the impact of season on drivers' likelihood to comply with different weather-related messages displayed on DMS. The aim was to determine whether there was any significant difference in drivers' opinion on drivers' likelihood to comply with inclement weather-related DMS messages displayed to guide traffic during the summer and winter seasons. Table 4.4 is the distribution of the survey's responses by age and gender during each survey period. A total of 719 drivers responded to the survey during the summer, and 210 drivers responded during the winter.

Table 4.4: The distribution of drivers' responses by age and gender in summer and winter

Age/Gender	SUMMER				WINTER			
	Male	**Female**	**Others**	**Total**	**Male**	**Female**	**Others**	**Total**
16 - 20 Years	10	0	2	12	0	0	0	0
21 - 24 Years	18	7	1	26	0	0	0	0
25 - 40 Years	112	40	8	160	6	0	0	6
41 - 59 Years	185	94	5	284	28	26	1	55
60 - 64 Years	46	28	4	78	47	46	2	95
65 Years and Older	81	22	6	109	15	9	1	25
Others	6	2	42	50	16	10	3	29
Total	458	193	68	719	112	91	7	210

4.4.4.1 Impact of the season on types of travel information drivers seek after they had started their journey

In this analysis, the impact of season on the type of trip/route information sought was analyzed. The aim was to investigate whether the type of trip/route information sought in the summer is different from what is sought during the winter season. Figure 4.11a and 4.11b are the descriptive statistics and the weighted averages for each trip/route information sought during the two seasons (winter and summer), respectively. To differentiate results from the two seasons graphically (Figure 4.11a), the positive signs on the number axis represent the percentage distribution of responses in winter, and the negative numbers are the percentage distributions during the summer season. The results show that drivers frequently seek all suggested route/trip information in both seasons, but the frequency was higher during winter than during summer. These results suggest that the frequency of drivers seeking trip/route information increases during the winter season. Such observation is not surprising because weather conditions that affect traffic might be changing more frequently during winter.



4.11a: Descriptive statistics 4.11b: Weighted averages

Figure 4.11: Types of travel information sought during summer and winter

The Mann-Whitney U (MWU) test results in Table 4.5 show that there was a significant difference ($p<0.05$) between trip/route information drivers sought during winter and those sought during summer. The difference is significant for the following trip/route information: weather conditions, traffic conditions, and incidents indicating that drivers were likely to seek weather information more frequently during winter than summer.

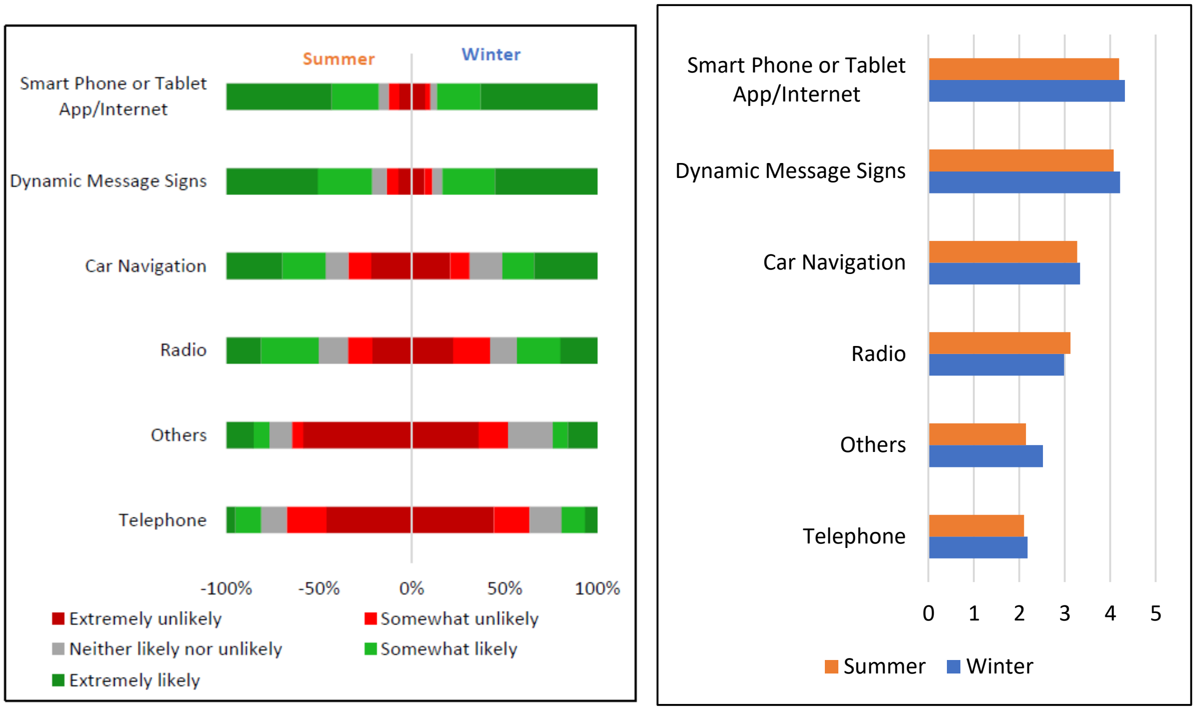
Table 4.5: The impact of season on types of travel information sought

Variable	Season	Obs	Rank sum	Expected	z	P > |z|
Travel time	Winter	209	99,859.5	94,990.5	1.511	0.131
	Summer	699	312,826.5	317,695.5		
Direction	Winter	199	90,431	87,759	0.869	0.385
	Summer	682	298,090	300,762		
Weather	Winter	204	105,009	91,392	4.312	0.000**
	Summer	691	295,951	309,568		
Traffic conditions	Winter	206	102,851.5	93,318	3.024	0.003**
	Summer	699	307,113.5	316,647		
Incidents	Winter	206	101,668	93,421	2.611	0.009**
	Summer	700	309,203	317,450		

Note: ** indicates a significant association at the 95 percent level of confidence

4.4.4.2 Association of the season and the source of trip/route information drivers use

It has been established previously in the general analysis that drivers use different sources to search for trip/route information after they have started their journey. This analysis investigated whether the sources of trip/route information drivers used during summer are significantly different from those used during winter. The descriptive statistics show that internet sources (e.g., smartphones) and DMS are used more frequently than other sources (Figure 4.12a and 4.12b). Results also show that all other sources are more used during winter than during the summer season except for the radio.



4.12a: Descriptive statistics

4.12b: Weighted averages

Figure 4.12: Sources of trip/route information during summer and winter

Results from the MWU test in Table 4.6 show that only the digital message signs are significantly used more often during winter than summer (albeit at the 90 percent confidence level). That is to say, drivers used DMS as a source of their trip/route information at a significantly higher rate during winter compared to summer.

Table 4.6: The impact of season on drivers' responses about source of information sought

Variable	Season	Obs	Rank sum	Expected	z	P > |z|
DMS	Winter	208	98,469	93,496	1.651	0.099*
	Summer	690	305,182	310,155		
Internet	Winter	207	97,233	92,632.5	1.592	0.111
	Summer	687	302,832	307,432.5		
Car navigation	Winter	202	89,797	88,173	0.532	0.595
	Summer	670	290,831	292,455		
Radio	Winter	201	84,363	87,736.5	-1.104	0.270
	Summer	671	296,265	292,891.5		
Telephone	Winter	197	84,465	82,543	0.686	0.493
	Summer	640	266,238	268,160		

Note: * indicates a significant association at the 90 percent level of confidence

4.4.4.3 Impact of the season on the usefulness of digital messaging signs

Analysis of the impact of season on the usefulness of DMS in guiding traffic during different traffic scenarios and conditions revealed that drivers agreed that DMSs are useful regardless of the season. However, drivers rated them as more useful during winter than during the summer season for each road scenario presented. The descriptive statistics and the weighted averages presented in Figures 4.13a and 4.13b support this finding. These results connect well with the analysis for the type of trip/route information sought during winter and summer, in which drivers sought trip/route information more in winter than in summer. They also connect well with the results for the source of trip/route information drivers used during winter and summer, in which DMS was significantly used more during winter than summer. Thus, as anticipated, DMS are generally considered by motorists to be more useful in the winter season than in the summer.

4.13a: Descriptive statistics

4.13b: Weighted averages

Figure 4.13: Usefulness of DMS in guiding traffic during summer and winter

The MWU test results (Table 4.7) show a significant difference between drivers' opinions on the usefulness of DMS during winter and summer. Drivers found DMS to be significantly more useful during winter than in summer to guide traffic during the following road scenario and conditions: lane closure due to road work, inclement weather, and display of traffic safety messages. These results show how the guidance from DMS during roadwork, inclement weather, and display of safety messages is relatively more important to drivers in winter than in summer.

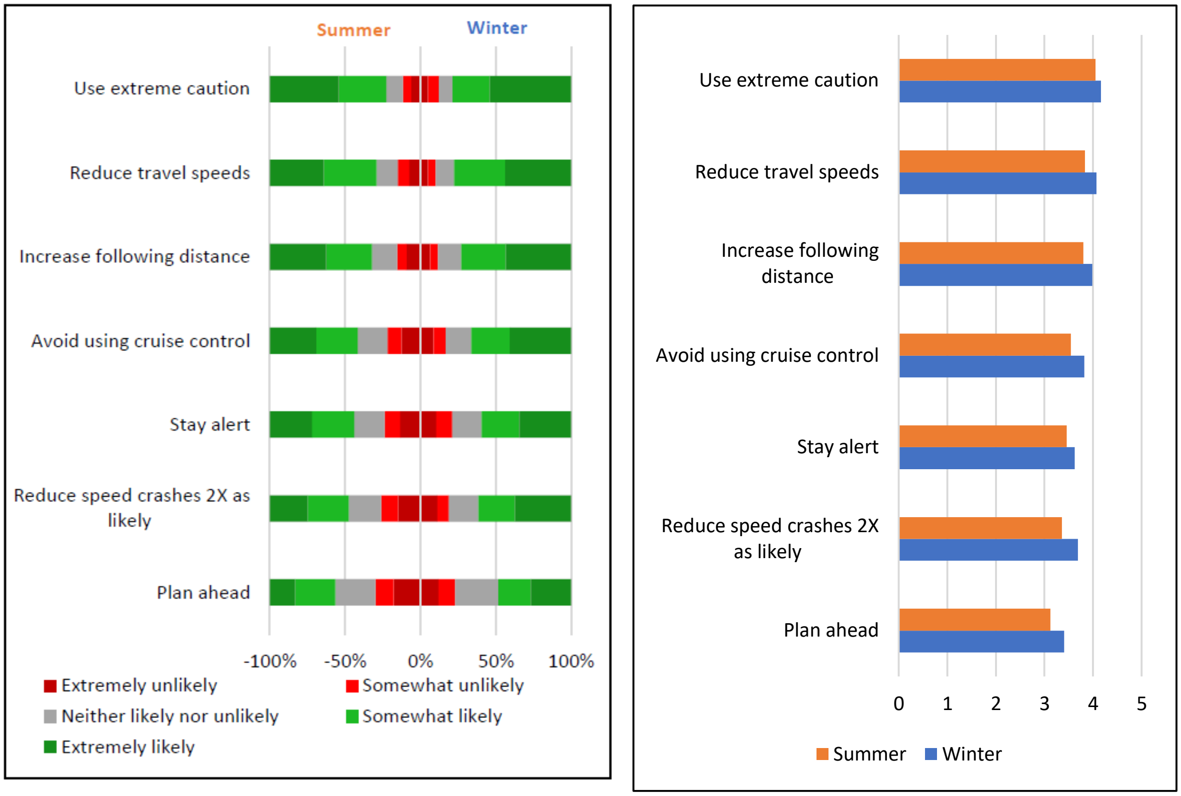
Table 4.7: The impact of the season on drivers' responses about the usefulness of DMS

Variable	Season	Obs	Rank sum	Expected	z	*p*-value
Congestion/ Ramp Back-ups	Winter	207	98,945.5	94,081.5	1.568	0.117
	Summer	701	313,740.5	318,604.5		
Lane closure due to roadwork	Winter	209	100,343.5	95,095	1.753	0.080*
	Summer	700	313,251.5	318,500		
Full roadway closure due to roadwork	Winter	208	96,841	94,224	0.917	0.359
	Summer	697	313,124	315,741		
Roadway blockage because of an incident	Winter	208	98,195	94,432	1.287	0.198
	Summer	699	313,583	317,346		
Lane blockage because of an incident	Winter	208	95,691.5	94,432	0.425	0.671
	Summer	699	316,086.5	317,346		
Inclement weather	Winter	209	105,315	95,199.5	3.150	0.002**
	Summer	701	309,190	319,305.5		
Real travel time or delay information	Winter	208	99,208.5	94,328	1.540	0.124
	Summer	698	311,662.5	316,543		
Traffic safety message	Winter	207	102,839	94,081.5	2.699	0.007**
	Summer	701	309,847	318,604.5		

Note: ** indicates a significant association at the 95 percent level of confidence
* indicates a significant association at the 90 percent level of confidence

4.4.4.4 Impact of the season on compliance of recommended actions during inclement weather that affects traffic

It was revealed previously in the general analysis of how drivers were likely to comply with different inclement weather-related messages that drivers were likely to comply with respective recommended actions displayed. The analysis of the impact of season on the compliance of drivers with DMS messages displayed to guide traffic during inclement weather revealed the same trend (Figure 4.14a and 4.14b). Results show that the likelihood of drivers' compliance is higher in the winter time than in the summer time. Such results are not surprising because winter conditions may exacerbate the perception of hazards associated with specific conditions.



4.14a: Descriptive statistics

4.14b: Weighted average

Figure 4.14: Drivers' compliance with DMS messages related to inclement weather in summer and winter

The MWU test results (Table 4.8) confirm that the observed difference in compliance between the two seasons was statistically significant. Drivers were likely to comply with recommended actions during inclement weather more in winter than in summer. Specifically, they were likely to comply with the following recommended actions during inclement weather: "PLAN-AHEAD", "REDUCE TRAVEL SPEED", "USE EXTREME CAUTION", "INCREASE FOLLOWING DISTANCE", "AVOID CRUISE CONTROL", and "REDUCE TRAVEL SPEED CRASHES ARE 2X AS LIKELY."

Table 4.8: The impact of season on drivers' compliance with DMS messages during inclement weather

Variable	Season	Obs	Rank sum	Expected	z	P > |z|
Plan Ahead	Winter	209	102,950.5	945,72.5	2.596	0.009**
	Summer	695	306,109.5	314,487.5		
Reduce Travel Speed	Winter	208	101,710.5	93,912	2.492	0.013**
	Summer	694	305,542.5	313,341		
Use Extreme Caution	Winter	207	98,807.5	93,564	1.713	0.086*
	Summer	696	309,348.5	314,592		
Increase Following Distance	Winter	208	99,703	93,912	1.843	0.065*
	Summer	694	307,550	313,341		
Avoid Using Cruise Control	Winter	208	102,724	93,912	2.765	0.006**
	Summer	694	304,529	313,341		
Stay Alert	Winter	208	99,132	93,912	1.631	0.103
	Summer	694	308,121	313,341		
Reduce Speed Crashes 2X As Likely	Winter	207	103,711.5	93,357	3.239	0.001**
	Summer	694	302,639.5	312,994		

Note: ** - There is a significant association at the 95 percent level of confidence
* - There is a significant association at the 90 percent level of confidence

4.4.5 Summary of general analysis results

This section provided summary results from the general analysis that involved the following variables: the descriptive statistics and weighted average for each question asked, the association of gender with drivers' responses, the association between age and drivers' responses, and the impacts of the season on drivers' perceptions and compliance of DMs messages.

Results from the descriptive statistics and the weighted averages revealed the following:

- Traffic conditions and incidents are the two types of trip/route information drivers frequently seek after starting their journey.
- Internet and DMS were the two sources of trip/route information that drivers used most often to search for trip/route information after starting their journey.
- The most problematic DMS feature that drivers faced was reading messages from two screens during message phasing. In addition, drivers preferred overhead mounted DMS to the side of the road mounted DMS.

- In general, DMS were found useful in guiding traffic during different road conditions and scenarios.
- Drivers preferred and clearly understood a message that provided information about both the event and the exact location where it had occurred.
- In general, drivers were more likely to comply with DMS messages displayed during different road conditions and scenarios.

Further, results show that there was a significant association ($p<0.05$) between age and drivers' responses on the following:

- The likelihood of drivers to seek weather condition information and the use of the internet as a source for trip/route information after they have started their journey.
- Drivers' opinions on the following specific DMS design and operation features: the ability to read both messages from two screens when message phasing is applied, understanding of DMS contents, clarity of DMS characters, and whether yellow color increases the visibility of the displayed message.
- Drivers' opinions on the usefulness of DMS during inclement weather that affect traffic.
- Drivers' opinions on DMS messages specifically for the following messages; watch for back-ups, use caution, be prepared to stop, and stay alert.

Results from the analysis of the association of gender with drivers' responses revealed that there exist significant association ($p<0.05$) between gender and drivers' responses for the following:

- Drivers' opinions on the type of trip/route information they sought before starting the journey. Specifically, a significant association was observed on the incident type of travel information.
- Drivers' opinions on the likelihood of using a telephone as a source of trip/route information.
- Drivers' opinions on the usefulness of DMS in guiding traffic during different road conditions and scenarios. Specifically, the gender influenced their opinions for the following road conditions: congestion and ramp back-ups, lane closure due to

roadwork, full road closure due to roadwork, inclement weather that affects traffic and safety, real-time or delay information, and traffic safety messages.

The analysis of the impact of season on drivers' responses revealed the following:

- There was a significant difference between types of trip/route information drivers seek after starting their journey between winter and summer. That is to say, drivers were likely to seek one type of trip/route information more during one season than during the other. Specifically, the frequencies of drivers seeking trip/route information related to weather, traffic, and incident information were significantly higher in winter than in summer.
- The likelihood of using different sources of information to search for trip/route information had an almost similar frequency in summer and winter. However, the frequency of using DMS as a source of trip/route information was significantly higher ($p<0.1$) during winter than during summer.
- Drivers reported that DMS was more useful in guiding traffic during different road and traffic conditions in winter than in summer. DMS's usefulness in guiding traffic during inclement weather and displaying traffic safety messages was significantly higher in winter than in summer.
- Drivers' compliance with DMS recommended actions during inclement weather was significantly higher in winter than in summer.

4.5 Results of Analysis of Drivers' Understanding and Compliance with DMS Messages

This section presents statistical analyses of factors associated with understanding the DMS messages and those for drivers' compliance with DMS messages. Two separate analyses were conducted. The logistic regression analysis first investigated factors associated with the drivers' compliance with different actions recommended on DMS displays. The second analysis was the detailed structural equation modeling (SEM) analysis that identified the factors associated with the general understanding of the DMS content. The second analysis was the continuation of the first general analysis in which understanding of DMS content was found to be a significant factor in improving drivers' compliance with different actions recommended on DMS displays. Since understanding could not be measured directly, the SEM explained factors associated with understanding DMS content.

4.5.1 Drivers' compliance with DMS messages during congestion/ramp back-ups

Table 4.9 presents the logistic regression results on factors affecting drivers' compliance with different actions recommended to guide traffic during congestion/ramp backups.

Table 4.9: Factors associated with drivers' compliance with DMS messages during congestion/ramp back-ups

Variable	**Odds Ratio**	**Std. Err.**	**z**	**P>z**	**95% Conf. Interval**	
Congestion / Ramp Backups – Watch for Backups						
Understanding DMS Content	2.886	0.936	3.270	0.001	1.529	5.449
Using DMS as a source of information	4.119	0.789	7.390	0.000	2.830	5.995
DMS usefulness on congestion	5.517	2.149	4.380	0.000	2.571	11.837
Older drivers	1.548	0.261	2.590	0.010	1.112	2.155
Female	1.963	0.350	3.780	0.000	1.383	2.785
Congestion / Ramp Back-ups – Use Caution						
Understanding DMS Content	1.864	0.602	1.930	0.054	0.990	3.509
Using DMS as a source of information	3.520	0.647	6.850	0.000	2.456	5.046
DMS usefulness on congestion	5.620	2.194	4.420	0.000	2.615	12.079
Older drivers	1.853	0.283	4.030	0.000	1.373	2.501
Female	2.685	0.440	6.030	0.000	1.948	3.700
Congestion / Ramp Back-ups – Reduce Speed						
Understanding DMS Content	1.810	0.565	1.900	0.057	0.982	3.338
Using DMS as a source of information	3.960	0.727	7.490	0.000	2.763	5.675
DMS usefulness on congestion	4.105	1.637	3.540	0.000	1.878	8.971
Older drivers	1.818	0.273	3.980	0.000	1.354	2.440
Female	2.506	0.395	5.830	0.000	1.840	3.412

The results show that understanding of DMS content, the use of DMS as the source of trip/route information, drivers' perception of the usefulness of DMS to guide traffic during congestion/ramp backups, age, and gender were significant factors affecting drivers' compliance with DMS messages displayed to guide traffic during congestion/ramp backups. For instance, the likelihood of drivers who use DMS as a source of trip/route information to comply with the recommended action "WATCH FOR BACKUPS" was 4.12 times higher than drivers who used other sources. On the other hand, older drivers aged 60 years and above were 1.85 times more likely to comply with the recommended action “USE CAUTION” than other drivers.

4.5.2 Drivers’ compliance with recommended actions during lane closure due to roadwork

Table 4.10 shows the logistic regression results presenting the impact of different factors on drivers' compliance with different recommended actions during lane closure due to roadwork. Results show that understanding of DMS content, the use of DMS as the source of travel information, drivers’ perception of the usefulness of DMS to guide traffic during lane closure due to roadwork, age, and gender are the significant factors that affect the compliance of drivers’ with recommended actions during lane closure due to roadwork. Drivers who found DMS to be useful in guiding traffic during lane closure because of roadwork were more likely to comply with DMS messages than other drivers. For example, their likelihood of compliance with the recommended action “SEEK ALTERNATIVE ROUTE” was 7.52 times higher than other drivers. On the other hand, female drivers were 2.3 times more likely to comply with the recommended action “BE PREPARED TO STOP” than male drivers. Other factors for each sample message provided are presented in Table 4.10.

Table 4.10: Factors associated with drivers’ compliance with recommended actions during lane closure because of roadwork

Variable	**Odds Ratio**	**Std. Err.**	**z**	**P>z**	**95% Conf. Interval**	
Lane closure - Watch for backups						
Understanding DMS Content	2.654	0.864	3.000	0.003	1.403	5.022
Using DMS as a source of information	4.246	0.814	7.540	0.000	2.916	6.182
DMS usefulness during lane closure	8.690	4.164	4.510	0.000	3.398	22.229
Older drivers	2.195	0.380	4.540	0.000	1.564	3.082
Female	1.538	0.264	2.500	0.012	1.098	2.154
Lane closure - Seek alternative Route						
Understanding DMS Content	2.384	0.737	2.810	0.005	1.300	4.372
DMS usefulness during lane closure	3.653	0.663	7.140	0.000	2.559	5.213
DMS useful during lane closure	7.519	3.576	4.240	0.000	2.961	19.096
Female	1.428	0.245	2.080	0.038	1.020	1.998

Variable	Odds Ratio	Std. Err.	z	P>z	95% Conf. Interval	
Lane closure - Follow Detour						
Understanding DMS Content	2.163	0.683	2.440	0.015	1.164	4.017
Using DMS as a source of information	3.681	0.679	7.060	0.000	2.564	5.285
DMS usefulness during lane closure	6.882	3.504	3.790	0.000	2.537	18.669
Older drivers	1.341	0.220	1.780	0.074	0.972	1.850
Female	1.526	0.262	2.460	0.014	1.089	2.138
Lane closure - Use caution						
Understanding DMS Content	2.248	0.740	2.460	0.014	1.180	4.286
Using DMS as a source of information	4.096	0.784	7.370	0.000	2.815	5.959
DMS usefulness during lane closure	6.485	3.251	3.730	0.000	2.428	17.321
Older drivers	2.030	0.348	4.130	0.000	1.451	2.840
Female	1.654	0.286	2.910	0.004	1.179	2.321
Lane closure - Be prepared to stop						
Understanding DMS Content	2.256	0.709	2.590	0.010	1.218	4.177
Using DMS as a source of information	3.072	0.574	6.000	0.000	2.129	4.432
DMS usefulness during lane closure	6.689	3.222	3.950	0.000	2.602	17.194
Older drivers	1.946	0.321	4.040	0.000	1.409	2.688
Female	2.306	0.401	4.800	0.000	1.640	3.243
Lane closure - Be alert for workers						
Understanding DMS Content	2.259	0.710	2.590	0.010	1.220	4.184
Using DMS as a source of information	3.283	0.610	6.400	0.000	2.282	4.725
DMS usefulness during lane closure	6.048	2.838	3.830	0.000	2.411	15.174
Older drivers	1.699	0.270	3.330	0.001	1.244	2.321
Female	2.272	0.383	4.870	0.000	1.633	3.160

4.5.3 Drivers’ compliance with recommended actions during lane blockage because of incident

Results of the logistic regression modeling presented in Table 4.11 show that drivers compliance with DMS messages displayed to guide traffic during lane blockage due to an incident was significantly impacted by the following factors: understanding of DMS content, the use of DMS as a source of trip/route information, the usefulness of DMS during lane blockage because of an incident, drivers’ age and gender.

Table 4.11: Factors associated with drivers' compliance with recommended actions during lane blockage due to an incident

Variable	Odds Ratio	Std. Err.	z	P>z	95% Conf. Interval	
Lane blockage because of an incident - Use I-475 / North / Exit 111						
Understanding DMS Content	1.605	0.521	1.460	0.145	0.850	3.032
Using DMS as a source of information	3.697	0.688	7.020	0.000	2.567	5.326
DMS usefulness during lane blockage	4.219	1.834	3.310	0.001	1.800	9.890
Older drivers	1.451	0.235	2.300	0.021	1.057	1.992
Female	1.470	0.244	2.320	0.020	1.062	2.035
Lane blockage because of an incident - Use Caution /Merge Left						
Understanding DMS Content	2.311	0.754	2.570	0.010	1.219	4.380
Using DMS as a source of information	3.531	0.676	6.590	0.000	2.427	5.139
DMS usefulness during lane blockage	4.409	1.902	3.440	0.001	1.893	10.268
Older drivers	1.519	0.261	2.430	0.015	1.084	2.129
Female	1.902	0.345	3.550	0.000	1.334	2.713
Lane blockage because of an incident - Use Caution						
Understanding DMS Content	2.202	0.700	2.480	0.013	1.181	4.105
Using DMS as a source of information	3.465	0.657	6.550	0.000	2.389	5.026
DMS usefulness during lane blockage	2.973	1.208	2.680	0.007	1.341	6.593
Older drivers	1.733	0.291	3.270	0.001	1.247	2.410
Female	2.120	0.379	4.200	0.000	1.493	3.010
Lane blockage because of an incident - Watch for backups						
Understanding DMS Content	2.527	0.807	2.900	0.004	1.351	4.726
Using DMS as a source of information	3.516	0.667	6.620	0.000	2.424	5.101
DMS usefulness during lane blockage	3.416	1.375	3.050	0.002	1.552	7.518
Older drivers	2.032	0.339	4.250	0.000	1.465	2.818
Female	1.947	0.335	3.880	0.000	1.390	2.728
Lane blockage because of an incident - Be prepared to stop						
Understanding DMS Content	3.255	1.068	3.600	0.000	1.711	6.193
Using DMS as a source of information	4.098	0.779	7.420	0.000	2.824	5.947
DMS usefulness during lane blockage	4.500	1.870	3.620	0.000	1.993	10.159
Older drivers	2.113	0.364	4.340	0.000	1.507	2.963
Female	1.602	0.277	2.730	0.006	1.141	2.247

Drivers who understand DMS content are more likely to comply with DMS messages displayed during lane blockage because of an incident than drivers who don't understand the content of the message. For example, results show that drivers who understand the DMS content are 3.26 times more likely to comply with the recommended action "BE PREPARED TO STOP." In addition, drivers who found DMS useful to guide traffic during lane blockage because of the incident were 3.47 times more likely to comply with the recommended action "USE CAUTION" than other drivers. Other significant factors are presented in Table 4.11.

4.5.4 Drivers' compliance with recommended actions during inclement weather that affects traffic

Table 4.12 summarizes the factors that increase drivers' compliance with different actions recommended on DMS to guide traffic during inclement weather that affects traffic and safety. Results show that understanding DMS content, using DMS as a source of trip/route information, the usefulness of DMS to guide traffic during inclement weather, gender, and age were the significant factors that were associated with drivers' compliance. For instance, drivers who understood DMS content were found to be 1.73 times more likely to comply with the recommended action "INCREASE FOLLOWING DISTANCE." Further, drivers who found DMS useful in guiding traffic during inclement weather were 15.17 times more likely to comply with the recommended action "USE EXTREME CAUTION" than other drivers. The season also influenced driver compliance with specific recommended actions during the weather. Specifically, in winter, drivers were 1.29 times more likely to comply with the recommended action "PLAN AHEAD" than in summer. Also, drivers were 1.492 times more likely to comply with the recommended action "REDUCE SPEED CRASH 2X AS LIKELY" in winter than in summer. Other factors are presented in Table 4.12.

Table 4.12: Factors associated with drivers' compliance with recommended actions during inclement weather that affects traffic and safety

Variable	Odds Ratio	Std. Err.	z	P>z	95% Conf. Interval	
Inclement weather that affects traffic - Plan Ahead						
Understanding DMS Content	1.179	0.389	0.500	0.617	0.618	2.249
Using DMS as a source of information	5.668	1.057	9.300	0.000	3.933	8.170
DMS usefulness during inclement weather	6.817	2.385	5.490	0.000	3.434	13.534
Female	1.585	0.214	3.410	0.001	1.216	2.066
Winter	1.290	0.192	1.710	0.087	0.964	1.727
Inclement weather that affects traffic - Reduce Travel Speeds						
Understanding DMS Content	1.191	0.372	0.560	0.576	0.645	2.199
DMS usefulness during lane closure	4.463	0.822	8.120	0.000	3.110	6.403
DMS usefulness during inclement weather	14.732	4.851	8.170	0.000	7.726	28.090
Female	2.839	0.408	7.250	0.000	2.142	3.764
Inclement weather that affects traffic - Use Extreme Caution						
Understanding DMS Content	1.681	0.512	1.700	0.088	0.925	3.053
Using DMS as a source of information	3.813	0.701	7.280	0.000	2.660	5.466
DMS usefulness during inclement weather	15.166	5.084	8.110	0.000	7.862	29.256
Female	2.071	0.303	4.980	0.000	1.555	2.758
Inclement weather that affects traffic - Increase Following Distance						
Understanding DMS Content	1.731	0.526	1.810	0.071	0.954	3.139
Using DMS as a source of information	4.164	0.759	7.820	0.000	2.913	5.953
DMS usefulness during inclement weather	9.918	3.170	7.180	0.000	5.301	18.555
Female	2.326	0.329	5.970	0.000	1.763	3.070
Inclement weather that affects traffic - Avoid Using Cruise Control						
Understanding DMS Content	1.326	0.415	0.900	0.367	0.718	2.448
Using DMS as a source of information	3.966	0.707	7.730	0.000	2.797	5.624
DMS usefulness during inclement weather	8.706	2.791	6.750	0.000	4.644	16.320
Female	2.435	0.338	6.420	0.000	1.856	3.195
Inclement weather that affects traffic - Stay Alert						
Understanding DMS Content	0.922	0.298	-0.250	0.802	0.490	1.736
Using DMS as a source of information	5.204	0.960	8.940	0.000	3.624	7.471
DMS usefulness during inclement weather	9.675	3.328	6.600	0.000	4.931	18.985
Older drivers	2.311	0.766	2.530	0.012	1.207	4.426
Female	1.862	0.259	4.470	0.000	1.418	2.444
Inclement weather that affects traffic - Reduce Speed Crashes 2X As Likely						
Understanding DMS Content	0.867	0.281	-0.440	0.659	0.459	1.635

Variable	Odds Ratio	Std. Err.	z	P>z	95% Conf. Interval	
Using DMS as a source of information	5.260	0.982	8.890	0.000	3.648	7.585
DMS usefulness during inclement weather	7.277	2.450	5.900	0.000	3.762	14.076
Older drivers	1.767	0.571	1.760	0.078	0.938	3.328
Female	1.832	0.255	4.340	0.000	1.394	2.407
Winter	1.492	0.239	2.490	0.013	1.090	2.044

4.5.5 Factors associated with drivers' understanding of DMS messages

In the previous section, understanding DMS content was a significant factor influencing drivers' compliance with different DMS messages. However, understanding DMS messages is difficult to measure directly from the survey. This survey captured different factors that can explain the level of understanding reported by survey participants. These include demographic characteristics and DMS design and operation features and characteristics. Knowing which DMS design, operation features and characteristics are associated with understanding DMS content is crucial for the transportation agencies to recognize how to improve the general understanding of the DMS messages displayed, which increases drivers' compliance. Because DMS design and operation features and characteristics are quantitative factors, it is appropriate to associate them with DMS content understanding. However, due to the high correlation of the DMS design and operation features themselves, a unique modeling approach (SEM) was needed. Table 4.13 is the description of the variables used in the model.

Table 4.13: Description of variables used in the structural equation model

Endogenous	Exogenous variable	Description
DMS	Ofn	The density of DMS (whether drivers notices DMS or not)
	Sln	Ability to read two-phased messages (messages from two screens)
	Msp	Ability to read a message from the same screen
	Char	Clarity of the DMS message characters
	ylw	The yellow color increases the visibility of the message
	dy_	The use of DMS as a source of travel information
	Gender	Gender of a driver
	Age	Age category of the driver

The SEM explains a correlation between DMS design and operation features and how they were fitted in the DMS design and operation features and characteristics basket (DMS). In addition, factors associated with understanding DMS messages were identified. Figure 4.15 is the structural equation model's graphical representation and the contribution estimates. It shows a positive association between understanding of DMS messages and the DMS design and operation features characteristics, including density of DMSs, ability to read two-phased messages, ability to read single-phased messages, clarity of DMS messages, and the use of yellow color to increase visibility. Further, there exists an association between the use of DMS as a source of trip/route information and understanding of messages. However, there was no significant association between drivers' demographics (gender and age) and understanding of DMS messages.

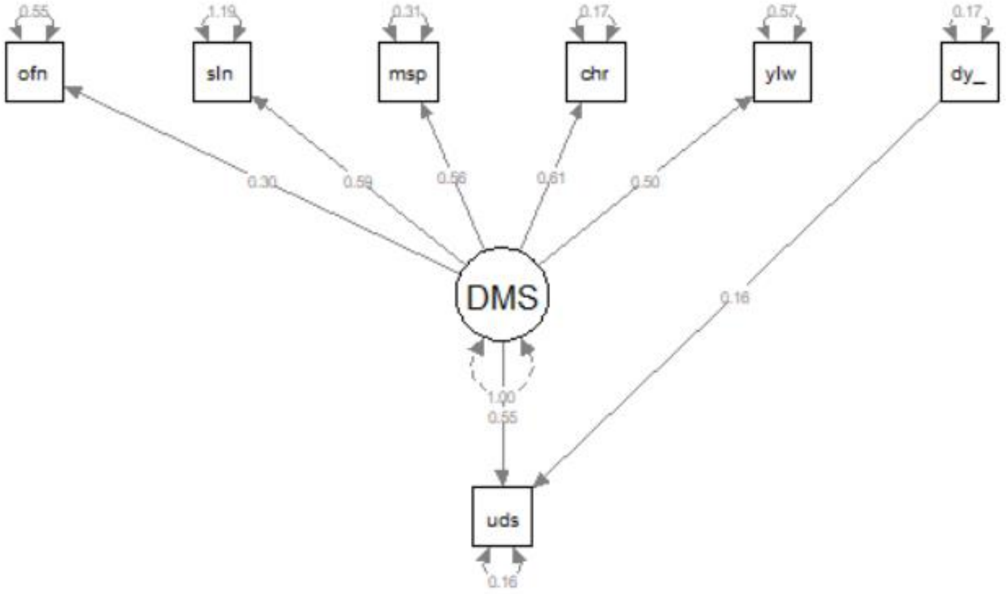


Figure 4.15: Factors associated with understanding of DMS messages

Table 4.14 presents the summary results from the regression analysis for the factors associated with the understanding of DMS content/messages. Results show that the DMS design and operation features and characteristics and DMS use as a source of travel information are significant factors associated with DMS content understanding. That is to say, improving DMS design and operation features and characteristics (clarity of characters) was associated with an increase in the understanding of DMS messages displayed. Gender and age were not significant enough to be included as factors that influence the understanding of DMS messages.

Table 4.14: Factors associated with understanding of DMS message

	Estimate	Std. Err.	z	P>z
Understanding of DMS messages				
DMS design and operation features and characteristics	0.550	0.021	26.426	0.000
Using DMS as a source of travel information	0.161	0.039	4.094	0.000

4.5.6 Summary results of analysis of drivers' understanding and compliance with recommended actions displayed on DMS

Section 4.5 presented results to analyze drivers' understanding and compliance with DMS messages. The analysis of drivers' compliance with different recommended actions showed that different factors are associated with DMS messages' compliance. In general, drivers' compliance with DMS messages is associated with factors such as understanding DMS content, the use of DMS as a source of information, drivers' opinions on the usefulness of DMS to guide traffic during different road scenarios, and traffic conditions, age, and gender. The season was a significant factor in some weather-related messages during inclement weather that affects traffic.

In addition, higher reliance on DMS as a source of information is associated with an increase in the understanding of the DMS message as this segment of drivers maybe pay more attention to the DMSs. Further, DMS design and operation features and characteristics are also associated with understanding DMS messages. Results show a significant positive association between the DMS design and operation features and characteristics. That is to say, improvements made on DMS design and operation features are likely to increase the likelihood of drivers' understanding DMS messages. DMS design and operation features and characteristics that can be improved are; the number of DMS that drivers can notice, the readability of messages displayed (whether displayed on the same screen or the message is long and is displayed in two screens), increasing the clarity of DMS and the use of yellow color.

4.6 Overall Conclusion and Recommendation

This chapter analyzed survey data collected in two different seasons: summer and winter. Results show that drivers generally seek different trip/route information types and use different sources to search for that information after starting their journey. Traffic conditions and incident information are the travel information most often sought by drivers. Drivers also mostly use internet sources (e.g., smartphones) and DMS to search for different types of information. Drivers reported incidents and roadwork to be the two road conditions during which DMS are most useful. In addition, among other factors, understanding DMS content was found to be a significant factor affecting drivers' compliance with DMS messages. The observation makes perfect sense because compliance is impossible if a message is not understood. Specific DMS design and operation features and characteristics that need high priority to facilitate understanding of DMS content include the density of DMS, message phasing, clarity of message characters, and text color.

Transportation agencies can use this analysis to prioritize different messages and types of trip/route information displayed on DMS during different seasons. The results can also be used to improve different DMS features and characteristics to influence drivers' compliance with the displayed messages. For example, most drivers complained about the inability to read messages displayed from two screens when driving at higher speeds. Results suggest the need to review the MDOT's message phasing guidelines to reflect expected operation speeds for different Michigan roadways.

5 Field Case Studies and Driving Simulation Experiment

The research team conducted field case studies to quantify the effectiveness and impacts of DMSs on traffic flow. These case studies targeted specific DMS messages, designs, and applications (operations). Specifically, studies conducted focused on the following aspects of DMS:

1. Impacts of weather-related DMS messages on traffic flow;
2. Analysis of travel times displayed on DMS;
3. Impacts of DMS messages on traffic diversion; and
4. Work zone management using Portable Changeable Message Sign (PCMS).

In addition to these field studies, the research team conducted a driving simulation experiment to study optional DMS message phasing designs. This chapter documents the details and findings from all case studies and the driving simulation experiment.

5.1 Impacts of weather-related DMS messages

Analysis of the impacts of weather-related DMS messages consisted of two parts: (1) evaluating the impact of specific weather-related messages on traffic flow, and (2) assessing the feasibility of using data from Environmental Sensor Stations (ESS) to automate the display of weather-related messages on DMS.

5.1.1 Impacts of weather-related messages on traffic speeds

Weather is one factor that impacts the traffic flow and safety on a roadway (Hermans *et al.*, 2015). The environmental hazards associated with certain weather and its effects on the pavement can increase the risk of crash occurrence. Speeding is one of the major causes of crashes and its impacts are generally more intense in adverse weather than normal conditions (Khattak *et al.*, 1995). Therefore, timely and accurate communication of weather conditions to motorists is expected to influence their speeds, and consequently crash risk. MDOT employs several methods during adverse weather conditions to improve road safety and mobility, including informing drivers of the circumstances ahead regarding a certain weather condition by posting weather-related messages on DMS (Toth *et al.*, 2016). This case study focused on assessing the effectiveness of displaying weather-related messages on traffic flow. In particular, the study investigated how the recommendation to “REDUCE SPEED” in two weather-related messages affects traffic speeds.

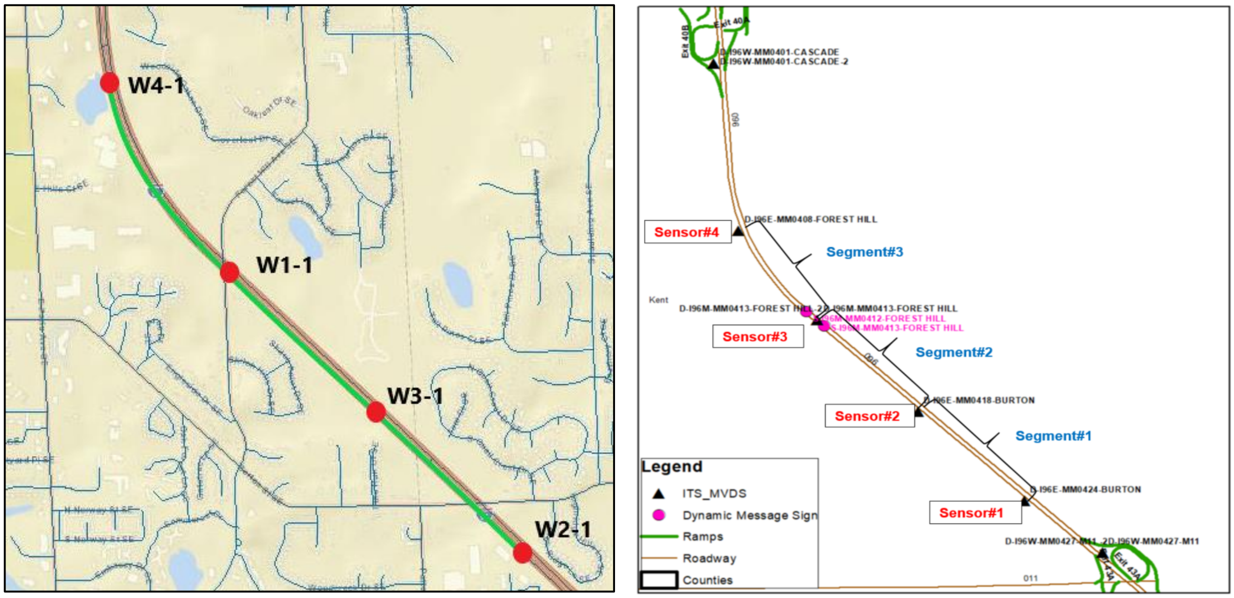
5.1.1.1 Selection of study sites

DMS density was the main criterion for selecting the DMS for this study. This is because where multiple DMS are available, the same weather-related message would be posted at all DMSs and hence capturing the effect of a specific DMS would be impossible. Therefore, an isolated DMS located on a section of the I-96 freeway in Grand Rapids, Grand Region, namely S196W-MM0413-Forest Hill, was selected. Snow showers and rainfall were expected during the study period, triggering posting weather-related messages.

5.1.1.2 Study setup

To obtain all necessary data, the Bluetooth sensors and video cameras were installed before the forecasted days of rainfall and snow showers. The field data observation occurred from 22 February 2021 to 01 March 2021. A total of four Bluetooth sensors were mounted on four existing poles, as shown in Figure 5.1. The mounted Bluetooth sensors divided the site into three segments (segments 1, 2, and 3). Segment 1 was between sensor1 (W2-1) and sensor 2 (W3-1), while segment 2 was between sensor 2 (W3-1) and sensor 3 (W1-1). Segment 3 was between sensor 3 (W1-1) and sensor 4 (W4-1). Sensor 3 (W1-1) and the video camera were mounted at the DMS, which displayed the weather-related messages. Both segments 1 and 2 were 0.55 mi, while segment 3 was 0.49 mi long.

To determine the effect of a particular message, segment 1 was used as the control site, while segments 2 and 3 were considered the test sites. Segment 1 was chosen as the control site because it captured the traffic condition (speed profiles) of drivers before they could read the DMS message. Since the weather-related messages recommended speed reduction, speed changes between the segments were used as the metric. The speed difference between segments 2 and 1 would capture the immediate effect, which is the impact just after reading the DMS message. The prolonged impact of the weather-related message would be captured by the speed difference between segments 3 and 1.



(a) Sensor layout (b) Site layout

Figure 5.1. Bluetooth sensors and camera mounting locations.

5.1.1.3 Data used

Data utilized in this study include DMS messages provided by MDOT and field traffic data. MDOT provided the research team with DMS messages logs used to identify when the weather-related messages were posted. Field data included traffic speed deduced from the Bluetooth sensors and traffic volume extracted from the video cameras.

- *DMS Messages (from MDOT):* The DMS message logs contained a timestamp at which a specific message was displayed. When a new message was posted, it recorded a new timestamp. Since this study was concerned with weather-related messages, the weather-related messages posted were extracted from the logs.
- *Traffic volume:* Speed reduction is also a function of traffic congestion in the roadway. Congestion occurs when more vehicles use the road facility than its capacity. Therefore, when the highway capacity of a certain highway section is exceeded, the traffic flow ceases, and therefore, speeds are reduced. It was, therefore, important to account for changes in the traffic volume during the data collection period. The traffic counts were manually extracted from the video camera for test days and control days. The test days are the days when the weather-related message was posted. Control days were identified for each test

day to compare the traffic speeds by segment. The control days had normal weather conditions with no weather-related message posted to determine the normal (baseline) operating conditions. Table 5.1 shows the test days where the two messages were posted and their respective control dates.

Table 5.1. The time at which the traffic volume was determined

Message	Test date	Message	Control date	Message
Message 1	27 Feb 2021 08:00-11:30	ROAD MAY BE, SLIPPERY, REDUCE SPEED	01 Mar 2021 08:00-11:30	OFF
Message 2	28 Feb 2021 15:00-19:00	REDUCE SPEED ON WET PAVEMENT	26 Feb2021 15:00-19:00	OFF

- *Traffic speed:* The two weather-related messages instructed the drivers to reduce speed. To determine the speeds, the vehicles' travel times were deduced from the Bluetooth sensors. A thorough procedure was established to process the raw timestamp data from the Bluetooth sensor and convert it into speed profiles. The sensors detected the Bluetooth Media Access Control (MAC) addresses/fingerprints emitted from smart devices such as smartphones, tablets, wearable devices, and vehicular embedded systems. The MAC address does not change, and it is unique for each device. This enabled tracking a particular MAC address or fingerprint over time and, therefore, a vehicle that moves with the device. The detection range of each sensor was 328 ft (100m). The raw log data contained the timestamps for each MAC address. Because of the large detection radius, it was possible for multiple timestamps to be registered for a single MAC address. Therefore, the average timestamp value was used for each MAC address at a given sensor location. The vehicle speed between two points was calculated by taking the distance divided by the time difference between the two sensor locations. The calculated vehicle speeds were further preprocessed using a five-minutes moving median filter to remove superfluous speeds. The 25th percentiles of the speed above and below five-minutes moving median filter were retained in the analysis. The final speed profiles for the three segments are shown in Figure 5.2. The portion of the speed profiles for the test dates and control dates (Table 5.1) were then extracted to study the association of weather-related messages and driver speeds.

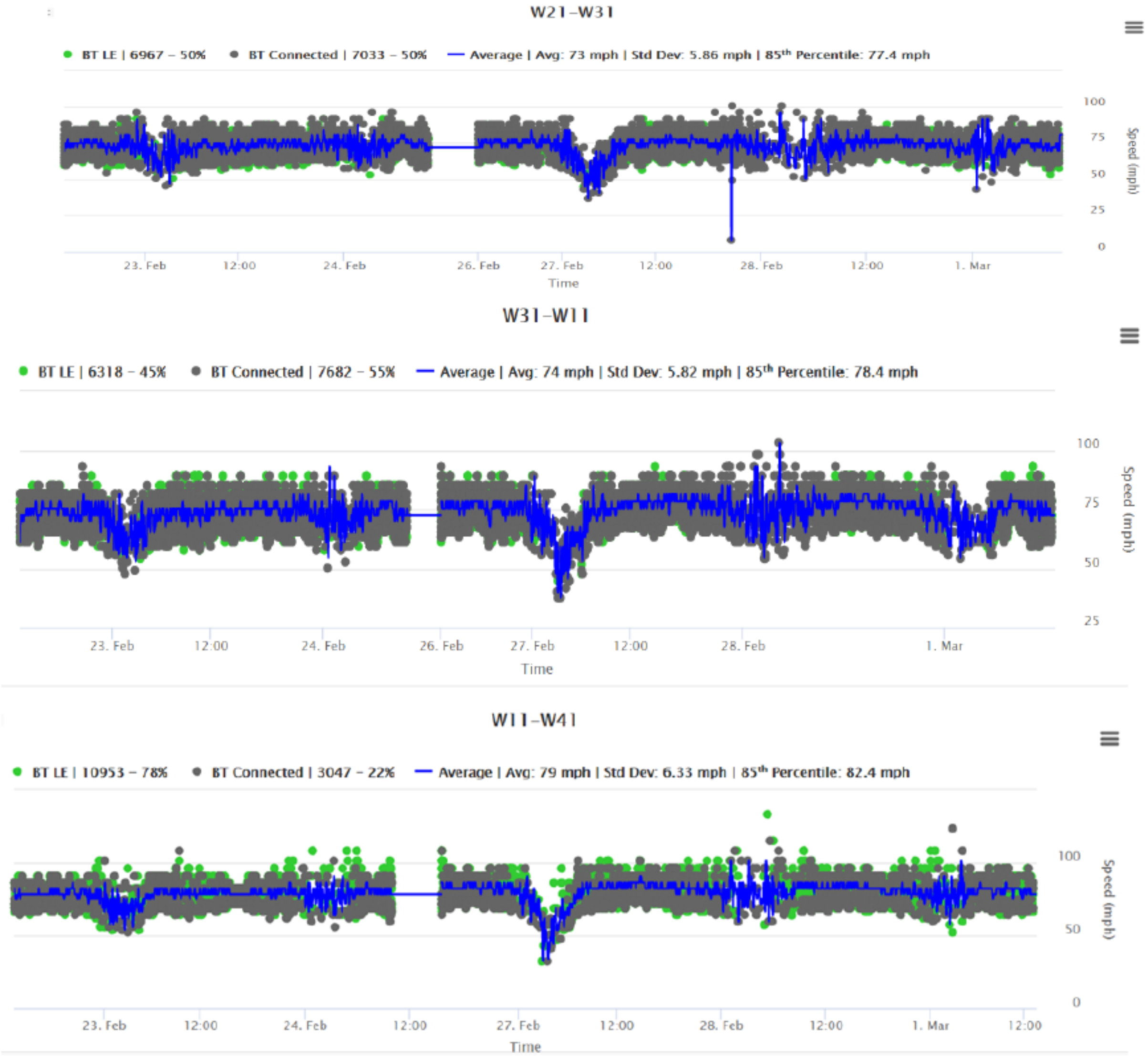


Figure 5.2. Processed speed profiles of vehicles at each segment

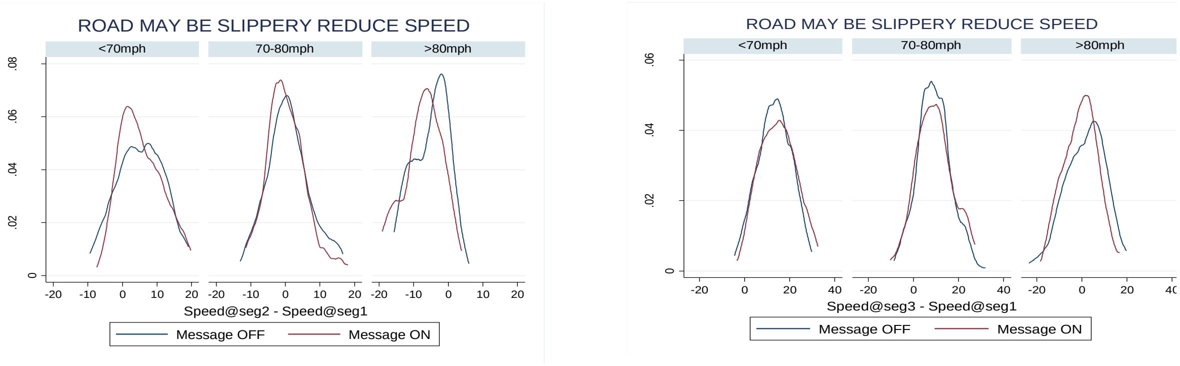
5.1.1.4 *Analysis of Descriptive Statistics*

The variables included in this study were the approaching speeds and traffic volumes. The approaching speeds were determined on segment 1 before any drivers could see the DMS message. Drivers' speeds were categorized into three categories which are below the speed limit of 70 mph, between 70-80 mph, and above 80 mph. This was done to assess how the weather-related message impacted the different drivers driving at different speeds. For the first message, the highest percentage of drivers were driving at a speed between 70-80 mph (46.05%), followed by those driving below 70 mph (37.90%). The least proportion of drivers was driving at a speed above 80mph (16.05%). In the second message, more than half of the drivers (52%) were driving at speeds between 70-80 mph. The percentage of drivers driving below 70 mph and above 80 mph was approximately equal (24%). Traffic volume was treated as a continuous variable and was aggregated at a five-minute interval.

Table 5.2. Descriptive summary

"ROAD MAY BE SLIPPERY REDUCE SPEED"			**"REDUCE SPEED ON WET PAVEMENT"**		
Approaching Speed	**Obs.**	**Percentage**	**Approaching Speed**	**Obs.**	**Percentage**
Below 70mph	288	37.90	Below 70mph	244	24.20
Between 70-80mph	350	46.05	Between 70-80mph	524	52.00
Above 80 mph	122	16.05	Above 80 mph	240	23.80

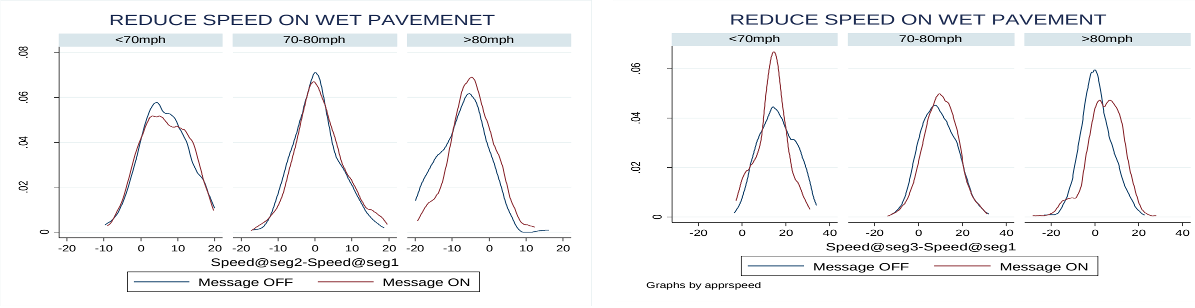
The speed distributions were plotted for both messages to visualize the changes in speed associated with the messages. For the first message, "ROAD MAY BE SLIPPERY REDUCE SPEED," a change in speed was identified between the control site (segment 1) and test sites (segment 2 & segment 3). A similar analysis was conducted for its respective control dates when the weather-related message was not displayed. Analysis of the differences between segment 1 and segment 2 (Figure 5.3a) shows that the distribution of speeds for drivers driving below 70 mph and those driving between 70-80 mph overlapped when the message was ON and OFF. Moreover, for drivers driving above 80 mph, their speed decreased when the message was ON, as shown in Figure 5.3a. A similar trend was observed when considering the prolonged impact of the message, which was computed as the difference between segment 3 and segment 1. For the drivers driving at a speed above 80mph, their speeds reduced when the message was ON compared to when the message was OFF (Figure 5.3b).



(a) Speed difference: Segment 1 and 2 (b) Speed difference: Segment 1 and 3

Figure 5.3. The immediate and continuous impact of the first message

Also, for the second message, “REDUCE SPEED ON WET PAVEMENT,” the speed difference was identified between the control site (segment 1) and test sites (segment 2 and segment 3), as shown in Figure 5.4. Considering the immediate impact computed as the difference in speed between segment 2 and segment 1, from the three categories of speeds, the distribution of speeds for drivers driving below 70 mph and those between 70-80 mph overlapped when the message was ON and OFF. On the other hand, the drivers with speeds above 80 mph increased their speed when the message was ON (Figure 5.4a). Similarly, considering the prolonged impact of the message (Figure 5.4b), the distribution of speeds for drivers driving below 70 mph and those driving between 70-80 mph overlapped when the message was ON and OFF. Moreover, drivers driving at speeds above 80 mph increased their speeds when the message was ON.



(a) Speed difference: Segment 1 and 2 (b) Speed difference: Segment 1 and 3

Figure 5.4. The immediate and continuous impact of the second message

5.1.1.5 Analysis of Variances (ANOVA)

The Analysis of Variance (ANOVA) test was used to determine the change in speed on the roadway when the two messages were posted on the DMS. ANOVA is a statistical method that uses variances to determine the differences in group means by testing two hypotheses, the null hypothesis, which assumes all the group means are the same (Equation 1), and the alternative hypothesis, which assumes that at least one of the group's mean is different. After computing the test statistic (F-statistic), the ANOVA contrast was used to determine the differences in speed means when the weather-related message was ON and OFF. ANOVA contrast is the weight that represent a specific comparison over means (Gonzalez, 2011). For this case, the ANOVA contrast was used to determine the difference in speed across the message status categories, ON and OFF.

ANOVA test was used to determine the difference in mean speeds between two segments (segments 2 and 1 & segments 3 and 1) across two independent variables. The two independent variables were the message status (ON/OFF) and the five-minute traffic volume. The analysis was done with and without including the traffic volume to see whether the speed reduction was associated with traffic volume or not. The ANOVA results for the two messages are summarized in Table 5.3 and Table 5.4. The contrasts are reported as the speed difference (ON/OFF) on both the immediate and prolonged impact.

Table 5.3. ANOVA test results for “ROAD MAY BE SLIPPERY, REDUCE SPEED”

Approaching speed	**Criteria**	**Seg2 vs. Seg1 (Immediate Impact)**		**Seg3 vs. Seg1 (Continuous Impact)**	
		Difference (ON-OFF)	**Prob>F**	**Difference (ON-OFF)**	**Prob>F**
Overall	Without Volume	-0.31	0.569	0.43	0.539
	With volume adj.	0.10	0.879	**5.45**	**0.000**
<70mph	Without Volume	0.31	0.717	1.39	0.188
	With volume adj.	**2.74**	**0.001**	**7.87**	**0.000**
70-80mph	Without Volume	-1.78	0.232	-0.10	0.902
	With volume adj.	-0.62	0.447	**4.60**	**0.000**
>80 mph	Without Volume	-2.32	0.016	-2.34	0.127
	With volume adj.	**-5.66**	**0.000**	-2.37	0.198

Table 5.4. ANOVA test results for “REDUCE SPEED ON WET PAVEMENT”

Approaching speed	**Criteria**	**Seg2 vs. Seg1 (Immediate Impact)**		**Seg3 vs. Seg1 (Continuous Impact)**	
		Difference (ON-OFF)	**Prob>F**	**Difference (ON-OFF)**	**Prob>F**
Overall	Without Volume	-0.20	0.335	0.37	0.750
	With volume adj.	-0.51	0.312	**1.26**	**0.036**
<70mph	Without Volume	0.40	0.685	-1.05	0.149
	With volume adj.	0.14	0.890	0.38	0.761
70-80mph	Without Volume	1.04	0.970	2.05	0.999
	With volume adj.	0.73	0.219	**2.71**	**0.000**
>80 mph	Without Volume	**2.91**	**0.0002**	**4.57**	**0.000**
	With volume adj.	**2.22**	**0.020**	**5.26**	**0.000**

5.1.1.6 Analysis of overall (all speeds)

In this analysis, the speed difference was determined using all speeds to assess the general impact of the two messages. Since the traffic volume can impact the speeds, the change in speed was identified with and without accounting for the volumes. For the first message, “ROAD MAY BE SLIPPERY REDUCE SPEED,” the analysis without adjusting for the traffic volume showed that drivers immediately slowed down when the message was ON and reduced their speeds by 0.31 mph in segment 2, but this was not statistically significant (p=0.569). When accounting for the traffic volumes, there was an immediate increase of 0.1mph in speed but was not statistically significant (p=0.879). Moreover, there was a significant increase in speed by 5.45 mph in segment 3 when this message was on.

The second message, “REDUCE SPEED ON WET PAVEMENT,” had an immediate speed reduction of -0.20mph when the message was posted but was not significant (p=0.335). When the traffic volume was incorporated, there was an immediate speed reduction of 0.51 mph when the message was on, but this was not statistically significant (p=0.312). Moreover, a prolonged effect of this message was significant at a 95% confidence interval (p=0.036) with an increase in speed by 1.26mph in segment 3.

The analysis of all speeds combined suggested that the two messages had no significant speed reduction but rather a prolonged effect of speed increase was observed. It was therefore important to evaluate the impact of weather-related messages on drivers driving at different speeds as they approach the DMS. Speeds below 70 mph were analyzed differently from those between 70-80 mph and those above 80 mph.

Vehicles traveling below speed limit (<70 mph)

Without adjusting for traffic volume, the first message, “ROAD MAY BE SLIPPERY REDUCE SPEED” had a 0.31 mph immediate speed increase just after the drivers saw the message. Moreover, these drivers increased their speed by 1.39mph in segment 3 from the control site, but this was not statistically significant. When adjusting for traffic volume, it was statistically significant at the 95% confidence interval that this message impacted the drivers driving below the speed limit (p=0.00). This message had both immediate and prolonged impact on the drivers since there was a 2.74 mph immediate increase in speed just after seeing the message. This was prolonged with an increase of 7.87 mph from the control site when drivers were in segment 3.

The second message, “REDUCE SPEED ON WET PAVEMENT,” had a speed reduction impact on these drivers by 1.05 mph as the prolonged impact was statistically not significant (p=0.149). On accounting for traffic volume, there was an immediate speed increase by 0.14mph (p=0.890) and a prolonged effect by 0.38mph, which was not statistically significant at the 95% confidence interval (p=0.761). This message did not have any significant speed reduction on these drivers.

It can be concluded that both messages did not have any significant speed reduction on the drivers who were driving below the speed limit. It should be noted that drivers are usually advised to lower their speeds during adverse weather conditions. Therefore, after seeing this message, these drivers may not have seen the need to reduce speed as they perceived their speed to be safe.

Vehicles traveling within 70-80 mph

Without accounting for the traffic volumes, the second category of drivers (those traveling between 70-80 mph) had an immediate decrease in speed (1.78 mph) when the message was “ROAD MAY BE SLIPPERY REDUCE SPEED” was ON, but this was not statistically significant (p=0.232). On the other hand, when accounting for the traffic volumes, the message had a 0.62mph immediate speed reduction, but similarly, this was not significant at the 95% confidence interval (p=0.447). However, this message had a prolonged negative effect on these drivers since their speeds increased by 4.6mph in segment 3, which was significant at the 95% confidence interval. For the second message ("REDUCE SPEED ON WET PAVEMENT"), drivers had increased their speeds within segment 2 by 0.73mph, but this was not significant at the 95% confidence interval (p=0.219). On the other hand, this message had a statistically significant prolonged impact since the drivers' speed increased by 2.71mph on these drivers. The two messages did not significantly reduce speed just after drivers saw the message. Furthermore, it was observed that in both messages, drivers increased their speeds after they passed the DMS (segment 3).

Vehicles traveling above 80mph

The third category consisted of speeding drivers who were driving above 80 mph as they approached the DMS. Without adjusting for traffic volume, the message "ROAD MAY BE SLIPPERY REDUCE SPEED" had an immediate speed reduction of 2.32 mph when the message was on. Similarly, when the traffic volume was incorporated, there was an immediate speed reduction of 5.66 mph which was statistically significant (p=0.000).

On the other hand, the second message, "REDUCE SPEED ON WET PAVEMENT," did not impact the speeding drivers. The drivers increased their speeds by 5.26 mph in segment 3. This can be explained by the differences in the structure of the two messages. The first message, "ROAD MAY BE SLIPPERY REDUCE SPEED", is a warning statement on the actual ground condition instructing drivers to reduce their speed because the road can be slippery, while the second message, "REDUCE SPEED ON WET PAVEMENT", is an advisory statement to the driver to reduce their speed whenever they pass through a wet pavement.

5.1.1.7 Findings

Weather-related messages are usually posted on the DMS to inform drivers of the circumstance ahead and the recommended action to be taken. This study investigated the impact of the recommended action "REDUCE SPEED" in two weather-related messages on traffic flow. Despite having similar weather conditions, the display of two different messages had a significant impact on the speeding drivers (driving above 80mph).

The findings suggest that the message “ROAD MAY BE SLIPPER REDUCE SPEED” had a statistically significant reduction in speed of 5.66 mph just after drivers saw the message. A similar message sign was used in Luoma and Pirkko (2000) study to warn drivers of the slippery road and significantly reduced the speed. On the other hand, the message, “REDUCE SPEED ON WET PAVEMENT” did not impact the speeding drivers significantly. In this message, the speeding drivers increased their speeds by 2.22mph just after seeing the message, and after about 1 mile, they increased their speed by 3.04 mph.

The differences in driver compliance across the two messages may be attributed to the difference in message content and connotation. Research has shown that for a message to be effective, it must be clear, short, and on-point (Dudek *et al.*, 2006). Furthermore, DMS messages should consider simplicity, standardized words, and brevity (Belz and Gårder, 2009). This study shows how the content of a message can influence its effectiveness. The weather-related message that stated/implied the actual ground condition “ROAD MAY BE SLIPPER REDUCE SPEED” had high compliance compared to the general weather advisory message “REDUCE SPEED ON WET PAVEMENT.” These conclusions are in line with Jeihani *et al.* (2018) that DMS messages which are specific are more effective. The study provides insight to the transportation agencies on how drivers’ compliance may be improved by properly phrasing the weather-related DMS messages to reflect actual conditions.

5.1.2 Automation of weather-related messages using Environmental Sensor Stations (ESS)

When an ESS is properly located with respect to the location of a DMS, its environmental data can be used to automate the process of displaying weather information on DMS. Automatic display of weather-related messages on DMS would ensure that most relevant messages are displayed timely and efficiently.

5.1.2.1 Study location and setup

For this study, feasibility of automating weather-related messages on a DMS (S-US131S-MM0732-92nd) located on US-131 using environmental data from one ESS (US131S-MM061.0-WAYLAND) located 12 miles south of the DMS was evaluated. To achieve this, the display of weather-related messages was automated from 01 January 2021, to 08 February 2021, by implementing a predeveloped decision matrix (Appendix 9.6). Then, the automatic display of weather-related message was disabled for the remainder of the winter season and no weather-related message was displayed. Figure 5.5 shows the study location.

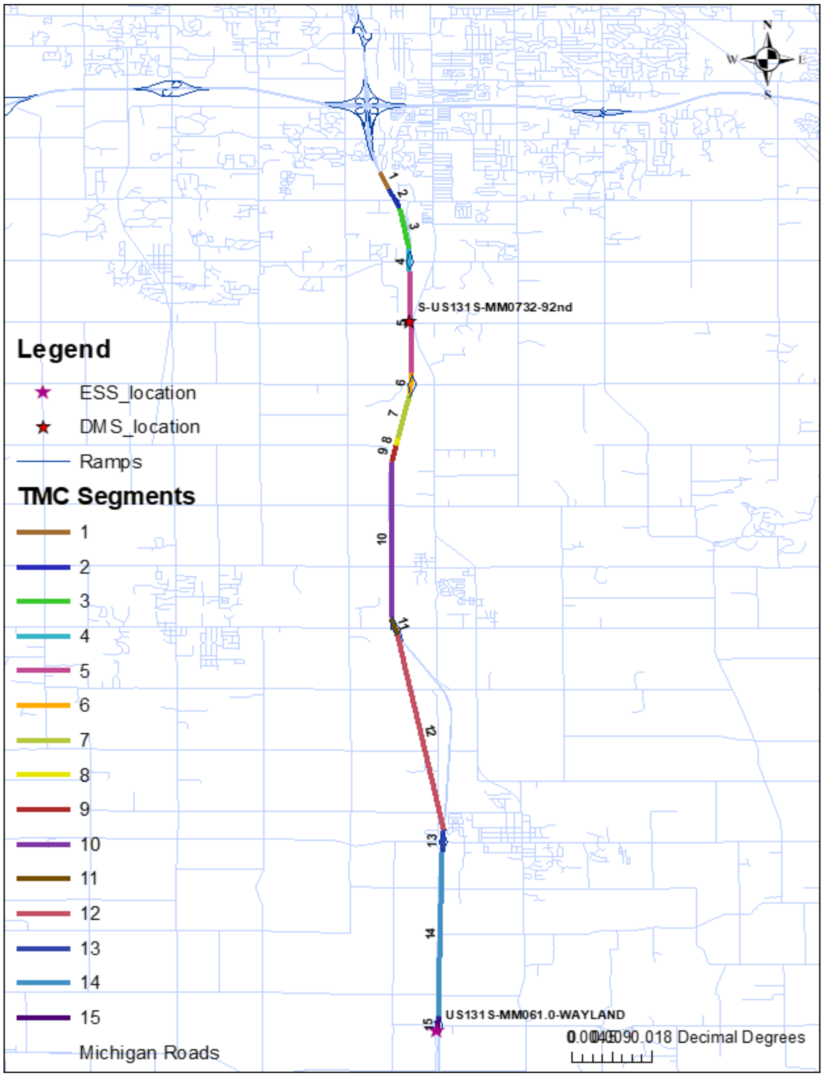


Figure 5.5. TMC segments used for speed data analysis

5.1.2.2 Data used

a) ESS and DMS operational data

The research team obtained raw ESS data from MDOT from January 1st to April 30th 2021. The data contained multiple atmospheric parameters and their corresponding timestamp at an interval of five minutes. The parameters included surface temperature and status, air temperature, dew point temperature, surface ice or water depth, relative humidity, precipitation situation, wind speed and direction, visibility, surface salinity, and atmospheric pressure. To quantify the impact of message automation, the ESS data were categorized into two scenarios of “ON” (01 January 2021 to 08 February 2021) and “OFF” (09 February 2021 to 30 April 2021). During the “ON” period, weather-related messages were automatically displayed on the DMS when the conditions warranted, while during the “OFF” period, no weather-related message was posted but the weather data were logged and post-analyzed to determine if any condition warranted posting a weather-related message. For the “ON” period, matching the displayed DMS messages and ESS conditions was accomplished by using the algorithm used by MDOT to determine which message should be displayed given specific weather conditions detected by ESS as shown in the decision matrix (Appendix 9.6). For the “OFF” period, the decision matrix was used to derive the message that should have been displayed on the DMS.

For a specific weather-related message to be analyzed, it was imperative that it was displayed during the “ON” period, and the conditions warranted it to be displayed in the “OFF” period. After assessing the frequency of weather conditions and their corresponding messages, the message “FREEZING RAIN DETECTED AT 179” and “LIGHT SNOW DETECTED AT 179” were considered as most suitable for analysis because they occurred in both study periods. Furthermore, drivers may be more likely to respond to these two messages unlike other messages such as “LOW VISIBILITY DETECTED AT 179.” The conditions that warranted posting of low visibility message were “no precipitation” as well as visibility of less than 1 mile, which may not dictate speed alteration. Moreover, the recommended action associated with “LOW VISIBILITY” message was to put “HEADLIGHTS ON, BE SAFE”, which also may not necessarily command speed reduction.

b) Speed data

INRIX speed data from 01 January to 30 April 2021 was obtained from PDA RITIS. This data consisted of the average speed of a particular segment at a given timestamp. Figure 5.5 shows the fifteen segment whose speed data were used. Details of the segments are shown in Appendix 9.7. The first four segments were used to observe the approaching speed before motorists were able to read the DMS message. Segments five to fifteen were used to observe how the speed changed after the drivers read the message at the DMS. For each segment, speed and travel time information at a particular timestamp was provided. To track the speeds of vehicles on subsequent segments, the travel time documented in the data was used to adjust the timestamps before matching them with speed. The speed data was then joined to the ESS data for further analysis.

5.1.2.3 Analysis of “LIGHT SNOW” conditions

One of the messages that were displayed on the DMS when the automation was “ON” was “LIGHT SNOW DETECTED AT M179”. This message is displayed when the precipitation type is light snow and the visibility is greater than 0.9 mile. The average speeds across the fifteen segments were computed and compared. Figure 5.6 shows the spatial distribution of speeds by segments when the message was posted (when automation was ON) and when the condition warranted posting the message but automation was OFF. The speed averages across the fifteen segments during normal conditions (i.e., no winter weather) were also plotted as baseline. In the normal conditions, only travel time messages were displayed on the DMS.

It is evident that speeds were significantly lower during adverse weather conditions compared to normal conditions, regardless of the status of message display (ON or OFF). Moreover, the approaching speed of drivers (segment one to segment four) before seeing the DMS message was relatively similar during snow condition regardless of message display status. However, when automatic message display was ON, motorists responded to the message by reducing their speeds in segment five and maintained relatively lower speed in the subsequent segments.

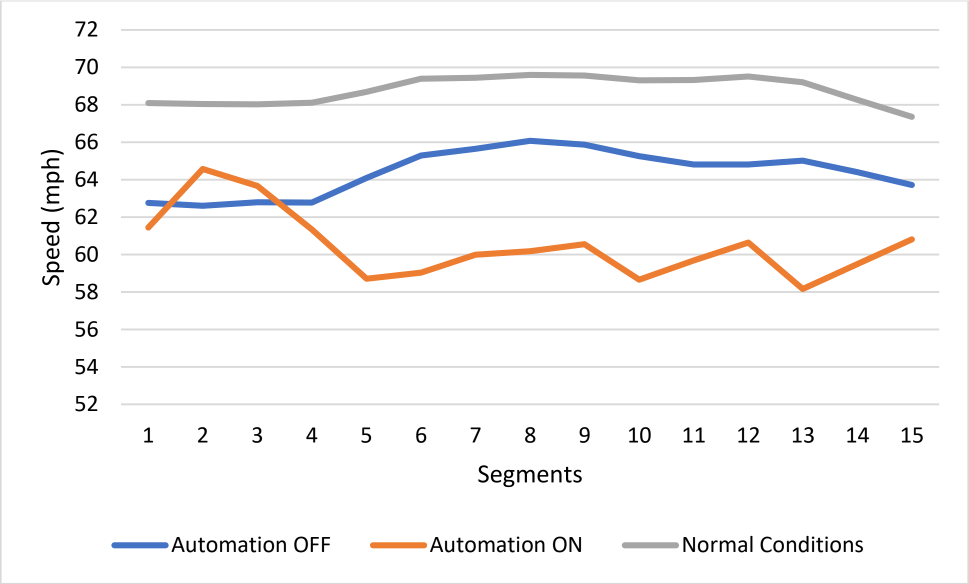


Figure 5.6. Light snow condition average speed by segment for automation on and off

Furthermore, the t-test comparing the mean speeds by segments when automation was “ON” and when it was “OFF” was performed. This analysis aimed at identifying whether the differences in speeds are significantly different as a result of drivers’ response to the automatic message displayed on DMS. Table 5.5 confirms that in segments 1-4 where drivers have not seen the message on the DMS, the mean speeds are statistically similar regardless of message display status (i.e., automation ON or OFF) However, beginning from segment 5 when drivers are able to see the DMS message, the mean speeds were significantly lower when the automation was “ON” than when it was “OFF.” It can also be observed that the difference begin to diminish downstream when vehicles reach segment 15. These findings indicate that automation of DMS message by using ESS detections have the potential to significantly influence traffic flow. While the same impact would be observed if message posting was done manually, automatic posting would ensure the relavant message is posted timely.

Table 5.5. T-test results for speeds during light snow conditions

Segment	Mean Speeds		t-statistic	p-value
	Automation ON	Automation OFF		
1	61.436	62.654	0.4213	0.3376
2	64.564	62.553	-0.8296	0.2053
3	63.667	62.696	-0.3768	0.3539
4	61.346	62.660	0.4504	0.3272
5	58.705	64.020	1.7468	0.0433**
6	59.038	65.248	2.1345	0.0188**
7	59.987	65.581	1.9848	0.0262**
8	60.179	66.012	2.0963	0.0205**
9	60.564	65.805	1.9265	0.0298**
10	58.667	65.240	2.4021	0.0100**
11	59.680	64.785	1.9051	0.0312**
12	60.641	64.789	1.6764	0.0498**
13	58.167	64.990	2.5556	0.0068**
14	59.500	64.354	2.0123	0.0247**
15	60.808	63.701	1.2096	0.1159

*indicates significantly different at 90% confidence interval
**indicates significantly different at 95% confidence interval

5.1.2.4 Analysis of "FREEZING RAIN" conditions

Similarly, durations which warranted posting of the message "FREEZING RAIN DETECTED AT M179", were analyzed. The average speeds across the fifteen segments were computed for when the automation was ON and OFF. Note that when automation was OFF, no weather-related message was posted and the data were post-analyzed to determine if conditions warranted posting a message at any time. Also, the normal conditions in which no weather message was warranted were included in the analysis. In the normal conditions and when automation was "OFF" only travel time messages were displayed on the DMS.

The analysis for the freezing rain condition was first done in similar manner to that of "light snow" described in 5.1.2.3 above. However, the analysis did not produce any explainable results. Since the ESS data contain information about pavement condition (e.g., chemically wet, dry, ice warning, snow warning, trace moisture or wet), we further filtered the data by incorporating pavement condition. The analysis utilized data from the durations when freezing rain conditions and ice was detected on the pavement surface.

Figure 5.7 shows that there exists a considerable speed reduction due to adverse weather conditions when comparing speeds during normal conditions to speeds when there is freezing rain (and ice conditions), regardless of message display status. Also, it can be observed that the approaching speed is relatively the same regardless of message display status. Another key observation in Figure 5.7 is that normally, drivers increase their speed in segment 6 as exhibited by the speed profile under normal conditions (i.e., when there was no adverse weather). However, when the automatic message display was ON, drivers maintained lower speeds when approaching segment six compared to when no message was displayed. Again, this response by motorists could be observed if the message was posted manually. However, automatic display ensures that the message is relevant and timely, especially if the location of the ESS sensor is conducive.

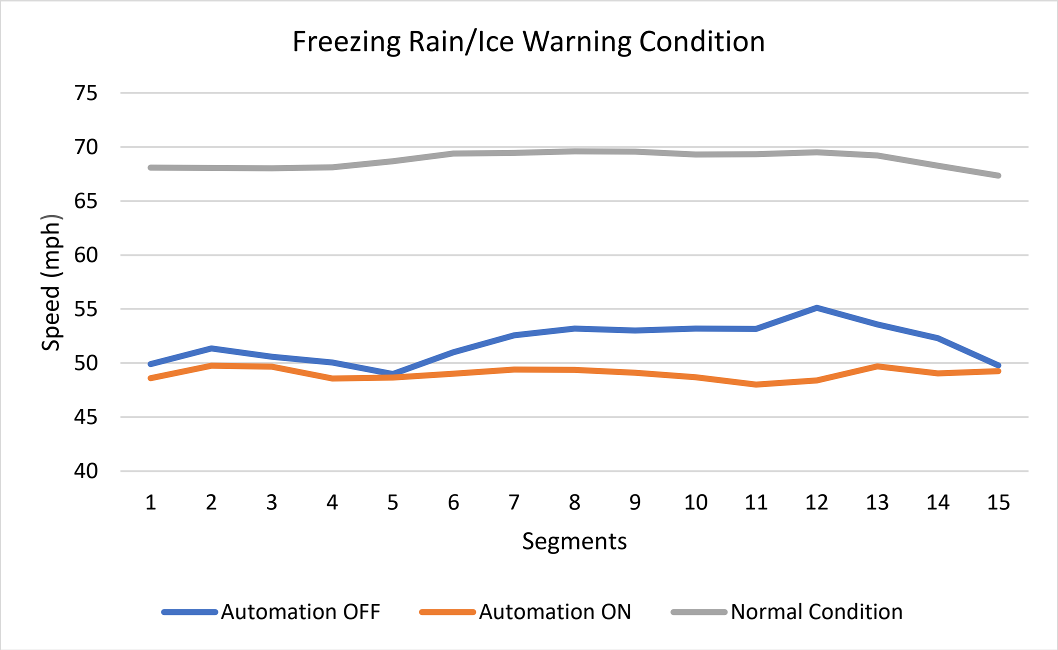


Figure 5.7. Freezing rain condition average speed by segment for automation on and off

Furthermore, the t-test was used to compare the mean speeds during the “ON” and “OFF” automation status when “FREEZING RAIN” and ice conditions were detected. Table 5.6 presents the results, which show that starting from segment 6 (after drivers see the DMS message), speeds were significantly lower when automation was "ON" compared to when automation was "OFF." This significant difference persisted through segment 14. In segment 15, the difference in speeds was insignificant.

Table 5.6. T-test results for speeds during freezing rain conditions

Segment	Mean Speeds		t-statistic	p-value
	Automation ON	Automation OFF		
1	48.604	49.889	0.902	0.1844
2	49.753	51.360	1.067	0.1440
3	49.669	50.571	0.614	0.2702
4	48.557	50.039	1.047	0.1485
5	48.666	48.996	0.244	0.4040
6	49.018	51.008	1.431	0.0776*
7	49.405	52.582	2.121	0.0180**
8	49.361	53.193	2.669	0.0043**
9	49.098	53.022	2.721	0.0037**
10	48.694	53.192	3.154	0.0010**
11	48.019	53.170	3.604	0.0002**
12	48.397	55.118	4.629	0.0000**
13	49.704	53.564	2.702	0.0039**
14	49.045	52.307	2.200	0.0148**
15	49.258	49.775	0.317	0.3760

*indicates significantly different at 90% confidence interval
**indicates significantly different at 95% confidence interval

5.1.2.5 Conclusion

This study aimed at investigating the impact of automating DMS weather-related message on traffic speeds. The speeds of drivers were compared along the fifteen TMC segments on US 131 for automation "ON" and "OFF" scenarios. The analysis focused on "LIGHT SNOW" and "FREEZING RAIN" conditions. The "FREEZING RAIN" scenario was specifically when icy pavement surface was also detected. The results indicate that when the weather-related message was displayed automatically (i.e., automation was "ON"), drivers reacted to the message posted on the DMS by reducing their speeds significantly. This reduction persisted for a short distance before the speeds became statistically similar again. The findings suggest that conditions detected by ESS can be used to automatically display an appropriate message on the DMS. While similar results can be obtained if the message is posted manually, automating the process would ensure timely and relevant message display on DMS.

5.2 Analysis of travel times displayed on DMS

The analysis of travel times displayed on DMSs also had two parts: (1) assessing accuracy of travel times displayed on DMSs, and (2) analysis of statewide travel time variations.

5.2.1 Accuracy of travel time displayed on the Digital Message Signs

Travel time, stating the minutes (often with distance) to a specific destination, is one of the information drivers find useful when displayed on DMS. Past studies conducted in other states have indicated that travel time information displayed on DMS has been viewed as useful by the public (Meehan, 2005; Flick, 2009). The survey of 908 users of Michigan roadways conducted as part of this study (see Chapter 4) indicated that travel time was among the top types of information sought by drivers (other top information being traffic condition and incident) after they start their journey. To obtain the travel time displayed on the DMS, different procedures are employed by transportation agencies and may include use of sensors to detect volume, occupancy, speed, or direct travel time (Kothuri et al., 2004). With the significance of travel time information to motorists, its accuracy is very crucial so that travelers do not lose their trust in the DMS information. This case study focused on assessing the accuracy of travel time information displayed on the DMS.

5.2.1.1 Selection of study site

A study site along US131 in Grand Rapids, Grand Region was selected, focusing on the DMS named S-US131S-MM0900-North Park. The selected DMS displayed travel time to 44TH street (destination) which is 11 miles from the DMS location. To assess the accuracy of the displayed travel time, there has to be considerable travel time variations on a specified route. The selected case study area is in urban area where frequent travel time variations are expected. This study was done in two phases: Phase 1 from 29th March

2021 12:00pm to 30th March 2021 5:00pm; and Phase 2 from 5th April 2021 10:00am to 8th April 2021 04:00pm.

5.2.1.2 Study setup

Two Bluetooth sensors were used in this study to measure travel times between the origin and the destination by detecting Bluetooth devices and match their MAC address. The first sensor was mounted at the MVDS pole at the DMS location (sensor W1-2). Similarly, the second sensor (W2-2) was mounted at the MVDS pole at the 44th street exit (Figure 5.8).

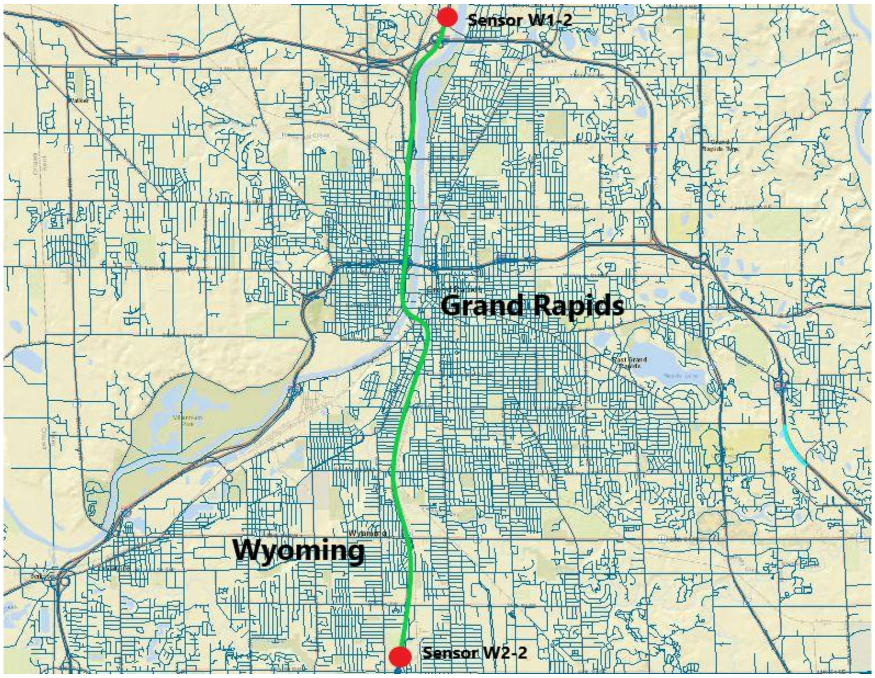


Figure 5.8. Study layout

5.2.1.3 Data used

(a) Sensor travel times

The travel time between the points was calculated from the time difference of the timestamps from the two Bluetooth sensors. This sensor travel time was compared to the time displayed on the DMS. In five minutes moving interval, the 25th percentile and 75th percentile were calculated. To remove the outliers, which may include vehicles that exited the route and rejoined back, equations (1) and (2) were used to set boundaries for data that was within the inter-quartile range. Figure 5.9 shows an example of how outliers were removed from Phase 1 data.

$$\text{Lower Limit} = 25^{th}\text{ percentile} - 1.5 * (75^{th}\text{ percentile} - 25^{th}\text{percentile}) \qquad 5.1$$

$$\text{Upper Limit} = 75^{th}\text{ percentile} + 1.5 * (75^{th}\text{percentile} - 25^{th}\text{percentile}) \qquad 5.2$$

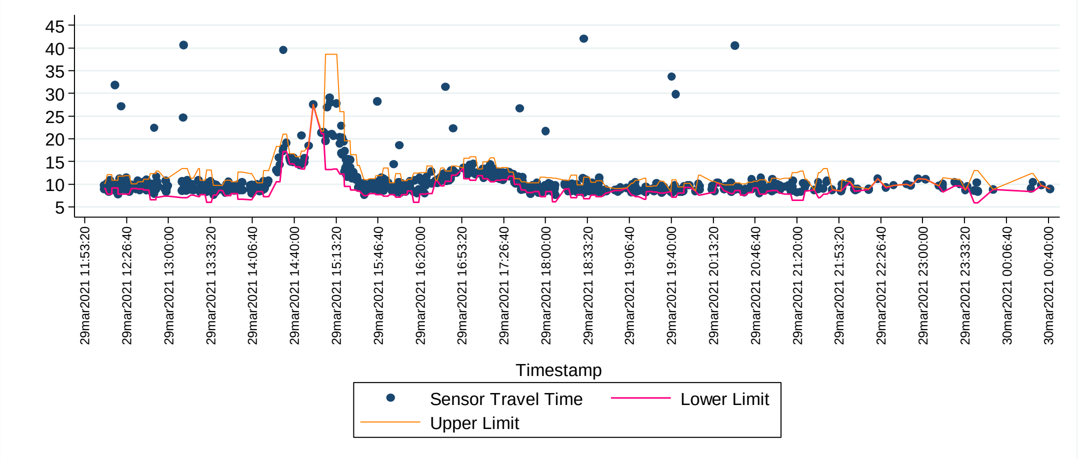


Figure 5.9. Phase 1 Bluetooth sensor travel time within the interquartile range

Since MDOT calculates the displayed travel time from speeds not exceeding the speed limit (70mph), the sensor data utilized in this study considered three categories. The first category included the travel time in which the associated speed was not exceeding 70mph only. The vehicle speed between two points was calculated by taking the distance (11 miles) divided by the time difference between the two sensor locations. In this category, all the observations which had speeds greater than 70mph were removed. The second category consisted of all speeds, including those above the speed limit. This was done not only to see the accuracy of the method used by MDOT but also to see the impact of excluding the speeding drivers. The third category focused on speeds above speed limit only. Travel time derived from Bluetooth sensors (i.e., the actual travel time experienced by drivers) were compared to the travel time displayed at the DMS when they passed it. Although motorists understand that the displayed time is an estimate calculated based on vehicles ahead of them, they may expect to experience the same time. When they experience different travel time from what was displayed, they may consider DMS travel time inaccurate.

(b) DMS Travel Times

To assess the accuracy of the displayed travel time in the DMS, the displayed DMS message logs were provided by MDOT and they contained the travel time posted on the DMS, the timestamp, the DMS name and destination. The research team extracted the posted travel times for the dates when the experiment was done. Using the timestamps in both the MDOT travel time logs and the Bluetooth data, the travel times were then matched for further analysis.

5.2.1.4 Descriptive analysis of travel times

Figure 5.10 presents an example of graphical comparison of DMS travel times and Bluetooth sensor travel times from Phase 1. It indicates that the sensor travel time were generally similar to those displayed by DMS even during congestion periods.

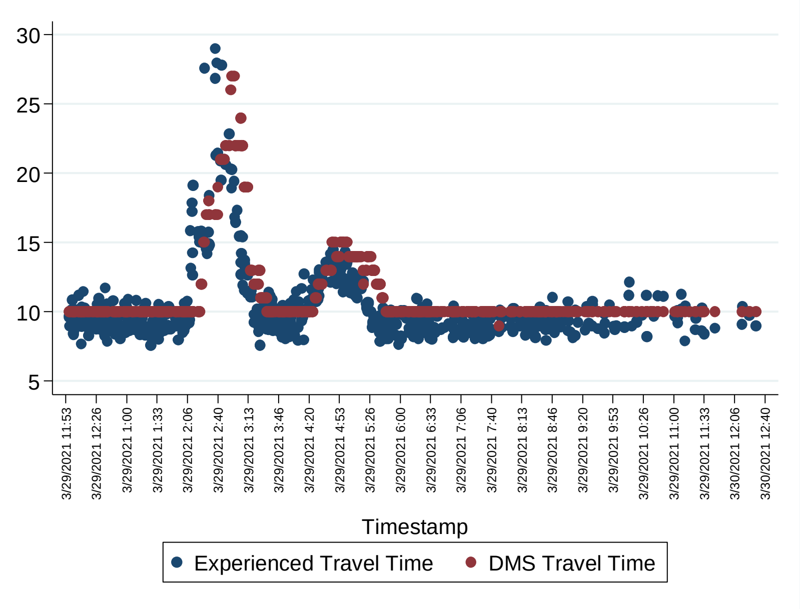


Figure 5.10. Comparison of DMS and Bluetooth sensor travel time for Phase 1

5.2.1.5 Analysis results

To assess the accuracy of the displayed time on the Digital Message Sign (DMS), two analyses were performed. To understand the distribution of errors in travel time experienced by motorists driving at different speeds, we plotted the distributions of errors for the three speed categories (within speed limit, above speed limit, and all speeds). The error was calculated by subtracting the travel time measured in the field (using Bluetooth sensors) from the time displayed on the DMS when the motorist passed it. As Figure 5.11 shows, all three distributions overlap, indicating that the errors are distributed similarly. However, the distribution for errors experienced by motorists driving above the speed limit is skewed to the right, suggesting that, compared to the displayed travel time, these motorists experience relatively less travel time compared to those driving within the speed limit.

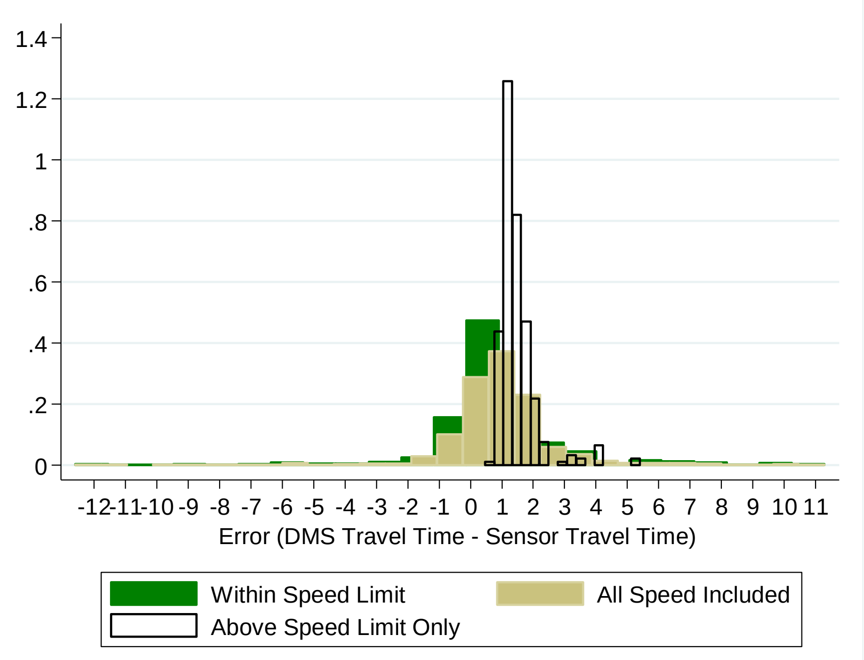


Figure 5.11. Comparing travel time error distributions by motorists' speed category

Furthermore, the Mean Absolute Percentage Error (MAPE), calculated using DMS displayed travel time as the base, were determined. As stated above, three categories of travel times were assessed, namely motorists driving within the speed limit, those driving above the speed limit, and all motorists combined. This was done in order to examine the average travel time error experienced by motorists driving at different speeds since MDOT excludes vehicles traveling above the speed limit when calculating the travel time to display on DMS. Table 5.7 presents the MAPE estimates for the three speed categories. Overall, the error experienced by all motorists, regardless of their driving speed status, is reasonable. However, as expected, those driving above the speed limit are more likely to experience relatively shorter travel time. This could explain some feedback received from participants of the survey (Chapter 4) stating that it takes shorter time to travel the distance compared to what the DMS is saying. It should be noted that research has shown that an error rate of up to 20% in estimated travel times is reasonable as it can still provide useful information to motorists (Toppen, et al., 2004).

Table 5.7. Estimated travel time errors

Category	Observations	MAPE	Std. Dev.
All speeds	865	12.29%	10.9%
Above the speed limit	315	14.66%	5.0%
Within the speed limit	550	10.94%	13.0%

5.2.1.6 Conclusion

The findings indicated that the displayed DMS travel time was reasonably accurate, similar to findings from other previous studies (Monsere et al., 2006; Haghani et al., 2013). Even though the data utilized proved to have travel time variations, observed travel time and DMS travel time were very similar. These findings are in line with a study done by Haghani et al. (2013) were they found the difference between actual travel time and DMS travel time was less than a minute with standard deviation of less than two minutes when outliers were removed.

5.2.2 Analysis of statewide travel time variations

When there’s no special event, it is recommended that the travel time information be the default message (Dudek, 2004). This provides the effective use of the DMS given the vast investment cost incurred in its installation. However, some research has shown that travel time messaging is most effective in roadways with some level of traffic congestion or varying traffic. In corridors where traffic is not dynamic, same travel time message would be posted for a long time and could cause the DMS to be viewed as a static sign which would affect its reliability (Meehan, 2005). Since travel time variation affects its reliability, it should be considered by transportation agencies when deciding whether and where to display travel times on DMS. This case analysis aimed at assessing the factors associated with DMS travel time variations to determine locations and time periods in which display of travel time would be more beneficial to the motorists. The analyses covered variations by time of the day, day of the week, season, traffic volume, MDOT regions, as well as geographical area (urban versus rural).

5.2.2.1 Data used

The data used in this case study included DMS messages and traffic data (AADT). After preprocessing the DMS messages files from MDOT as explained in Chapter 3, the travel time to a particular destination was extracted from the messages. Only DMSs that had displayed travel time were combined to create a data set that has the timestamp, travel time in minutes for a particular DMS and distance to specific destination. This dataset was merged with the excel file provided by MDOT containing DMS names with respective latitudes and longitudes to enable viewing these DMS spatially in Arc GIS. Only 175 DMSs (with 204 origin-destination pairs) were used in the analysis.

The 2019 AADT shapefile was obtained from MDOT GIS open data. This file was spatially joined with the DMS shapefile. For each DMS, the associated AADT on the adjacent roadway was identified. This was done to check the association between the travel time variation and traffic volume.

Similarly, urban boundaries shapefile was obtained from MDOT GIS open data source and was spatially joined with the DMS shapefile. This was done to determine the location where the DMS are located (rural or urban areas). The majority of the DMS are in urban areas compared to rural areas as shown in Figure 5.12.

5.2.2.2 Analysis of travel time variations

The coefficient of variation (CV), which is the ratio of the mean to the standard deviation, was used to determine how the travel time displayed on the DMS varied throughout the year (2019). For each DMS, the average travel time per mile was determined. This was done to standardize the CV values and enable the comparison of one DMS to another since the origin-destination pairs have different distances. The CV was calculated as the standard deviation per mile divided by average travel time per mile. Higher values of CV indicate higher travel time variation for that DMS. The CV values were compared for the 204 origin to destination observations across multiple factors that can cause travel time variation. Different factors which are likely to be associated with travel time variations, including traffic volume, urban/rural area, MDOT region, season as well as the time of the day/day of the week, were considered as documented below.

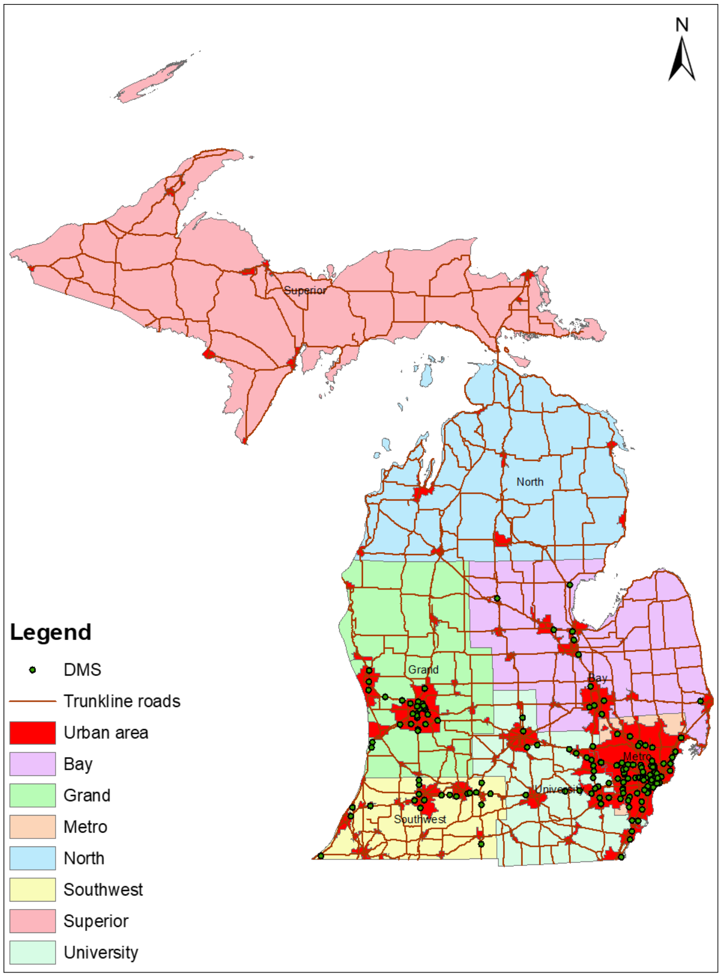


Figure 5.12. Spatial distribution of DMS by location

a) *Travel time variations by MDOT regions*

The Analysis of Variance (ANOVA) was used to investigate the association of travel time variations and MDOT regions. The 2019 data showed that the travel time messages were displayed on DMSs in Bay, Grand, Metro, Southwest, and University regions but not in

North and Superior regions. The null hypotheses for the ANOVA test was that all regions had the same average travel time coefficient of variation. Table 5.8 shows the summary of the ANOVA analysis, which suggests rejecting the null hypothesis, concluding that there are statistically significant (p=0.000) differences in travel time variations between regions. As expected, the Metro region was observed to have high variations (Mean=0.301) followed by Grand region (Mean=0.269). On the other hand, Bay had the lowest variations (Mean=0.144).

Table 5.8. ANOVA results comparing travel time variations in different MDOT regions

Region	**Mean Coefficient of Variation**	**Standard Deviation**	**Frequency**
Bay	0.144	0.0709	10
Grand	0.269	0.1356	37
Metro	0.301	0.0974	103
Southwest	0.147	0.0459	21
University	0.257	0.1105	33

Analysis of Variance	**Value**
Number of observations	204
F statistic	13.57
p-value	0.0000

These findings suggest that displaying travel time messages should consider different characteristics of regions/ locations. For example, it would be more important to display travel time messages in the freeways in Metro compared to those in Bay region given the differences in variations.

b) Travel time variations by AADT

One of the factors causing travel time variation is the difference in traffic volume. For the road segments where each DMS was located, the associated AADT was identified. The 2019 AADT data from MDOT Open GIS was spatially joined to DMS location. Figure 5.13 shows the relationship between the coefficient of variation and the AADT. As expected, it shows that as the AADT increased, the coefficient of variation also increased. It can be said that roadways with higher AADT have higher travel time variations, as expected.

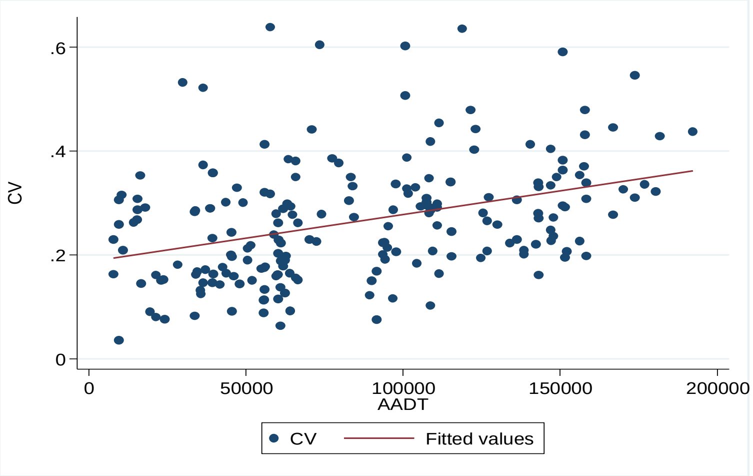


Figure 5.13. Association of travel time variation (CV) and AADT

To identify AADT categories, clustering analysis was used to group the AADT volumes as shown in Table 5.9. The associated mean CV and the confidence interval were also calculated. The group with very high AADT (above 120K) had the highest mean CV (0.319) while the group with the lowest AADT (less than 29K) had the lowest mean CV (0.206). This indicates that higher AADT freeways are associated with high travel time variations. It suggests that displaying travel time on higher AADT freeways is very crucial as travel time varies the most in these freeways. On the other hand, travel time displayed on lower AADT freeways may not be very useful since it does not fluctuate as much.

Table 5.9. Categories of AADT and mean CV values

Category	**Observations**	**AADT**	**Mean CV**	**95% Confidence Interval**	
Very low	21	<29K	0.206	0.164	0.247
Low	35	29K- 52K	0.230	0.193	0.267
Moderate	54	52K-84K	0.245	0.212	0.277
High	51	84K-120K	0.287	0.254	0.319
Very high	43	>120K	0.319	0.289	0.349

c) *Travel time variations by area (urban/rural)*

Another important variable considered in this analysis was the travel time variation by area (urban or rural). Travel time is expected to vary more in urban areas compared to rural areas due to the associated traffic patterns. To visualize the association of area (urban vs rural) and travel time variation, the coefficient of variation was plotted against AADT for both urban and rural areas. Figure 5.14 shows that the impact of AADT on travel time variation has similar trends in both urban and rural areas. Moreover, the coefficients of variation appear to be higher in urban areas than rural areas, as hypothesized. To statistically confirm these differences, the t-test analysis was used to check the differences in CV means between urban and rural areas. Table 5.10 shows the summary of t-test results, which confirms a statistically significant difference in travel time variations between urban and rural areas. This suggests that it is more important to display travel time in urban areas than rural areas. These findings are in line with those by Wisconsin DOT where they observed that travel time doesn’t vary frequently in rural areas (FHWA, 2020).

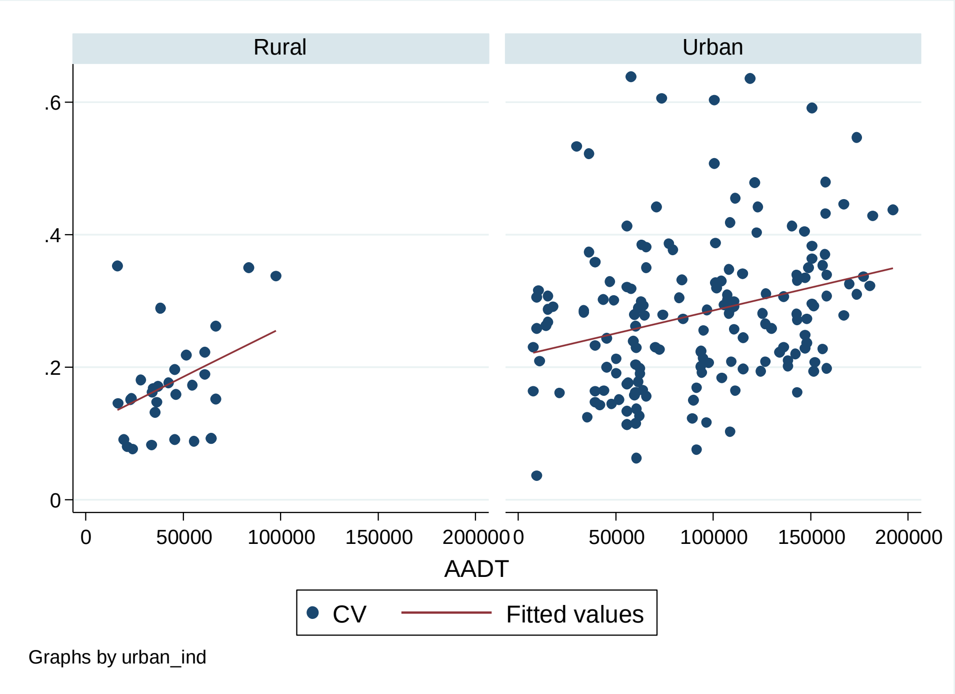


Figure 5.14. Impact of AADT in Urban/rural

Table 5.10. T-test results for urban/ rural area

Group	**Observations**	**Mean**	**Standard Error**	**P-value**
Rural	31	0.18	0.014	0.0000
Urban	173	0.28	0.009	
t-statistic	-4.876			
difference		-0.10	0.021	

d) Travel time variations by season

One of the factors which can impact travel time to a particular destination is weather condition. To assess the association between seasons and travel time variations, two months of winter and summer were analyzed. The winter months were January and February while the summer months were July and August. The travel time per mile was calculated from travel time displayed on the DMS during each season divided by the distance to destination.

First, the research team checked the difference between average travel time by season, at both statewide and MDOT region levels using the Wilcoxon signed-rank test. The Wilcoxon signed-rank test is a non-parametric test which compares two paired datasets. The null hypothesis is that the median of differences between the paired data is zero (King & Eckersley, 2019). The test results in Table 5.11 indicates that the average travel time during winter is significantly higher than in summer, as expected.

Table 5.11. Comparison of average travel time between summer and winter

Region	**Observations**	**Z-statistic**	**p-value**
Bay	9	-2.073	0.0382
Grand	24	-3.143	0.0017
Metro	65	-4.303	0.0000
Southwest	20	-3.449	0.0006
University	29	-3.920	0.0001
Overall	**147**	**-7.820**	**0.0000**

Second, the travel time variations by season were compared at statewide and MDOT region levels. Table 5.12 shows a summary of the Wilcoxon signed-rank test for the coefficient of variation for summer and winter statewide and across the MDOT regions. Statewide, the results show a statistically weaker evidence (p = 0.0798) of difference in travel time variation. However, the University region showed a statistically significant difference in travel time variations between summer and winter. Specifically, the results show that travel time varies more in summer than in winter. On the other hand, results show that travel time variations in the Southwest region were higher during winter than summer. This can be explained by the fact that the Southwest region usually experience lake effect winter weather which may impact travel times significantly.

Table 5.12. Wilcoxon signed-rank test on CV between summer and winter

Region	**Observations**	**Z-statistic**	**p-value**
Bay	9	1.244	0.214
Grand	24	0.514	0.607
Metro	65	1.297	0.195
Southwest	20	-1.941	0.0522
University	29	2.606	0.0092
Statewide	147	1.752	0.0798

Overall, the analysis of travel time variations by season shows that season does not affect travel time variations significantly. However, displaying travel times in summer in University region could be more important.

e) Travel time variation by day of the week and time of the day

Traffic, and consequently travel time, varies by time of the day. As such, the analysis of daytime and nighttime variations was done to capture their association with the time of the day. Moreover, the association of travel time variations with day of the week (i.e., weekdays and weekends) was performed. The daytime was considered from 8:00 am to 5:00 pm while the nighttime was from 10:00 pm to 4:00 am. Saturday and Sunday were considered as weekend while the rest of the days were considered weekdays. The

Wilcoxon signed-rank test was again used to compare the coefficient of variation of daytime and nighttime. Similarly, this test was used to compare the coefficient of variation of weekday and weekend. The results in Table 5.13 show that more travel time variations were observed on weekdays than weekends and during daytime than nighttime.

Table 5.13. Wilcoxon signed-rank test for time of the day/day of the week

	Day vs. Night	Weekday vs. Weekend
Observations	198	200
Z-statistic	11.874	9.871
p-value	0.0000	0.0000

A study conducted by Yin et al., (2011) suggested displaying travel time in durations when the motorists are unable to easily predict the travel time, which are times with higher variations. Some state DOTs have adopted guidelines encouraging posting travel times on DMS at specific times, especially when variations are high, as shown in Table 5.14 (Center for Advanced Transportation Technology, 2012):

Table 5.14. Sample guidelines on when to display travel time on the DMS

State	Time to display travel times on DMS
Rhode Island	6 am - 7 pm
Maryland	5 am – 9 pm
North Carolina	6 am – 9 am and 4 pm – 7 pm
Georgia	5 am – 10 pm

5.2.2.3 Conclusion

This analysis identified potential areas and time periods in which display of travel time message would be more useful to the motorists. This was done by associating multiple factors which cause travel time variations to a particular destination with the displayed DMS travel time. Findings suggest that the strategies and procedures undertaken to display travel time should consider both location and time of the day. Freeways with high AADT should be given more priority in displaying travel time messages. Also, urban areas experience higher travel time variations, hence travel time display is crucial in those locations. The results also suggest that displaying travel times during peak hours, especially on daytime compared to nighttime, should be given priority.

5.3 Impact of DMS messages on traffic diversion

One of the information displayed on the digital message sign is the travel time information. The information helps drivers to select roadways that will potentially minimize their total journey time. There are two ways that multiple travel time information is displayed on the DMS. The first case is the travel time information to two or more destinations along the same route. The other case is the travel times to a single destination using multiple routes. The latter case forms the basis of this study and it was used to assess drivers' route choice behavior based on the travel time displayed on the DMS. The main objective of this case study, therefore, was to investigate whether the travel time differences between the two routes as displayed on DMS influence the drivers’ route choice to a specific destination.

5.3.1 Selection of study sites

The criteria used for site selection include but are not limited to the number of ramps between the origin and destination, and route length. Also, the destination point where the two routes merge again have to be well defined. This was an important criterion as it enabled the research team to correctly place the sensors at the origin and destination points. The 2019 historical DMS messages were used to identify DMS locations that met the criteria. There were several candidates in the Grand Region, Metro Region, and Bay Region as shown in Table 5.15. Sites no. 5, 6 and 7 displayed the travel time information to downtown but were excluded from the selection process as their destination were not a point along the route. Site no.1 and no.2 displayed travel times information to a specific junction using two alternative routes. After a thorough review of the sites, they were deemed unsuitable for the field study as they had multiple major interchanges between the origin and destination. The final decision was to use site no.3 (S-I75S-MM1562-Crane) and site no.4 (S-I75N-MM1472-Hess) which were located in Bay Region.

Figure 5.15 shows the layout of the site that was selected for field data collection. The site had DMS for both southbound and northbound directions. DMS named S-I75S-MM1562-Crane displayed travel time to M-46 using either I-75 Southbound or I-675 Southbound. A typical message that was displayed on the DMS read as follows “**TIME TO M-46, VIA I-75 6 MIN, VIA I-675 8 MIN**”. The DMS for the northbound traffic named S-I75N-MM1472-Hess displayed travel time to US-10 via either I-75 NB or I-675 NB. The typical message that was displayed on S-I75N-MM1472-Hess read as follows: message “**TIME TO US-10 VIA, I-75 15 MI 13 MIN, I-675 17 MI 15 MIN”.**

Table 5.15. DMS that displayed route option information

No.	NAME	REGION	TYPICAL ROUTE OPTION MESSAGE
1	S-I75N-MM1092-Dort	Bay	TIME TO JCT N I-475 VIA I-75 16 MIN VIA I-475 17 MIN
2	S-I75S-MM1271-Frances	Bay	TIME TO JCT S I-475 VIA I-75 14 MIN VIA I-475 16 MIN
3	S-I75S-MM1562-Crane	Bay	TIME TO M-46 VIA I-75 9 MIN VIA I-675 8 MIN
4	S-I75N-MM1472-Hess	Bay	TIME TO US-10 VIA I-75 15 MI 14 MIN I-675 17 MI 17 MIN
5	S-I196E-MM0618-32nd Ave	Grand	TIME TO DOWNTOWN VIA I-196 14 MIN VIA M-6/US-131 18 MIN
6	S-I96W-MM0481-Quiggle	Grand	TIME TO DOWNTOWN VIA I-96/I-196 14 MIN VIA M-6/US-131 20 MIN
7	S-M5S-MM0033-13 Mile	Metro	TIME TO DOWNTOWN 30 M VIA I96/M10 3 42 MIN VIA I696/M10 2 39 MIN

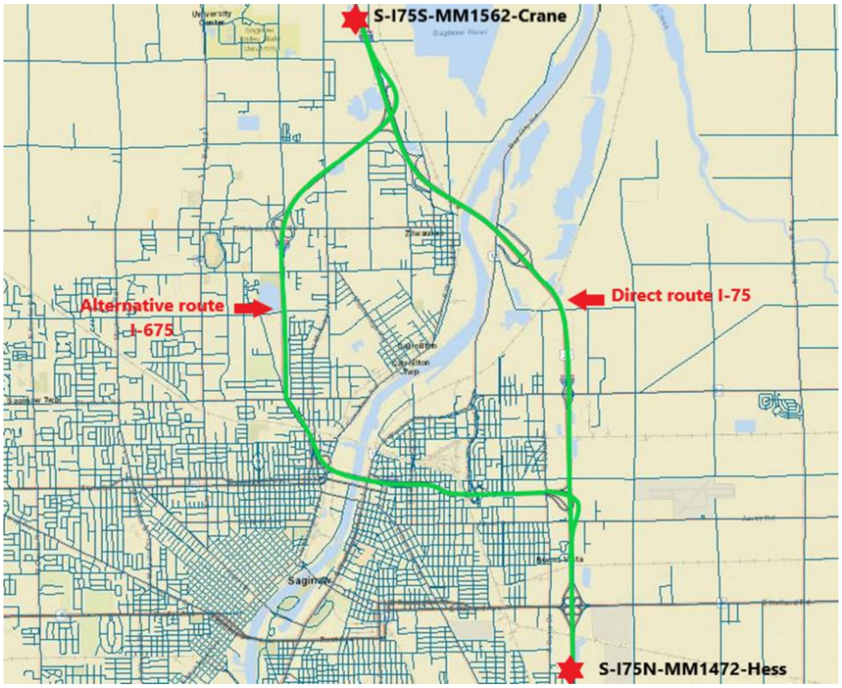


Figure 5.15. Details of the selected site at Saginaw, MI

5.3.2 Study setup

The Bluetooth sensors were mounted at four different locations as shown in Figure 5.16 and Figure 5.17. Sensor W3 was mounted at the DMS which displayed the travel time information for I-75 and I-675 southbound traffic. Sensor W2 was mounted after DMS which display the travel time information for the northbound traffic. Two sensors were placed at the midpoint of each route namely sensor W1 at I-75 and sensor W4 at I-675 (the alternative route). A vehicle was considered to have taken the I-675 southbound or I-675 northbound if it was detected at sensors W3, W4, and W2. Similarly, the vehicle was considered to have taken I-75 southbound or I-75 northbound if it was detected at points W3, W1, and W2.

The video cameras were installed at the same locations that the sensors were installed. The video camera data were later used for visual inspection of traffic conditions such as traffic congestion at the vicinity of DMS (site W3 & site W2) and the midpoint locations of each route. For site W2, the video records were obtained from the MDOT

CCTV camera which was available near to the site. Further, the video cameras were used for counting traffic for the duration of data collection.

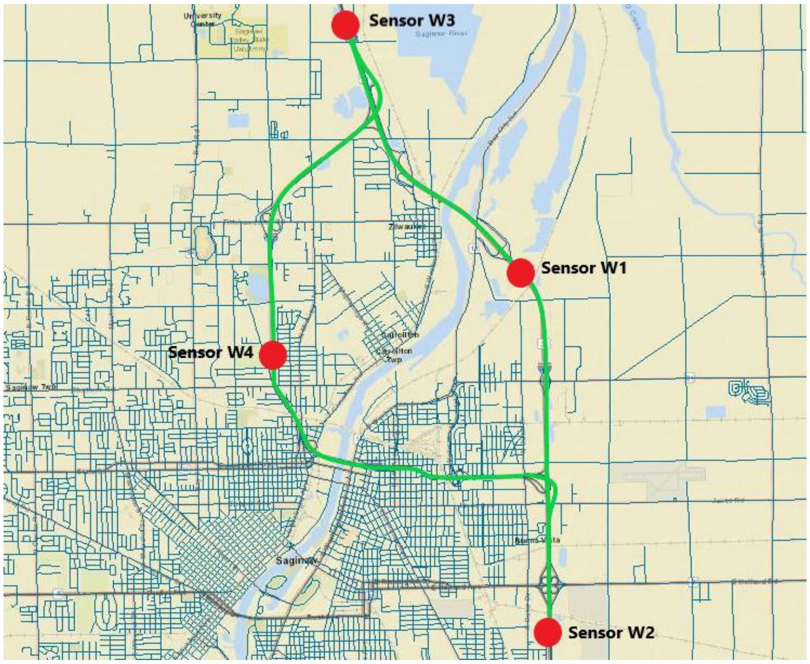


Figure 5.16. Bluetooth sensor mounting locations

Site W3 **Site W1** **Site W2**

Figure 5.17. Examples of sensor mounting mechanisms

Table 5.16 provides a schedule that was used for collecting DMS operational data, sensor data, and video recordings. The data collection period was three weeks. In the first week, the DMS travel time information was displayed (DMS ON) followed by the second week whereby the travel time was not displayed on the DMS (DMS OFF). For the case “DMS OFF” mode, the travel time data information was recorded internally but the information was not displayed on the DMS. The data was later retrieved and was made available to the research team. The display of travel time to the drivers resumed in the third week onwards.

Table 5.16. Schedule for field data collection

Week	Number	DMS Operation
Week 1	Wednesday, Oct 21, 2020 - Tuesday, Oct 27, 2020	DMS ON
Week 2	Wednesday, Oct 28, 2020 - Tuesday, Nov 3, 2020	DMS OFF
Week 3	Wednesday, Nov 4, 2020 – Tuesday, Nov 10, 2020	DMS ON
Week 4	Wednesday, Nov 11, 2020 – Sunday Nov 15, 2020	DMS ON

5.3.3 Data used

This section summarizes the data that was collected at the field which assisted in the evaluation of the driver’s response to the DMS travel time message between the alternative routes. The main data that were collected include travel time information and traffic volume.

5.3.3.1 Traffic volume

The traffic volume information was an important data item that was used in the evaluation of drivers’ response to DMS messages. The volume data was collected at the S-I75S-MM1562-Crane DMS using the existing continuous count station (CCS) managed and owned by MDOT. Also, manual count from video recorded was used to obtain traffic volume. The data was used to assess the level of congestion (peak and off-peak hour) in the vicinity of the DMS before the drivers decided to continue with the direct route (I-75) or to use the alternative route (I-675). The level of congestion at the DMS was hypothesized to have an impact on the drivers’ route choice behavior and it was, therefore, an important data item during the modeling process as will be discussed in the later section.

5.3.3.2 Number of Bluetooth device-trips for each route

Sample vehicles were tracked using Bluetooth devices detected at each node (W1, W2, W3, and W4). For each node, the fingerprint and timestamp at which the vehicle was detected were recorded. Below is the example of node data that were recorded for each node. The subsequent task involved connecting node data so as to be able to track vehicles at each route. Figure 5.18 shows the number of device trips that were detected at each route. The device trips were detected more in the I-75 route (98.8%) compared to I-675 (1.2%). I-75 was considered as the direct route but in some circumstances such as congestion in I-75 drivers would prefer the alternative route, I-675. It was the intention of this study to explore how the time differences between the two routes as displayed on the DMS affect drivers' route choice behavior. It should be noted that in Figure 5.18, the southbound traffic had more detection rate compared to the northbound traffic because the Bluetooth detectors were installed closer to southbound traffic. Figure 5.19 and Figure 5.20 show the daily distribution of device trips for the whole period of data collection for the southbound and northbound, respectively. More vehicles/devices were detected during the weekend compared to the weekday period.

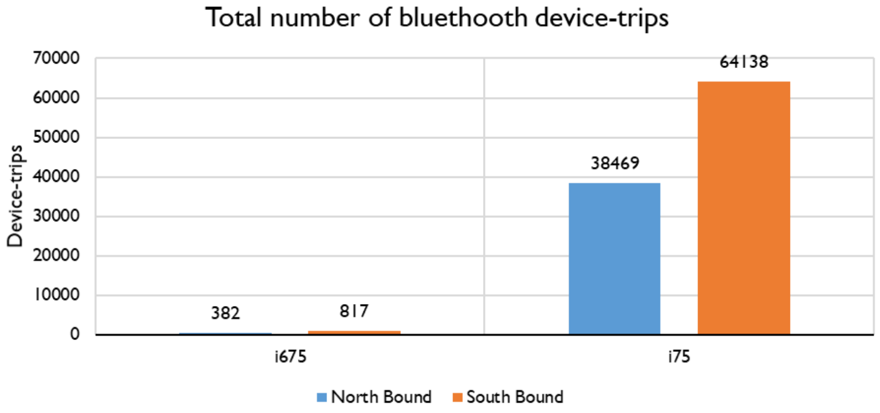


Figure 5.18. Total number of device trips for the southbound and northbound traffic

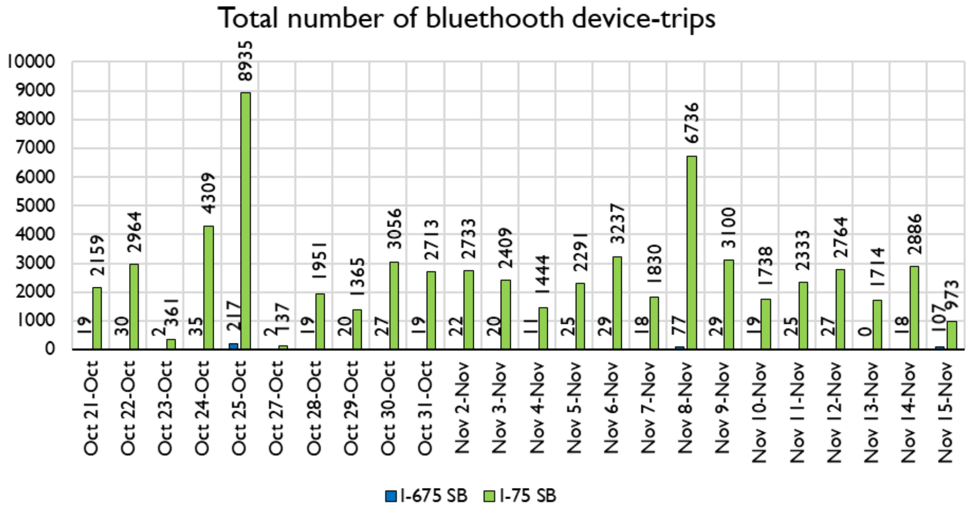


Figure 5.19. Number of daily device trips for the southbound traffic

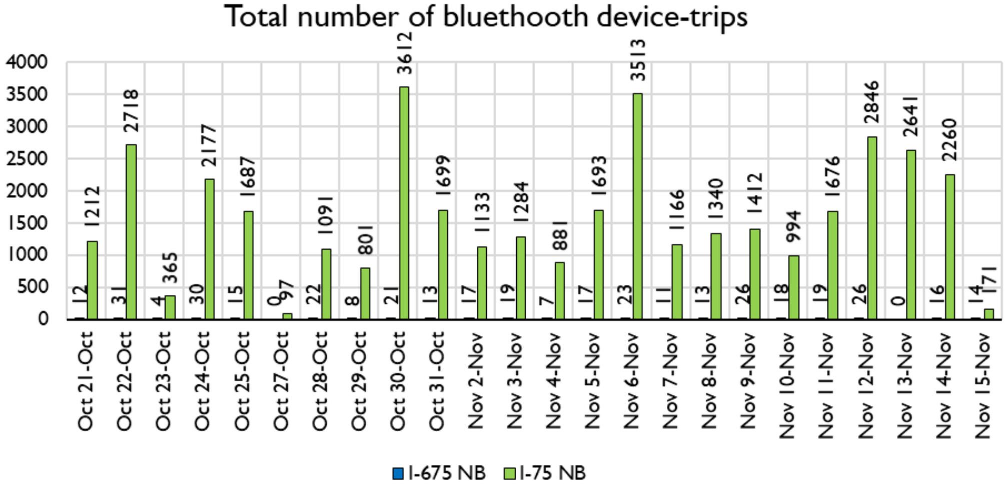


Figure 5.20. Number of device trips for the northbound traffic

5.3.3.3 DMS data

The DMS message logs were made available to the team after the completion of the field study. The logs contain the timestamp and message that was displayed at the DMS. The new timestamp was generated each time the message changed otherwise the message was continuously on the DMS until the next timestamp. For this study, the main component of the DMS message which triggers the change was the travel time as it was updated in real-time. A script was created to automatically extract the travel time information from the DMS messages for the two routes namely I-675 and I-75.

Analysis of the trends of travel time for the southbound and northbound traffic between the two routes indicated no significant variation. The direct route (I-75) had less travel time compared to the alternative route (I-675) almost always. However, in October 23, 2020, an incident occurred on I-75 northbound which caused the closure of two right lanes and variation in travel times (Figure 5.21). The I-75 NB has three lanes and therefore the incident caused the freeway to operate at one-third of its capacity. The message was first displayed on the S-I75N-MM1472-Hess DMS at 1733 hours which stated, "**RIGHT 2 LANES BLOCKED, AFTER M-81 EXIT 151, EXPECT DELAYS**". The last log of the message was at 1855 hours which indicated that the incident lasted for 1 hour and 22 minutes. Figure 5.22 shows the dynamics of travel time for the alternative routes during the incident duration. The travel time on I-75NB was faster than the alternative route, 1-675, before the incident. During the incident duration, the travel time for both routes increased because of the congestion created by the incident. However, the travel time increased at a much higher rate on the I-75 NB where there was an incident compared to the alternative routes, I-675 NB. The increase in travel time can be explained by a massive shift of vehicles from the affected route to the alternative route to avoid congestions.

The drivers' route choice behavior between the two routes due to incident or any other alike causes which triggered the changes in travel times was the main point of interest in this study. The statistical modeling procedure was used and results are presented in the subsequent section to understand the association between individual driver's route choice behavior in response to the travel time differences between the main route and the alternative route. Such analysis was possible because the sensors were effective in tracking the movement of each driver in both routes.

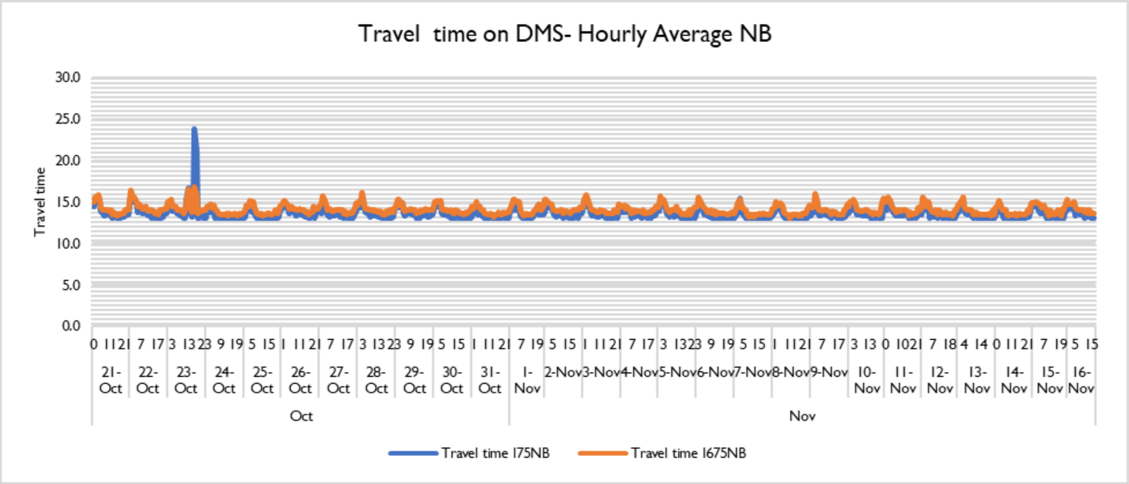


Figure 5.21. Average hourly travel time at I-75 NB and I-675 NB

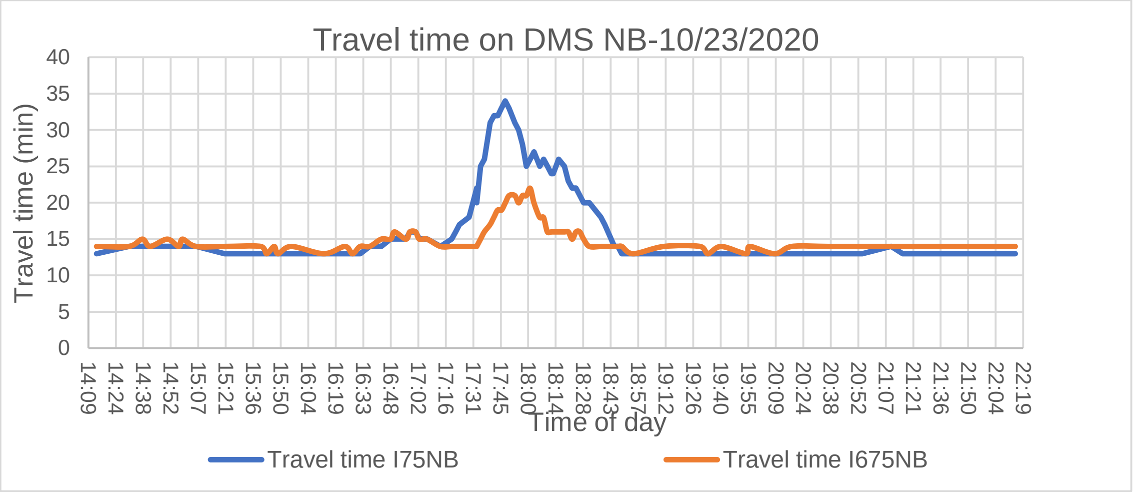


Figure 5.22. Travel time at I-75 NB and I-675 NB on Oct 23, 2020

5.3.4 Modeling of driver's route choice behavior

The aim of this case study to examine the impact of the travel time difference between the main and the alternative routes on driver's route choice behavior. Individual vehicles detected and tracked using Bluetooth sensors were used in this analysis as it was important to ensure the vehicle completed the trip (that is, did not exit the route in between). For this analysis, southbound detections were used because the sample size was larger in this direction than in northbound. This allowed for the analysis to be performed using vehicle detections throughout the study period. As it was explained in the experimental setup, two DMS operation modes were used during the field study namely “DMS ON” and DMS OFF”. The first setup was when the travel time information was displayed to the drivers on DMS. The second setup was when the travel time information was not displayed on the DMS but only recorded internally by MDOT. The second setup was used as a control scenario to determine the driver's route choice behavior when no prior information about travel time is available to them through DMS.

The logistic regression was used to investigate the route choice behavior. The model is appropriate for the cases where the dependent variable is dichotomous (Davis & Offord, 2013). For this study, a binary variable was created distinguishing drivers who chose the alternative route, I-675, from those who chose the direct route, I-75. The logistic model can be specified in the form of the generalized linear model with a link function g(.). The general linear model can be specified as (Kutner, Nachtsheim, Neter, & Li, 2002):

$$\mathrm{E}(\mathrm{y_i}) = \mathrm{g}(\beta_0 + \beta_1 \mathrm{x_i}) \qquad 5.3$$

The logistic regression model uses the logit function g(t) as:

$$\mathrm{g}(\mathrm{t}) = \frac{\mathrm{e^t}}{1 + \mathrm{e^t}} \qquad 5.4$$

The probability of success (i.e., taking the alternative route, I-675) given the vector of independent variables can be computed as:

$$\mathrm{P}|\mathrm{y_i} = \mathrm{App\ usage}|\mathrm{x_i} = \frac{\mathrm{e}^{\beta_0 + \beta_1 \mathrm{x_i}}}{1 + \mathrm{e}^{\beta_0 + \beta_1 \mathrm{x_i}}} \qquad 5.5$$

The estimation of parameters β_0 and β_1 which are the intercept value and vector of regression coefficients respectively can be estimated using the maximum likelihood method. It is often desirable to express the logistic regression results as odd ratios to facilitate the interpretability of the results. The odds ratios calculated as shown below provide the odd of success given an incremental change (Δ) of the response variable.

$$\mathrm{OR}(\Delta) = \frac{\mathrm{Odds}(\mathrm{sucess}|\mathrm{x} + \Delta)}{\mathrm{Odds}(\mathrm{sucess}|\mathrm{x})} = \frac{\mathrm{e}^{\beta_0+\beta_1(\mathrm{x}+\Delta)}}{\mathrm{e}^{\beta_0+\beta_1\mathrm{x}}} = \mathrm{e}^{\beta_1\Delta} \qquad 5.6$$

The model was calibrated separately for “DMS ON” and “DMS OFF” mode. As for the dependent variables, the main effect that was investigated is the travel time difference between the main route (I-75) and the alternative route (I-675) denoted in the model as *“DMSTime @ I-75 – DMSTime @ I-675”*. All the variables that were used for model calibration for “DMS ON” and “DMS OFF” operations are provided in Table 5.17. The two models for “DMS ON” and “DMS OFF” modes utilized the same variables to allow an unbiased comparison of the results between the two models.

Table 5.17. Descriptive summary of the variables used in the model

DMS Operation	**Variable**	**Obs**	**Mean**	**Std. Dev.**	**Min**	**Max**
DMS ON	Take I675(Alternative route)	24,341	0.036	0.186	0	1
	DMSTime @ I-75 – DMSTime @ I-675	24,341	-1.294	0.458	-3	0
	Driver’s frequency on the route	24,341	1.298	2.737	1	84
	Drivers exiting and rejoining the route	24,341	0.074	0.262	0	1
	Peak AM hours (0700-0900hrs)	24,341	0.088	0.284	0	1
	Peak PM hours (1400-1600hrs)	24,341	0.285	0.451	0	1
	Hourly traffic volume (per 100 vehicles)	24,341	23.819	11.224	1.04	49.37
DMS OFF	Take I675(Alternative route)	9,705	0.022	0.147	0	1
	DMSTime @ I-75 – DMSTime @ I-675	9,705	-1.370	0.485	-3	0
	Driver’s frequency on the route	9,705	1.620	4.140	1	84
	Drivers exiting and rejoining the route	9,705	0.136	0.343	0	1
	Peak AM hours (0700-0900hrs)	9,705	0.140	0.347	0	1
	Peak PM hours (1400-1600hrs)	9,705	0.265	0.441	0	1
	Hourly traffic volume (per 100 vehicles)	9,705	15.248	3.780	0.79	21.09

Table 5.18 provides a summary of the results for the two cases. The odds ratio of a given driver taking the alternative routes (I-675) increased by 35% when the alternative route was faster than the main route (I-75) by one minute, as displayed on DMS. Compared to when the travel time was not displayed on DMS but recorded internally (i.e., DMS OFF), the odds of taking alternative route was insignificant. This indicated that in the absence of travel time information, driver’s decision to take either route was a random choice that had no association with the travel time difference between the two routes. On the other hand, the odds of taking the alternative route were significant and positively associated with travel time only when it was displayed to the drivers.

Other variables accounted for in the model included the driver’s frequency of using routes, driver exiting and rejoining the route, peak AM hours, peak PM hours, and hourly traffic volume. The drivers’ frequency of using the routes was a proxy of drivers’ familiarity with the routes. The driver’s frequency of using the routes was derived from the sensor data. Using the sensor data, it was possible to count the number of device trips for each driver for the study duration because each driver had a unique and unchanged fingerprint/mac address. From the model results, a driver who was familiar with the two routes preferred to stick with the direct route (I-75) even when the DMS travel time indicated that they could save some time if they opted to use the alternative route. The association of driver familiarity and the choice of the alternative route was similar for both DMS ON and DMS OFF modes.

The model calibration also accounted for the drivers who chose the specific route not because of the travel time but simply because they wanted to access certain areas along that routes. These drivers later rejoined the route to continue with their journeys. They were identified as outliers from the sensors’ data using the travel time information. The outliers were the values above the upper quartile of the interquartile range. It should be noted that I-675 provides access to Saginaw downtown that has a mixture of land uses such as retail stores and malls and therefore was expected to have more drivers who intended to access abutting land. This assumption was proved by the model whereby drivers who exited and rejoined the route were found mostly to take the alternative route. For this group of drivers, their decisions were the same regardless of whether travel time was displayed on DMS or not. Their odds of taking the alternative routes increased both when the DMS was ON and when the DMS was OFF.

Table 5.18. Model results from logistic regression

Take an alternative route (I-675)	Message displayed on DMS				Message NOT displayed on DMS			
	Coef.	OR	Std. Err.	P>z	Coef.	OR	Std. Err.	P>z
DMSTime @ I-75 – DMSTime @ I-675	0.300	1.350	0.130	0.002	-0.166	0.847	0.128	0.271
Driver’s frequency on the route (Driver's familiarity with the routes) AND DMSTime @ I-75 – DMSTime	-0.027	0.973	0.004	0.000	-0.015	0.985	0.005	0.003
Drivers exiting and rejoining the route	1.436	4.204	0.456	0.000	1.910	6.755	0.968	0.000
Peak AM hours(0700-0900hrs)	0.769	2.159	0.359	0.000	0.390	1.477	0.272	0.034
Peak PM hours(1400-1600hrs)	0.875	2.399	0.194	0.000	0.051	1.052	0.192	0.782
Hourly traffic volume (per 100 vehicles)	0.068	1.070	0.004	0.000	0.065	1.068	0.025	0.005
Constant	-5.472	0.004	0.001	0.000	-5.726	0.003	0.002	0.000

Another important factor accounted for in the model was the traffic condition. Three variables were used to account for traffic conditions: peak AM hours, peak PM hour, and the traffic volume information. Analysis of CCS traffic data which depicted the hourly trend of traffic volume enabled the determination of AM peak and PM peak hours. The peak

AM hour was from 7:00 AM to 9:00 AM while the peak PM hour was from 2:00 PM to 4:00 PM. During peak hours at the direct route (I-75), the drivers were more likely to select the alternative route than during off-peak hours. This was hypothetically expected, especially during the peak hour. Similar results were obtained during the DMS OFF as the congestion was visible to drivers who were approaching the DMS even without looking at the DMS for the travel time information. In both DMS ON and DMS OFF modes, the increase in hourly traffic volume by 100 vehicles in the main route (I-75) increased the odds of taking the alternative route by 7%.

5.3.5 Case study conclusion

DMS travel time information significantly affects the drivers' route choice behavior. This finding provides empirical evidence on the first fundamental question of whether drivers seek and use travel time information displayed on DMS messages. It confirms the stated preference results from the survey data (documented in Chapter 4). In the survey results, drivers stated that they were using the DMS to seek various information, including travel time, and they found the information provided by the DMS to be useful.

This study also determined the empirical value that quantified the influence of DMS travel time information on drivers’ route choice decisions. It was found that the base likelihood of choosing an alternative route increases by 35% when the alternative route is 1 minute faster than the preferred route. This value was obtained after accounting for drivers’ familiarity with the route and traffic volume condition. The empirical value forms a basis for the cost-benefit analysis presented in Chapter 6.

5.4 Work zone management using Portable Changeable Message Sign (PCMS)

Portable Changeable Message Sign (PCMS) can supplement static signs to improve safety and mobility in the work zone areas. The PCMS can be used to inform drivers of the condition ahead and recommend the action to be taken by drivers, for example, switching lanes. The message displayed on the PCMS depend on several factors such as the scenario which is being described, the number of lanes, and traffic speed (FHWA, 2013a). In this case study, the impact of using a PCMS to inform drivers of the lane closure ahead due to construction work was examined. The specific message evaluated was “LEFT LANE CLOSED || 2 MILES AHEAD.”

5.4.1 Study location and experiment setup

This study was done in I-196 southbound in Saugatuck, Grand Region, from April 01st to April 02nd 2021. Figure 5.23 shows the study site, which was in the southbound with a single lane closure and the work zone length of 1 mile.

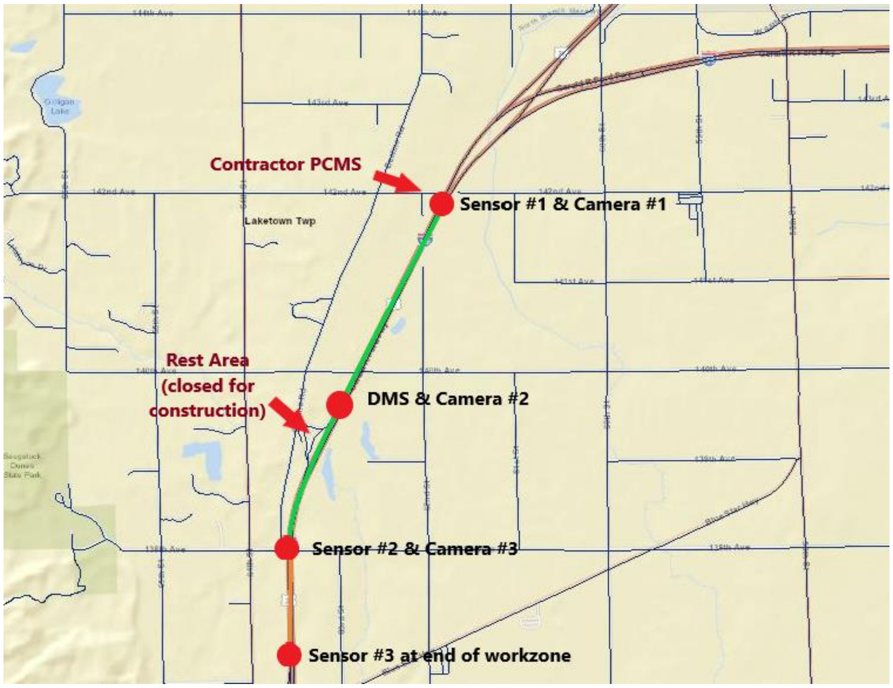


Figure 5.23. Site layout for work zone analysis at I-196 in Saugatuck, MI

Bluetooth sensors and video cameras were installed at different locations on the site by mounting them on temporary wooden poles. (Figure 5.23). The PCMS was located at 1.85 miles from the start of the work zone. To capture the base condition of the traffic flow characteristics, a Bluetooth sensor (sensor #1) and a camera (camera #1) were also mounted at this location on a local pole. A second camera (camera #2) was mounted on the DMS which was at 1.5 miles from the PCMS. This was done to capture the oncoming traffic volume and lane distribution changes of vehicles proceeding from the PCMS before entering the work zone area. Bluetooth sensor #3 and camera #3 were installed at the start of the work zone area (lane taper). Lastly, sensor #4 was installed at the end of the work zone area, 1 mile from the beginning of the work zone taper. The message was displayed for one day and turned off on another day to observe changes in traffic patterns. Table 5.19 shows details of the displayed message.

Table 5.19. The time the message was displayed

TIME	MESSAGE STATUS	MESSAGE @PCMS	MESSAGE @ DMS
3/31/2021 4:00 PM – 04/02/2021 6:00 AM	MESSAGE ON	LEFT LANE CLOSED 2 MILES AHEAD	LEFT LANE CLOSED AHEAD
04/02/2021 6:00 AM– 04/03/2021 6:00 AM	MESSAGE OFF	-------------	--------------

5.4.2 Data used

5.4.2.1 Bluetooth sensor data

The vehicles which used this route and had Bluetooth devices were detected by the Bluetooth sensors installed along the route. Each detection was assigned a fingerprint and timestamp, the same device had a similar fingerprint. The travel time used by the drivers to travel throughout the work zone area was deduced from the difference in time of the timestamps detected by two Bluetooth sensors. The PCMS, located before the work zone area, informed the drivers that the left lane was closed two miles ahead. With the provision of this information, it was expected that the drivers would merge early and this would consequently smoothen traffic flow and save travel time by minimizing potential delay caused by late merging (merging near the work zone).

Vehicles were tracked by matching device detections made by sensor 1 (located at the PCMS), sensor 2 (located at the taper), and sensor 3 (at the end of the work zone). Since the Bluetooth sensors can detect vehicles within a 0.2-mile circumference, the vehicles on northbound were also detected. The observations that had a negative travel time between the three sensors were removed from the data set to exclude the northbound detections. Furthermore, since one device could have multiple detections when passing a certain Bluetooth sensor, observations with similar fingerprints were averaged to obtain a single value.

5.4.2.2 Manual traffic counts and MVDS

Two sources of traffic volumes were used in this case study: traffic volume that was extracted manually from the video cameras and MVDS data. The manual counts were for twelve hours (from 07:00 am to 7:00 pm) at an interval of five minutes at both the PCMS and at the beginning of the work zone. The MVDS volume was from the detector device located near the DMS and was extracted directly from the detector, not from the ATMS. Nevertheless, the accuracy of the MVDS volume was checked by comparing the hourly volumes to a sample of manual counts to ensure its quality was acceptable. The comparison results are summarized in Table 5.20, where the absolute percentage error was also computed. The absolute percentage error was less than 10% for the four hours and hence was within the acceptable range and satisfactory to be used in this analysis.

Table 5.20. Comparison of MVDS volume and manual counts

Date	**Timestamp**	**Manual counts**			**MVDS**			**%Error**
		Outer lane	Inner lane	Total	Outer lane	Inner lane	Total	
04/02/2021	08:15-09:15	1077	189	1266	1130	176	1306	**3.16%**
04/02/2021	09:15-10:15	1150	185	1335	1156	206	1362	**2.02%**
04/02/2021	17:15-18:15	945	237	1182	992	250	1242	**5.08%**
04/02/2021	18:15-19:15	745	187	932	787	202	989	**6.12%**

5.4.3 Analysis results

5.4.3.1 Descriptive analysis

A scatter plot was used to visualize the travel times during the study duration (Figure 5.24). Generally, travel time from PCMS to the end of the work zone (2.85 miles) was less than 3 minutes during off-peak hours on both days. Travel time increased up to 15 minutes during peak hours in both scenarios (PCMS on and off).

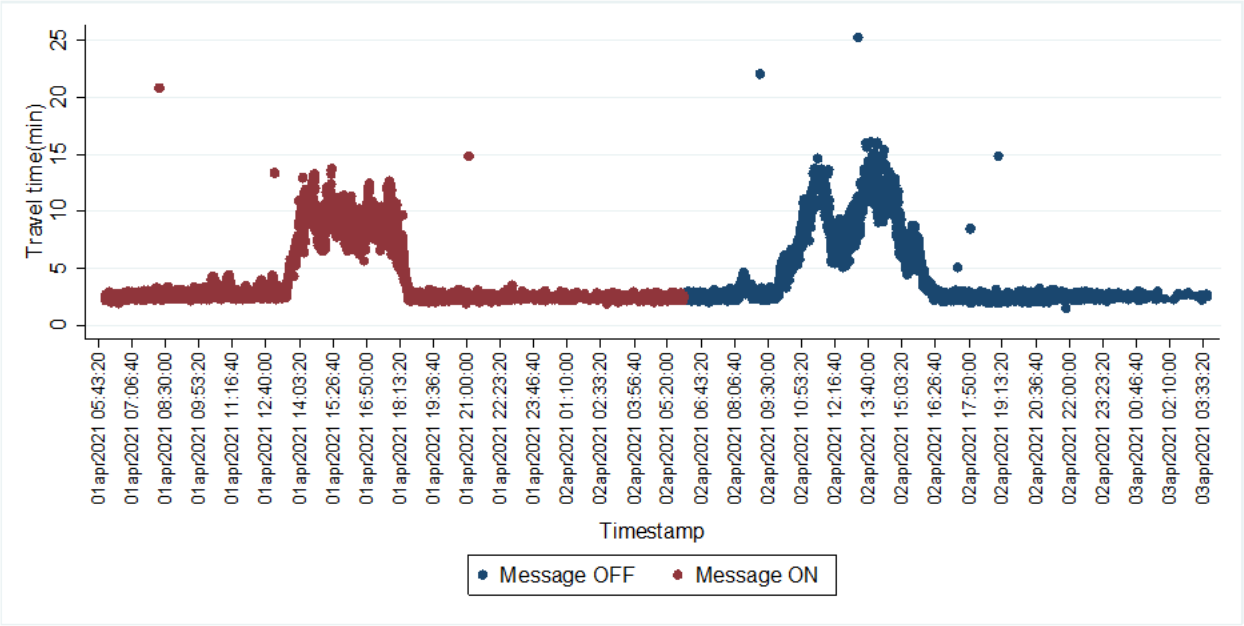


Figure 5.24. Travel time for PCMS “ON” and “OFF” periods

The speed of vehicles along the study section was also plotted as shown in Figure 5.25 and found to range between 50-80 mph, with an average of 70mph. During congestion, the speed dropped to about 15 mph in both scenarios (PCMS ON and OFF). The speed of vehicles from the PCMS to the beginning of the work zone (lane taper) during congestion was lower than those from the lane taper to the work zone end. Vehicles had to enter the work zone with much slower speeds due to congestion near or at the taper and afterward, increased their speeds to proceed out of the work zone.

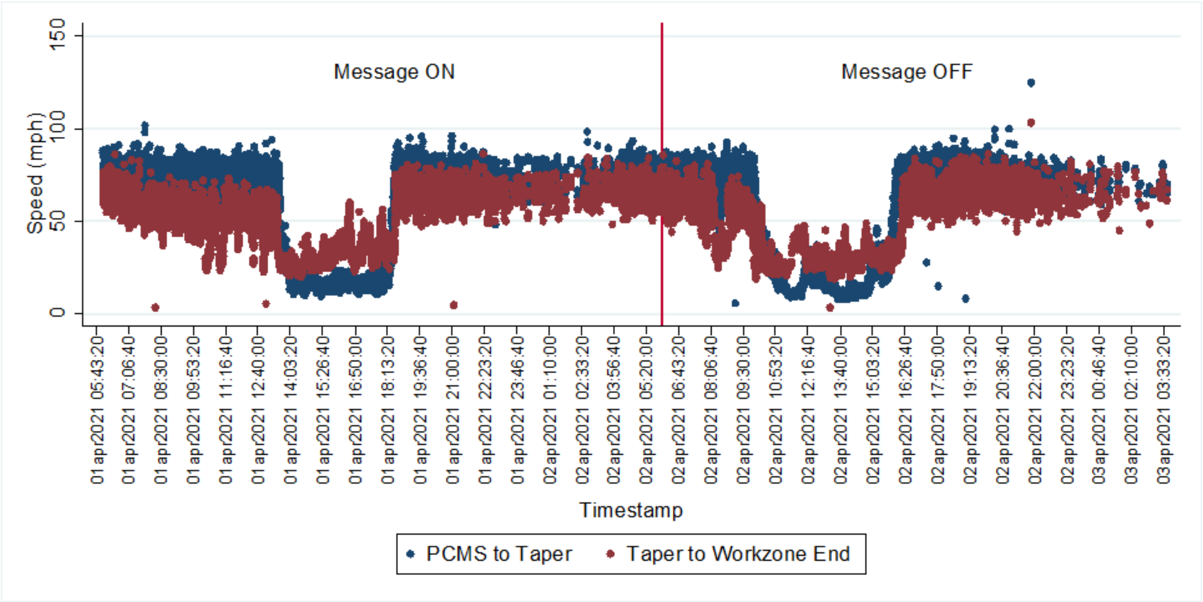


Figure 5.25. Speeds measured for PCMS to taper and taper to work zone end

5.4.3.2 Travel time saving

A generalized linear model was used to determine the time saving associated with the message displayed on the PCMS. Unlike the general linear model (such as linear regression and ANOVA), where the error follows the normal distribution, the error distribution is other than a normal distribution in the generalized linear model. The generalized linear model allows building of a linear relationship between the response variable and the predictors, even though their underlying relationship is not linear. This is done by using a link function that links the response to the linear model. Because of the restriction in the response variable that the travel time has to be positive, the generalized linear model with log link function was used to predict the travel time based on message status and traffic volume. The results for this model are summarized in Table 5.21.

When the Message is ON, 5.54% of the travel time between PCMS and work zone taper was reduced compared to when the message was OFF. The predictive margins of the travel time show that when the message was OFF the mean travel time was 3.19 minutes compared to 3.01 minutes when the PCMS message was ON. The difference of

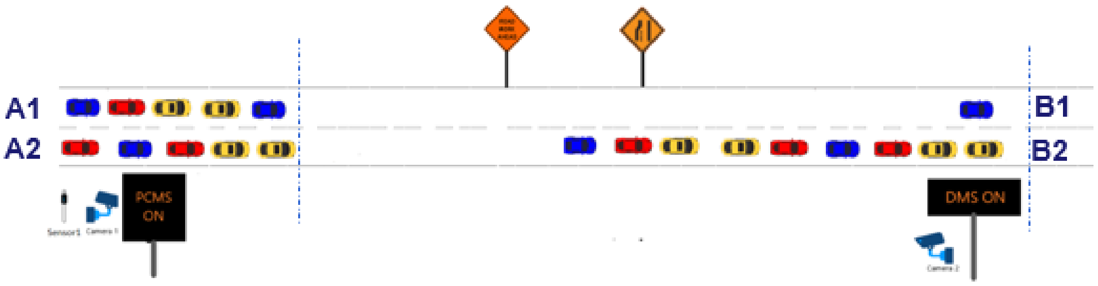
0.18 minutes per vehicle, which was statically significant, indicates the potential time saving per vehicle caused by informing drivers of lane closure ahead using the PCMS.

Table 5.21. Generalized model results of travel time from PCMS to the beginning of work zone

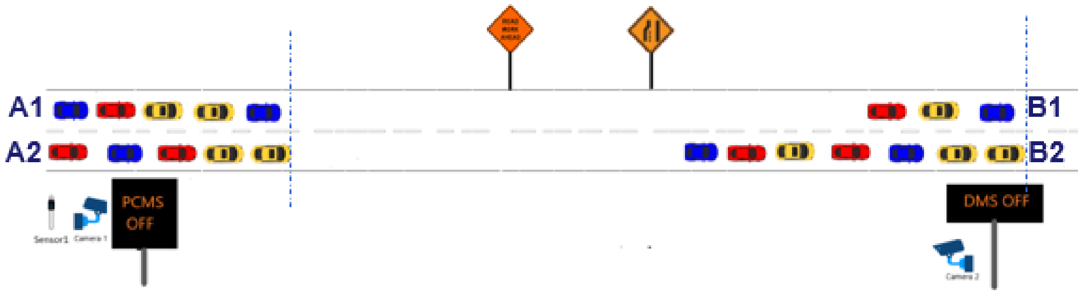
Generalized Linear Model		
Travel time	**exp(b)**	**p-value**
Message on	0.945	0.084
Flow at DMS	1.000	0.000
constant	1.540	0.000
Predictive Margins of Travel Time		
Message ON	3.190	0.000
Message OFF	3.013	0.000

5.4.3.3 Lane changing

It was anticipated that when the left lane closure warning message was displayed on the PCMS, drivers would merge to the right early, therefore reducing potential congestion caused by late merging (merging near the work zone). To assess the change associated with displaying the message on PCMS, the lane-by-lane traffic volumes at PCMS were collected and compared to the lane-by-lane traffic volume collected at the DMS location. Figure 5.26 elaborates how the vehicles are expected to occupy the two lanes when the message is ON and OFF at the PCMS and at a downstream point before the beginning of the work zone. From the figures, A1 represents the volume in the inner lane, the affected lane, while A2 represents the volume at the outer lane. Both A1 and A2 were determined at the PCMS after crossing a specific point identified by the dotted line. On the other hand, B1 represents the inner lane volume at the downstream point before the beginning of the work zone (DMS location) while B2 is the outer lane volume.



(a) Message ON



(b) Message OFF

Figure 5.26. Lane changing evaluation setup

From the five-minute interval lane-by-lane volume, the percentage volume of vehicles in the inner lane was determined in both locations. After that, the inner lane volume percentage change at the PCMS and DMS was computed for both scenarios (message “ON” and “OFF”). This percentage change (M) in the inner-lane volume between the two locations was computed as:

$$M = \frac{A1}{(A1 + A2)} * 100 - \frac{B1}{(B1 + B2)} * 100 \qquad 5.7$$

The t-test was used to determine the differences in the means between the percentage change in volume of vehicles in the inner lane when the message was ON and OFF. The difference in means of the percentage change in volume in the inner lane when the message was ON and OFF is summarized in Table 5.22. It shows that generally 23.21% of the vehicles which were in the inner lane (affected lane) at the PCMS merged early when the message was ON compared to only 20.04% when the message was OFF. The difference of 3.18% was statistically significant (p=0.0015).

The lane changing analysis was also assessed during the peak and off-peak time. The peak time was the entire duration when drivers used more than five minutes to travel from the PCMS location to the end of the work zone. During peak time, 27.3% of vehicles using the inner lane at the PCMS location merged early when the message was ON while only 23.3% of vehicles in the inner lane merged early when the message was OFF. The difference was statistically significant at a 95% confidence level (p=0.0142).

Table 5.22. T-test results for the percentage difference in the inner lane

OVERALL							
Message	**Avg. Volume at the PCMS**		**Avg. Volume at the DMS**		**% PCMS Inner - %DMS Inner**	**%ON-%OFF**	**p-value**
	A1	**A2**	**B1**	**B2**	**M**		
ON	37	62	13	85	23.21	3.18	0.0015
OFF	39	63	18	85	20.04		
PEAK TIME							
ON	48	61	19	100	27.33	4.01	0.0142
OFF	43	61	21	93	23.31		
OFF PEAK TIME							
ON	30	63	11	78	20.52	3.62	0.0004
OFF	35	65	16	78	16.90		

5.4.4 Case study conclusion

Traffic congestion, often resulting from late merges, is one of the issues which cause delays to motorists when traversing a work zone. PCMSs have been used to mitigate the associated traffic issues by conveying the real time travel information to motorists (FHWA, 2013a). In this case study, the message “LEFT LANE CLOSED 2 MILES AHEAD” was displayed on the PCMS located 1.85 miles from a work zone at I-196 Saugatuck to improve mobility. This study investigated the effectiveness of this message in improving traffic flow along the work zone.

The findings indicate that when the message was displayed on the PCMS, 5.54% of the total travel time from the PCMS to the beginning of the work zone (1.85 miles) was reduced compared to when the message was off. Similar findings were obtained by Datta, Schattler and Hill (2001) by introduced the lane merger system enticing drivers to merge early. Their system reduced traffic delays among other benefits.

Furthermore, the reduction in total travel time was further explained by the increase in the percentage of drivers who merge early when the PCMS was ON. The results showed that generally, 23.21% of the vehicles which were in the inner lane (affected lane) at the PCMS merged early when the message was ON compared to only 20.04% when the message was OFF. During peak time, 27.3% of vehicles using the inner lane at the PCMS location merged early when the message was ON compared to only 23.3% of vehicles in the inner lane that merged early when the message was OFF. These results are consistent with a previous similar study by Harb *et al.*, (2009) who found that early merging rate was higher in dynamic early merge system using PCMS compared to the late merge system.

These findings indicate that using PCMS to manage work zones improve traffic flow by providing awareness of the work zone scenario and triggering the required maneuvers ahead of the work zone. In so doing, PCMS save motorists' travel time.

5.5 Assessing DMS message phasing using a driving simulation study

5.5.1 Introduction

Numerous previous studies have utilized questionnaires to acquire driver feedback and perceptions on the impact of DMS on traffic flow. However, questionnaires only capture reported preferences, not real preferences. Several DMS designs and features have been investigated in driving simulation or a combination of driving simulation and surveys to bridge the gap between stated and actual preferences. Driving simulation can be used to study design and operational characteristics of DMS in a laboratory setting. Although the MDOT Digital Message Sign Guidelines provide guidelines for DMS message phasing, a survey of Michigan motorists conducted as part of this project found that not all drivers can see or understand the displayed message due to the limited time available to read the displayed messages given their driving speed. This simulation study, therefore, used a virtual reality (VR) driving simulator and computer software to simulate driving scenarios and evaluate drivers' comprehension of DMS messages with various phasing times and message length.

5.5.2 Virtual reality (VR) driving simulator

Driving in a virtual environment using a virtual reality (VR) simulator was used to test the effectiveness of different DMS phasing times and message lengths. Figure 5.27 depicts Western Michigan University's virtual driving simulator system, which consists of two primary components: an open driving cockpit with a steering wheel, gas pedal, and brake pedal, and a virtual headset where roadway environment including the DMS messages were displayed. The VR headset provides a 360-degree field of vision, which may be used to simulate real-world settings. The driving system can record vehicle speed and trajectory, steering wheel angle, and eye gazing.

Figure 5.27. Open cockpit VR driving simulator at WMU

5.5.3 Experiment design and execution

Each participant was asked to sign a consent form and complete a pre-survey to collect their demographic characteristics, freeway driving history, and knowledge of Digital Message Signs (DMS) before beginning the simulation session. Four virtual DMSs were placed on a 2-lane freeway with a total length of 11.5 miles and a 70 mph posted speed limit to test the effect of various DMS phasing times. Figure 5.28 shows a sample layout of the virtual driving environment showing the DMS and a simulated incident.

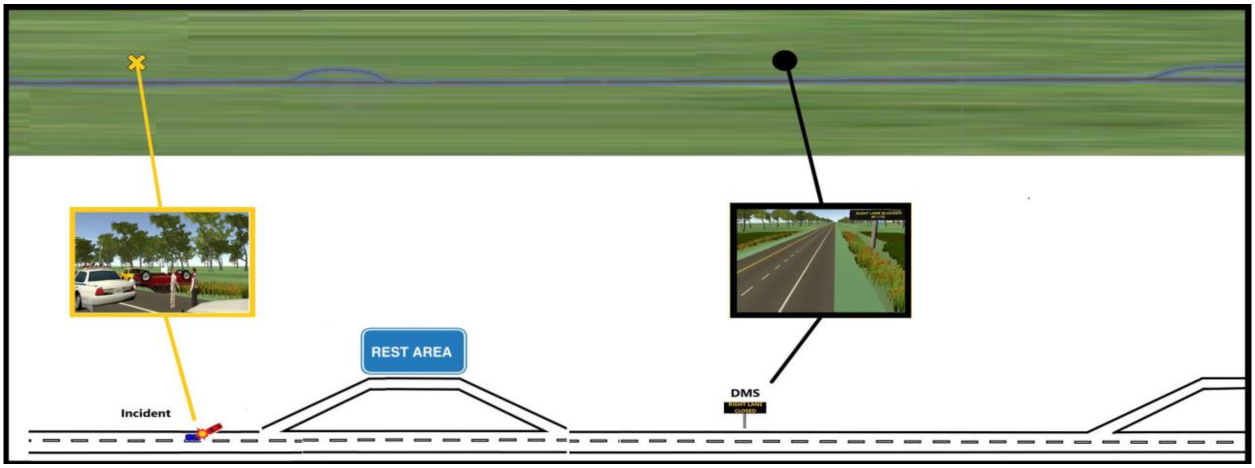


Figure 5.28. Sample virtual driving environment layout

In the simulation session, two types of message lengths (short and long) with two distinct phasing times (2.5 seconds and 4 seconds) for each type were used. As a result, participants were exposed to four different DMS scenarios depending on the message length and phasing time. After passing each DMS sign in the virtual environment, participants were required to stop and complete an intermediate survey (see Appendix 9.8). The intermediate questionnaire served as a driving break for participants and was used to collect driver feedback about the driving session. The virtual vehicle's trajectory and attributes (such as speed, lane position, eye gazing, and steering angle), as well as the user ID and the displayed DMS message were automatically collected by the simulation system during the experiment. Finally, when the participants had finished the experiment, a post-survey was conducted to collect their overall DMS and experiment perceptions as well as information on general freeway driving behavior.

5.5.4 Simulation participants

The research only included drivers having a valid driver's license and the ability to operate a motor vehicle. Subjects were recruited by e-mail, social media, and postcards/flyers, and invited to fill out an online form expressing their interest. Twenty-nine individuals of different gender, ages, and driving experiences participated in the study. Only three people were unable to complete the driving simulation study. Therefore, data from 26 participants were used in the analysis. Table 5.23 presents the demographics as well as the driving and freeway experience of the participants. The majority of the participants were males and were between the ages of 16 and 40. Moreover, a high proportion of participants had little driving experience, and they rarely used the freeway.

Table 5.23. Participants' demographic characteristics

Variable	**Category**	**Count (percentage)**
Age		
	16-24 years	12(46%)
	25-40 years	13(50%)
	41-60 years	1(4%)
Gender		
	Male	20(77%)
	Female	6(23%)
Driving Experience		
	Less than 5 years	13(50%)
	6-10 years	8(31%)
	11-15 years	3(12%)
	More than 15 years	2(7%)
Freeway Experience		
	1-2 days	17(65%)
	3-5 days	7(27%)
	Daily	2(8%)

5.5.5 Results and analysis

Figure 5.29 shows how the ability to read the DMS message varies depending on the phasing scenario. For all cases, the figure shows that the majority of participants were able to read the displayed messages on the DMS. However, regardless of the DMS phasing duration, the figure reveals that longer message scenarios (2.5 Long and 4 Long) have lower readability percentages than short message scenarios (2.5 Short and 4 Short).

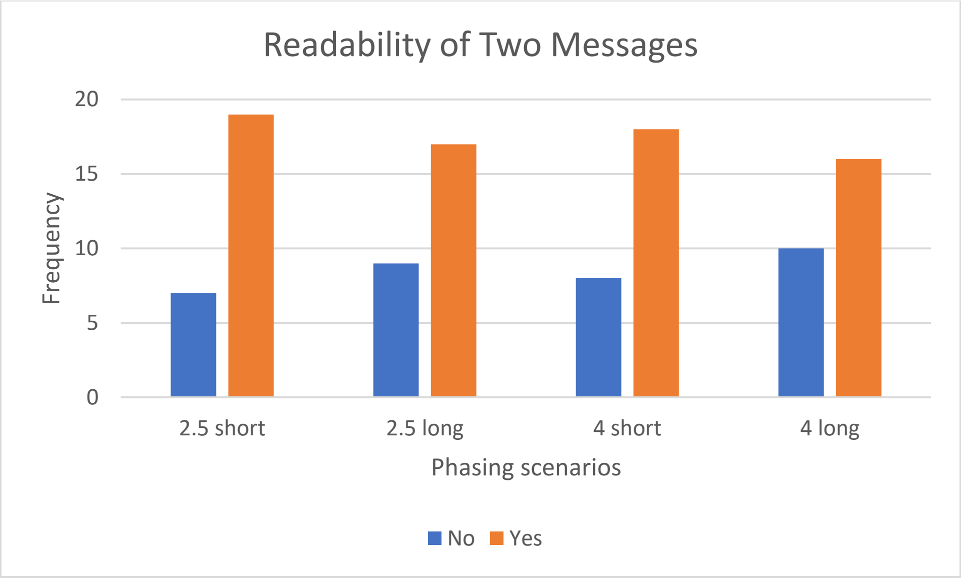


Figure 5.29. The distribution of DMS message readability by phasing scenarios

The Fisher's Exact test was conducted to check if there was a significant relationship between DMS readability and other factors. This test is often used to determine the statistical significance of two categorical variables, especially with a low sample size. Its null hypothesis is that the two variables are independent. Specifically, the test determined the statistically significant association between participant characteristics, experience, mean speeds, and ability to read the DMS under different phasing scenarios. Table 5.24 displays the descriptive statistics of factors by scenario type, while Table 5.25 presents the statistical results (p-values) when the participants' attributes were compared to the DMS readability. The findings show a significant association between highway experience and 2.5 long scenarios. This suggests that drivers with more freeway experience have a greater capacity to interpret a long DMS message in a short amount of time due to their DMS interaction experience. The driving speed was significant in 4 Short and 4 Long scenarios. Figure 5.30 shows that increasing freeway speed within the DMS reading distance (800 ft.) reduces the ability to read both DMS messages. This is because when travelling at high speeds while passing the DMS, there is insufficient time for the DMS message to alternate, causing the driver to believe that the message has been shown for a long time, as some survey participants stated.

Table 5.24. Readability for two messages with participants' characteristics

Variable	2.5 short		2.5 long		4 short		4 Long	
	No	Yes	No	Yes	No	Yes	No	Yes
Age								
16-24	2	10	4	8	0	12	2	10
25-40	0	13	2	11	3	10	3	10
41-60	0	1	0	1	0	1	0	1
Gender								
Male	1	19	3	17	2	18	4	16
Female	1	5	3	3	1	5	1	5
Driving Experience								
Less than 5 years	2	11	3	10	1	12	3	10
6-10 years	0	8	2	6	2	6	2	6
11-15 years	0	3	1	2	0	3	0	3
More than 15 years	0	2	0	2	0	2	0	2
Freeway Experience								
1-2 days	1	16	2	15	2	15	3	14
3-5 days	1	6	4	3	0	7	2	5
Daily	0	2	0	2	1	1	0	2
Mean Speed								
<70 mph	1	7	2	5	0	7	0	10
70-80 mph	2	13	5	11	3	11	4	8
> 80 mph	0	3	0	3	1	4	1	3

Table 5.25. P-values for readability to read both messages with participants' characteristics

	Ability to read both messages			
Variable	**2.5 short**	**2.5 long**	**4 short**	**4 long**
Age	0.280	0.522	0.310	1.000
Gender	0.415	0.112	1.000	1.000
Driving Experience	0.680	1.000	0.760	1.000
Freeway Experience	0.582	0.074*	0.235	0.747
Speed	1.000	1.000	0.017**	0.089*

*significant at 90% C.I
** significant at 95% C.I

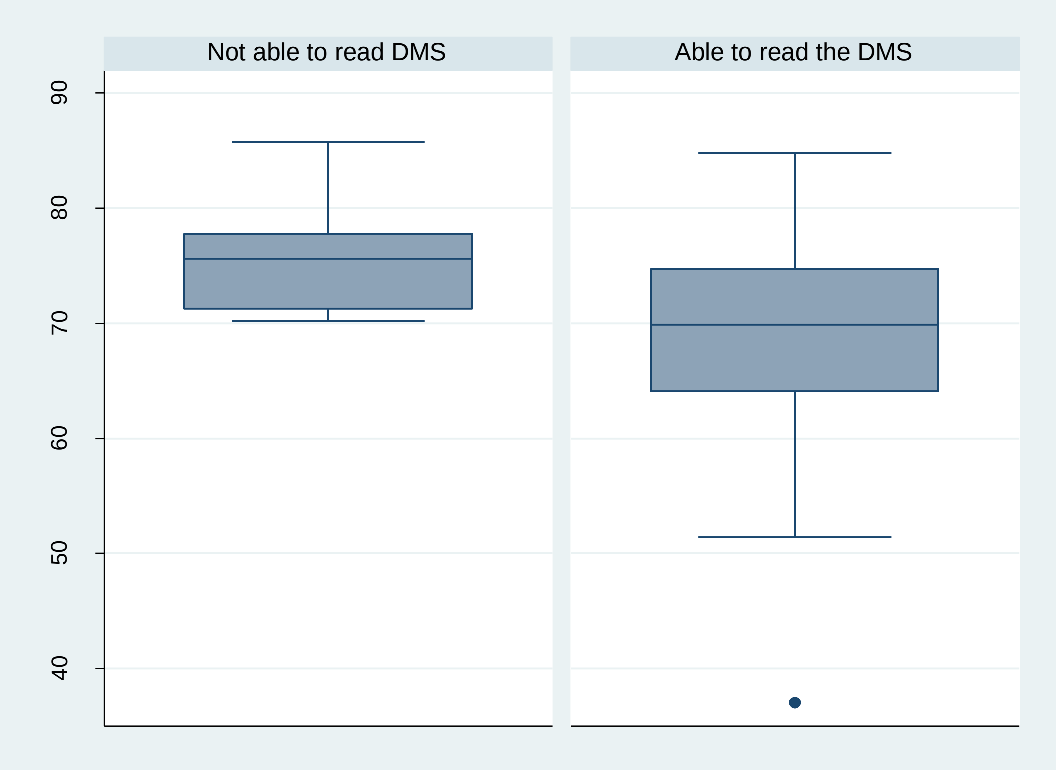


Figure 5.30. The relationship between mean speed and ability to ready DMS Message

5.5.6 Conclusion

As part of this project, a simulation study was conducted to determine the influence of phasing time on the readability of DMS messages. Although DMS messages are readable in most cases, reading long DMS messages to their entirety is a challenge to road users. This is consistent with findings from the survey presented in Chapter 4, in which survey participants stated similar challenges to read both messages when displayed in succession. Furthermore, the findings show that driver age, gender, and driving experience had no impact on the capacity to interpret a subsequent message shown on two DMS screens. The study also found that speed and highway experience substantially impacted the readability of DMS messages. The results suggest that DMS phasing time and message length should be investigated further to accommodate freeway features (such as speed) and message details (such as message length).

6 COST-BENEFIT ANALYSIS OF DIGITAL MESSAGE SIGNS

As documented in Chapters 4 and 5 above and in previous studies, Digital Message Signs (DMSs) impact traffic flow. Quantifying the costs and benefits associated with the impact of DMSs on traffic flow have proved to be difficult due to the challenges resulting from the difficulty monetizing them. Nevertheless, several studies have attempted to quantify the costs and benefits of using DMSs to provide information to travelers. In this study, several case studies documented in Chapter 5 generated quantifiable results that could be used to estimate the costs and benefits of DMSs. Specifically, it was found that deploying a Portable Changeable Message Sign (PCMS) to warn travelers of lane closure ahead helped them change lanes in advance to avoid the closed lane. This causes the traffic to flow relatively smoothly and hence saves travel time. Also, the case study on traffic diversion showed that when the displayed travel times on alternative routes were shorter, drivers diverted from a route with longer travel time to the alternative route, hence saving time. Finally, the case study on the impact of displaying weather-related messages on DMS showed that vehicles traveling at higher speeds are more likely to reduce their speed in response to the DMS message. This may reduce the overall number of crashes, especially speed-related severe crashes which have significant costs. The following sections document the cost-benefit analyses for the three case studies mentioned above.

6.1 Benefits of using Portable Changeable Message Signs to manage a work zone

6.1.1 Data used

The travel time between the PCMS and the work zone taper was extracted for both scenarios when the PCMS was ON and OFF to capture the travel time savings by PCMS. Raw traffic counts from the MVDS were extracted and verified manually (refer to Chapter 5) before using them in the analysis. The overall one-time cost of PCMS, according to the MDOT, is $6,950, which includes $5,450 for installation and $1,500 for operation and maintenance.

6.1.2 Quantifying the value of time

The value of time should be determined based on current conditions to transform the time savings of using the PCMS in the work zone to actual economic savings. As a result, the

Consumer Price Indices (CPI) for 2015 and 2021 from the United States Department of Labor's Bureau of Labor Statistics were used to predict the value of time for 2021. Table 6.1 displays the CPI value for the years 2015 and 2021 and the hourly inflation rate for passenger cars and trucks. Consequently, the value of time for passenger cars in 2021 was calculated as $23.58 per hour, while the value of time for trucks was $31.44.

Table 6.1. Value of time for 2021 based on Consumers Price Indices

Parameter	**Year 2015**	**Year 2021**
Consumer Price Index (CPI-U)	236.525	273.567
Ratio (CPI-U$_{2021}$/CPI-U$_{2015}$)	1.156	
Passenger Vehicles ($ per veh-hour)	$20.40	$23.58
Trucks ($ per veh-hour)	$27.20	$31.44

6.1.3 *Estimating travel time saving*

The average travel time between PCMS and work zone taper (1.85 miles) was assigned to the number of vehicles per minute (veh/min) to estimate the travel time savings for utilizing the PCMS. Following that, the average travel time of devices within a minute was calculated. As a result, the final data for ON and OFF conditions showed the number of vehicles and the average travel time for each minute. Then, the average travel time was obtained for minutes with the same number of cars. A sample of processed data is shown in Table 6.2. For example, a minute with 20 cars was assigned a 4.05-minute average travel time.

Table 6.2. Sample of data for the number of devices and travel time

Month	Day	Hour	Min	Veh/min	Number of Devices	Travel time	Average travel time
4	1	10	46	20	21	2.604676962	4.05
4	1	10	51	20	12	3.025509834	
. . .	. . .	. . .	. . .	. . .	. . .	. . .	
4	1	11	2	20	9	4.228083134	
4	1	15	29	22	8	8.947778702	5.20
4	1	17	45	22	3	7.863844395	
. . .	. . .	. . .	. . .	. . .	. . .	. . .	
4	1	18	4	22	34	5.647172451	

Finally, travel time - volume functions were generated for both PCMS study scenarios (PCMS ON and PCMS OFF). As a result, the expected travel time for each hourly equivalent volume was used to calculate the travel time savings by subtracting the travel time when the PCMS was ON from the travel time when the PCMS was OFF (i.e., Travel time when PCMS is OFF - Travel time when PCMS is ON). For both cases, the derived functions for travel time are shown in Figure 6.1. When the PCMS was turned off, it took longer to travel than when it was turned on, especially when there were more vehicles per hour. Finally, the daily saving time for utilizing the PCMS in the work zone was allocated to each minute of the day (for a total of1440 minutes) while PCMS was ON based on the observed number of vehicles during each minute.

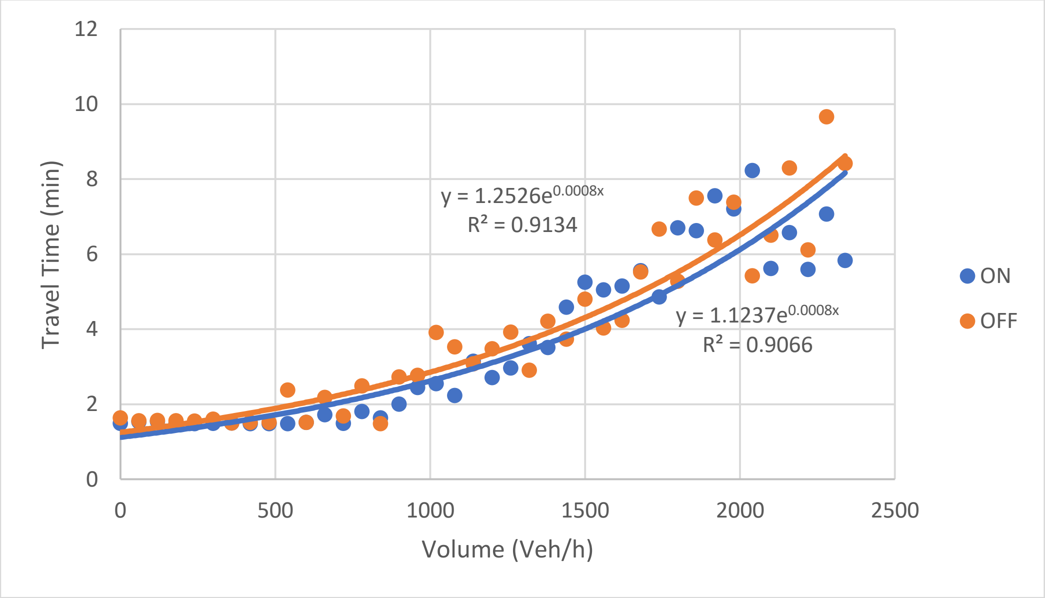


Figure 6.1. Travel time – volume function for “ON” and “OFF” conditions

6.1.4 Daily PCMS saving

Although using PCMS to manage a work zone may have additional safety benefits, only travel time saving benefits were quantified in this study. After estimating the travel time saving at a minute level for one day, the PCMS saving for each minute was determined by converting the travel time saving to actual saving using the hourly value of time

($23.58/60 = $0.393/min for passenger car and $31.44/60 = $0.524/min for trucks). The following equation was used to calculate the daily saving of PCMS at the work zone:

$$Daily\ saving = \sum_{\min=1}^{1440} (P \times VP + T \times TP) \times TS \qquad 6.1$$

where:

P = Number of vehicles per minute (Veh/min)

VP = Value of travel time for passenger car per minute ($0.393/min)

T = Number of trucks per minute (Veh/min)

TP = Value of time for truck vehicle per minute ($0.542/min)

TS = Travel time saving per min

6.1.5 Benefit-cost ratio

The benefit-cost ratio was calculated by dividing the daily savings from PCMS by the installation and operation cost. Note that the daily saving is a summation of minute-by-minute saving given the number of vehicles in each minute:

$$BCR = \frac{Daily\ saving\ by\ using\ PCMS}{Installation\ and\ opreation\ cost} = \frac{\$2{,}815}{\$6{,}950} \quad 0\ 41 \qquad 6.2$$

Figure 6.2 depicts the relationship between the BCR value and the number of work zone days for the Saugatuck case study. It clearly reveals an increase in BCR value as the number of days spent using the PCMS increases, which was expected given that the PCMS has a fixed cost and the benefit amount is based on the number of vehicles passing through the work zone.

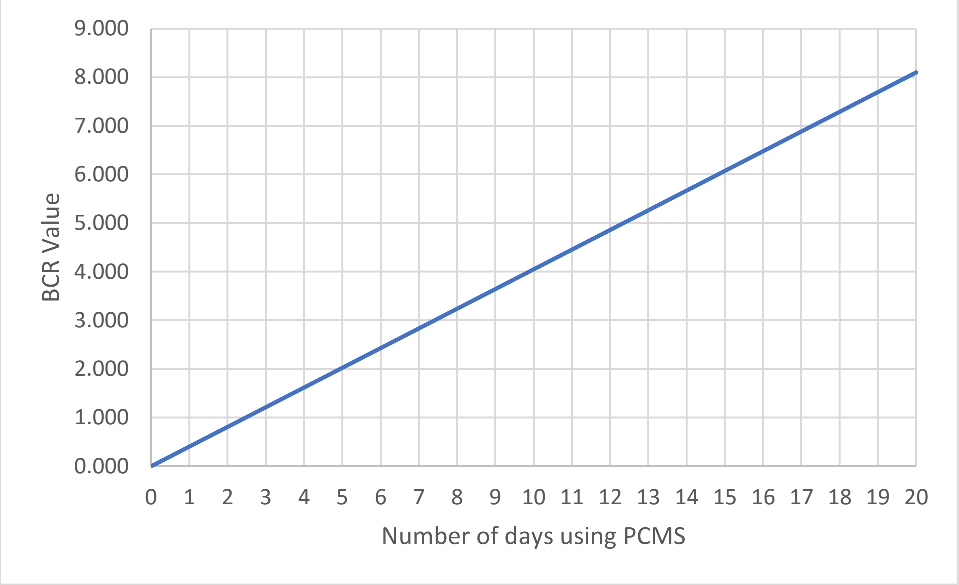


Figure 6.2. The relationship between BCR value and number of days of using PCMS

6.1.6 *Impact of work zone characteristics on BCR value*

The travel time saving above was estimated based on specific characteristics for the case study (I-96, Saugatuck). However, work zone characteristics may have an influence on savings. Therefore, different freeway characteristics such as truck percentage, AADT, and the distance between PCMS and work zone beginning (i.e., start of lane taper) were simulated to investigate the amount saved by using the PCMS under different roadway and traffic conditions.

6.1.6.1 Impact of truck percentage

Different traffic composition scenarios were simulated to capture the impact of truck percentage on PCMS benefit amount, and because the value of time for trucks differs from that of passenger car ($0.524/min vs $0.393/min). The base traffic composition (traffic with only passenger cars) was changed by increasing the percentage composition of trucks in the traffic mix (10%, 20%, 30%, 40%, 50%, and 100%). Figure 6.3 displays the percentage of trucks, the BCR value, and the number of days PCMS has been used. The figure clearly illustrates that the percentage of trucks has a slight effect on the BCR value and the number of days required to realize the time savings. For example, the figure shows that when there are no trucks in traffic (0%), it takes 2.5 days to reach the break-even point (BCR=1), whereas it takes almost 1.8 days to reach the break-even point for the PCMS when the composition of traffic is trucks only (100%). So, if the truck percentage increases from 0% to 100%, the number of days required to realize travel time savings will only be reduced by one day.

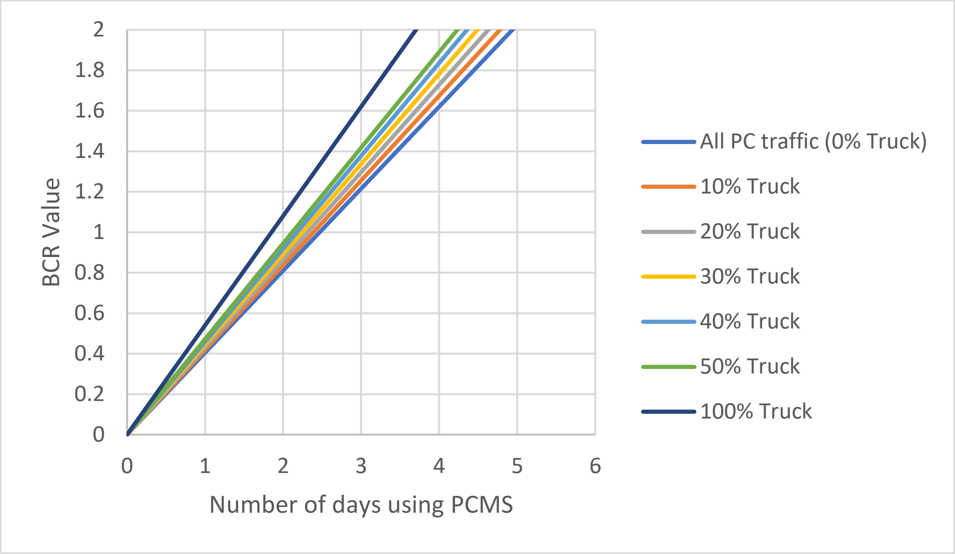


Figure 6.3. The relationship between trucks percentages and BCR value

6.1.6.2 Impact of AADT

The base scenario (I-196 in Saugatuck) was simulated under various AADT values to highlight the influence of AADT on BCR value while using PCMS. Using the traffic volume shapefile from MDOT, the 2019 AADT for all Michigan freeways that match the case study characteristics (number of lanes and speed limit) were extracted. The data was utilized to identify freeways with similar characteristics as the one studied at I-196 in Saugatuck and determine the AADT range to mimic BCR values for various AADT values. Therefore, several AADTs were simulated at an interval of 15000 veh/day (15000, 30000, 45000, 60000, and 75000). The impact of AADT on the BCR value is depicted in Figure 6.4. AADT appears to significantly influence on the BCR value, in contrast to truck percentage. Figure 6.4 shows that using PCMS in a work zone on a freeway with an AADT of 15000 veh/day takes about 10 days to reach the break-even threshold (BCR=1), whereas a freeway with a high AADT value, such as 75000, takes less than one day. Figure 6.5 depicts the change in the required time to break-even as a function of the AADT level. The increased number of units that travel through the work zone can explain the high impact of AADT on BCR and PCMS benefit values. As a result of the BCR analysis of AADT for work zone, the PCMS is strongly recommended for usage in high-AADT freeway work zone.

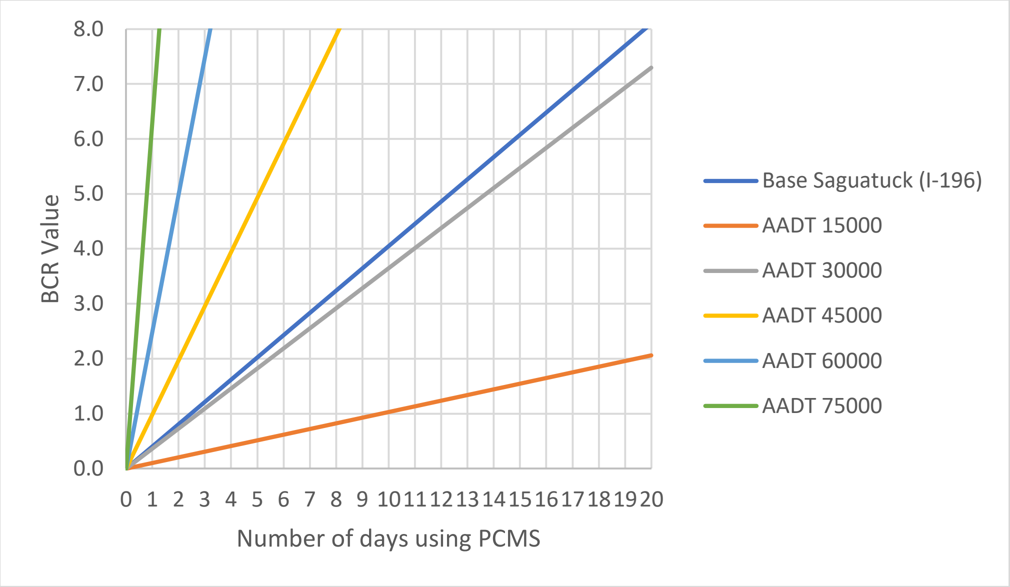


Figure 6.4. The relationship between AADT and BCR value

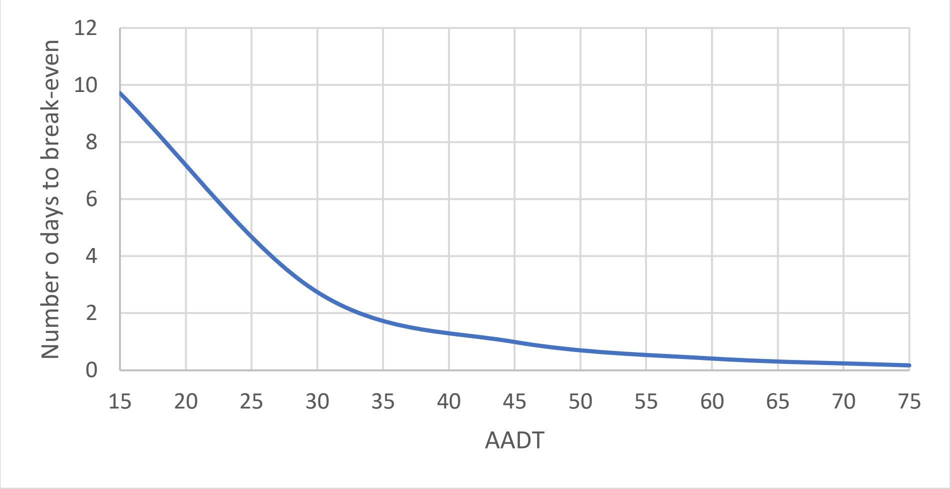


Figure 6.5. Number of days required to break-even by AADT

6.1.6.3 Impact of different PCMS-Taper length

As noted in the work zone analysis, the distance between the PCMS and the beginning of the work zone has a significant influence on travel time savings. This is because motorists use this distance to merge into a specified lane before the work zone. Therefore, instead of utilizing the base distance between PCMS and the beginning of the work zone (1.85 mile), the travel time saving was regenerated by using different distances between PCMS and the beginning of the work zone (1, 2, 3, 4 and 5 mile). Figure 6.6 shows how the PCMS-Taper distance impacts the time required to break-even (achieve a BCR of 1). By extending the distance between PCMS and the work zone beginning, the BCR value increases while number of days required to break-even decreases. Longer distance influences early merge and creates a smooth flow and therefore reduce travel. However, the relationship is not linear – savings vary appreciably for distances below five miles.

Figure 6.6. The relationship between PCMS-Taper and the required number of days to break-even

6.1.6.4 Impact of AADT, truck percentage and PCMS-Taper distance

After simulating travel time savings and BCR values under various AADT, truck percentages, and PCMS-Taper distance, a combined effect of these parameters on the number of days necessary to use PCMS to break-even was analyzed. Figure 6.7 provides an example of a combined effect of different AADT values and PCMS-Taper distance at 0 percent trucks (Passenger cars only). As can be seen, AADT and the distance between PCMS and the work zone beginning influence the number of days the PCMS should be used in the work zone. Figures for other truck percentages are included in Appendix 9.9.

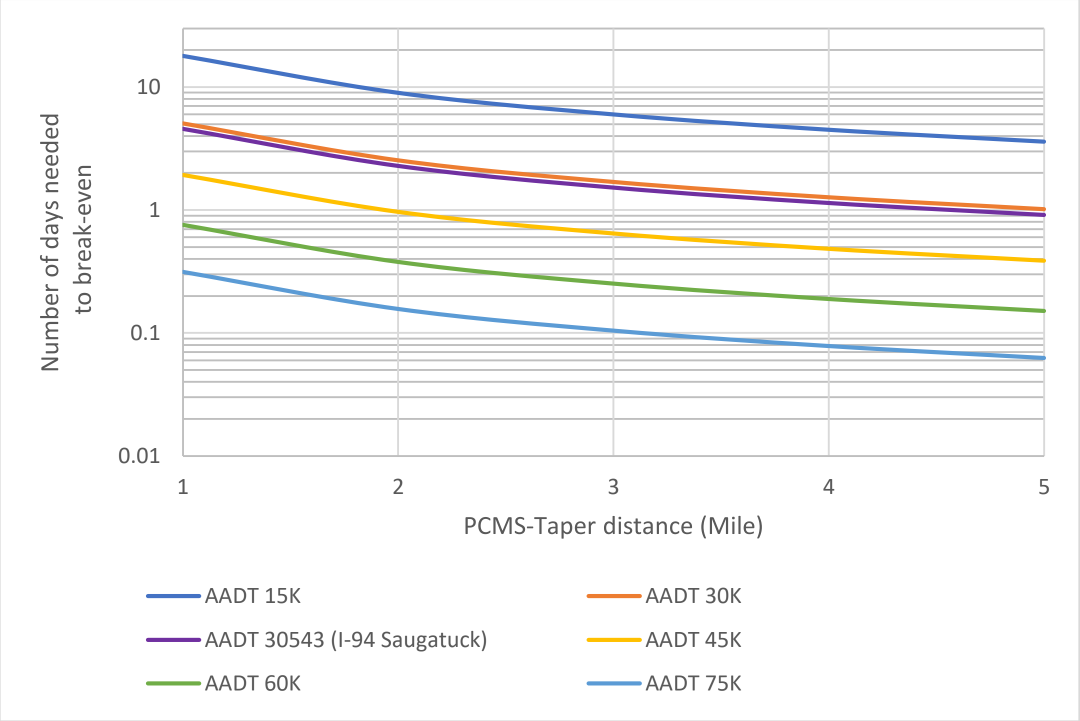


Figure 6.7. Combined effect of work zone characteristics for 0% truck

6.2 Benefits of displaying weather-related messages on DMS

6.2.1 Introduction

Based on the case study performed to assess the impact of the weather-related message on traffic speeds (refer to Chapter 5), it was observed that the message “ROAD MAY BE SLIPPERY, REDUCE SPEEED” led to a significant speed reduction of 5.66 mph for speeding drivers (those driving above 80 mph). Similarly, the case study assessing the feasibility of using ESS data to automate DMS messages (refer to Chapter 5) showed that drivers on average reduced their speed by about 5.67mph when the message “LIGHT SNOW DETECTED AT M179” was displayed on the DMS. Also, the message “FREEZING RAIN DETECTED AT M179” led to an average speed reduction of 4.05mph on drivers after seeing the message. These two case studies confirmed that drivers reduce speed in response to weather-related messages posted on DMS, especially when the message clearly communicates the hazard situation or recommend a clear action for motorists to take.

Speeding is among the main factors associated with fatal and injury crashes. As such, change in the average speed of drivers may affect the number and severity of crashes on the corresponding roadway. To quantify this, the observed speed reduction was related to the number of crashes that are likely to have been reduced. Several models have been introduced in the literature to relate the average speed of vehicles and the number of crashes and speed change. The Power model by Nilsson (1982) was the first to be introduced. It used the principles of kinetic energy to consider the associated impact of crash severity. The ratio of the speeds was raised to a power of 2 to indicate slight serious crashes, 3 to indicate serious crashes and 4 to indicate fatal crashes. This model was later modified by Elvik (2014) to an exponential model which took into account the initial speeds of the drivers. It was observed that the number and severity of crashes are higher when the initial speed is higher. The exponential model is shown in equation below, where A_1 and A_2 represent the number of crashes before and after speed change, respectively. Similarly, V_1 and V_2 represent the average speed before and after speed change, respectively while β is a coefficient that depends on crash severity.

$$A_2 = A_1\, e^{\beta(V_2 - V_1)} \qquad 6.3$$

The model above was developed using initial speeds between 20km/h to 120km/h within both urban and rural areas. The relationship between average speed and the number of crashes was found to be similar in urban and rural areas. This model was adopted in our analysis since it covered the freeway speed limit on our case study site (70 mph). The potential reduction in crashes associated with weather-related messages was derived and used to estimate benefits.

6.2.2 Data used

(a) Speed data

Speed reductions obtained from the case studies highlighted in the introduction above were used in the analysis. The benefit-cost ratio was calculated for different magnitudes of speed reductions ranging from 2 mph to 8 mph (similar to the 99% confidence interval of the reduction observed in our case study (5.66 mph). This was done to cover the range of speed reductions likely to occur because of weather related message displayed on the DMS.

(b) Crash data

The 2019 crash data from the case study site were analyzed to determine the crashes when the DMS was displaying a weather-related message. Out of a total of 20 crashes observed in the vicinity of the DMS in 2019, only one crash occurred when the weather-related message was displayed. This was a crash considered in the after period (A_2) and was used together with the speed reductions to estimate crashes that would have occurred if the weather-related messages were not displayed, and hence the potential crash reduction.

(c) Cost of crash

The Societal Costs of Traffic Crashes and Crime in Michigan (2017 update) was used to estimate the cost of crashes (Streff & Molnar, 2017). An average cost of all injury crashes was used in the analysis. The unit crash cost for all injury crashes was calculated using the costs for fatal, serious injury, moderate injury, and minor injury, and was found to be \$226,530.61 in the year 2017. The inflation rate was calculated using the Consumers Price Index for 2017 and 2019, which were 246.524 and 256.759, respectively. The 2019 cost of an injury crash was therefore $\$226{,}530.61 \times \frac{256.759}{246.524}$ = \$235,935.54.

(d) Cost of DMS

The costs of the DMS were provided by MDOT, which included the installation cost of \$72,000 and the annual operation cost of \$2,300. Moreover, the DMS has a service life of 15 years.

6.2.3 Analysis

The BCR was calculated for each year using multiple potential speed reductions and number of crashes.

(a) BCR variation by speed reduction

The change in magnitude of speed reduction impacts the potential number of crashes reduced. As mentioned earlier, the impact of speed reduction was simulated for a range from 2 mph to 8 mph. This was done to see how benefits vary with speed reduction associated with a weather-related message. Figure 6.8 shows the expected BCR values by speed reduction within the fifteen years of DMS service.

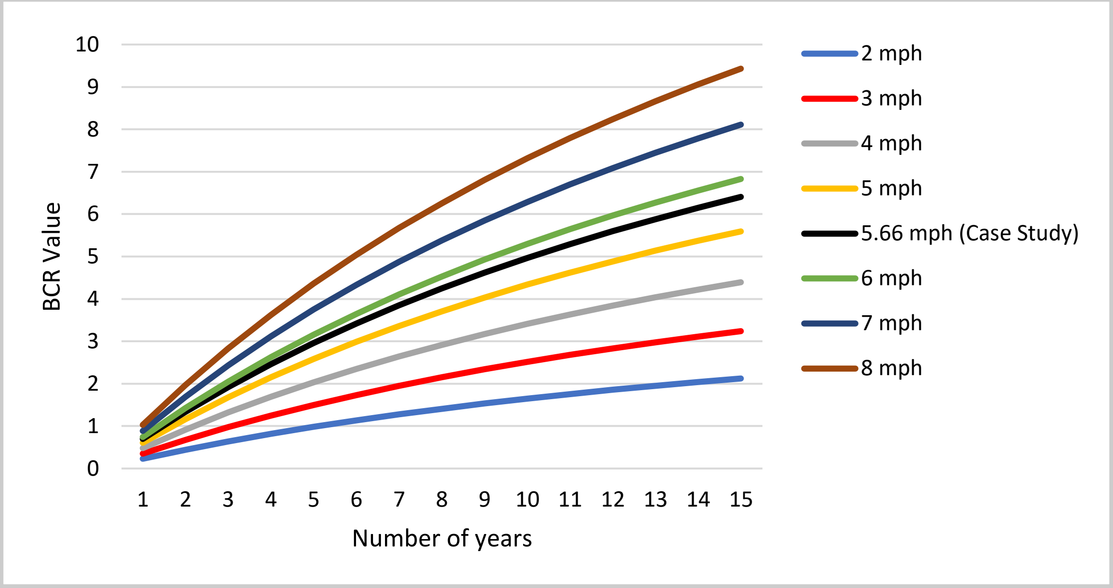


Figure 6.8. BCR by number of years as a function of speed reduction

Results indicate that realization of benefits depends on the speed reduction associated with a particular weather-related message. When the speed reduction is about 2 mph, for example, the break-even point (BCR = 1) is about six years after DMS installation. On the other hand, with higher speed reductions such as 8 mph, the break-even point is within the first year of DMS installation. For the value of 5.66 mph speed reduction which was observed in the case study, break-even point would be within the second year after DMS installation. These results suggest and emphasize the importance of selecting and displaying messages with the highest potential to influence driver actions such as weather-related messages that give a specific recommended action.

(b) BCR variation by number of crashes

The historical number of weather-related crashes that have occurred on a particular roadway in the DMS vicinity can easily be identified. So for a site similar to the one used in this case study which had 4 lanes (2 in each direction), located in an urban/suburban area and with speed limit of 70 mph, displaying specific weather message such as those discussed in Chapter 5 is likely to cause a 5.66 mph speed reduction. Using the exponential model discussed above, the expected reduction in the number of weather related crashes due to DMS message can be estimated. Therefore, the number of crashes expected to be reduced can be estimated and converted into expected benefits by using the crash cost. Figure 6.9 indicates when and how much benefits can be realized if an agency has observed a specific number of weather-related crashes at a given location and is considering installing a DMS. This graph is for a speed reduction of 5.66 mph. Appendix 9.10 shows expected benefits for other speed reduction values. Such graph can be used with other data to assess the potential benefits of installing a DMS and displaying weather-related message.

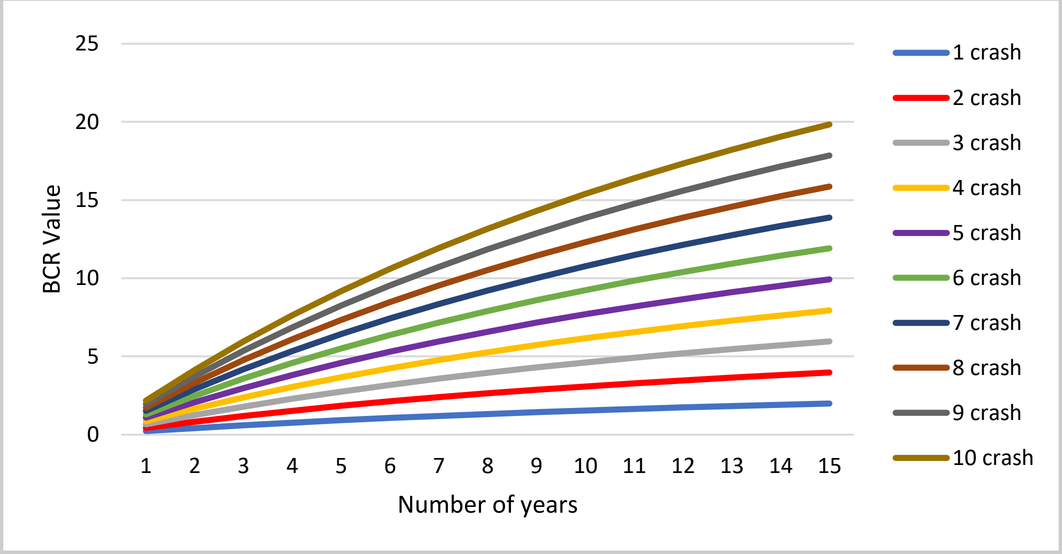


Figure 6.9. BCR by number of years year and number of crashes for speed reduction of 5.66mph

6.2.4 Conclusion

Generally, displaying weather-related messages on the DMS impacts the speed of drivers. Using the DMS to inform drivers of the hazardous weather condition is a cost-effective way to reduce potential crashes. The benefit can be realized instantly, especially if two or more weather-related crashes have been observed at the location that involve speed.

6.3 Benefits of displaying alternative route travel times on DMS

6.3.1 Introduction

This analysis utilized results obtained from a case study we conducted in this study to assess the impact of displaying travel time of alternative routes on DMSs (S-175S-MM1562-Crane and S-I75N-MM1472-Hess) located in Saginaw, Michigan (refer to Chapter 5). Throughout the study period, it was observed that under normal traffic conditions, the alternative route I-675 had a higher travel time than I-75. However, on 10/23/2020 at 17:16 hours, an incident occurred on I-75 northbound. This event led to a considerable increase in I-75 travel time, which provided ideal conditions for capturing the savings due to the DMS message. Figure 6.10 shows the travel times displayed on the DMS S-I75N-MM1472-Hess on the incident day. As it can be seen, after an accident occurred at 17:16, the northbound I-75 travel time rose, eventually exceeding the I-675 travel time. The message informing drivers about the incident and travel times on the alternative routes was posted on the DMS at 17:33 hours. Specifically, the message stated, “RIGHT 2 LANES BLOCKED, AFTER M-81 EXIT 151, EXPECT DELAYS || TIME TO US-10 VIA, I-675 17 MI 14 MIN, I-75 15 MI 20 MIN”. As shown in the graph, the travel time on the alternative route I-675 began to rise later – indicating that motorists started diverting to I-675 route in response to the posted message. In this case, motorists’ response was triggered by not only the displayed travel times but also the presence of incident. Therefore, this cost-benefit analysis focused on the savings realized by displaying travel time and incident information on a DMS.

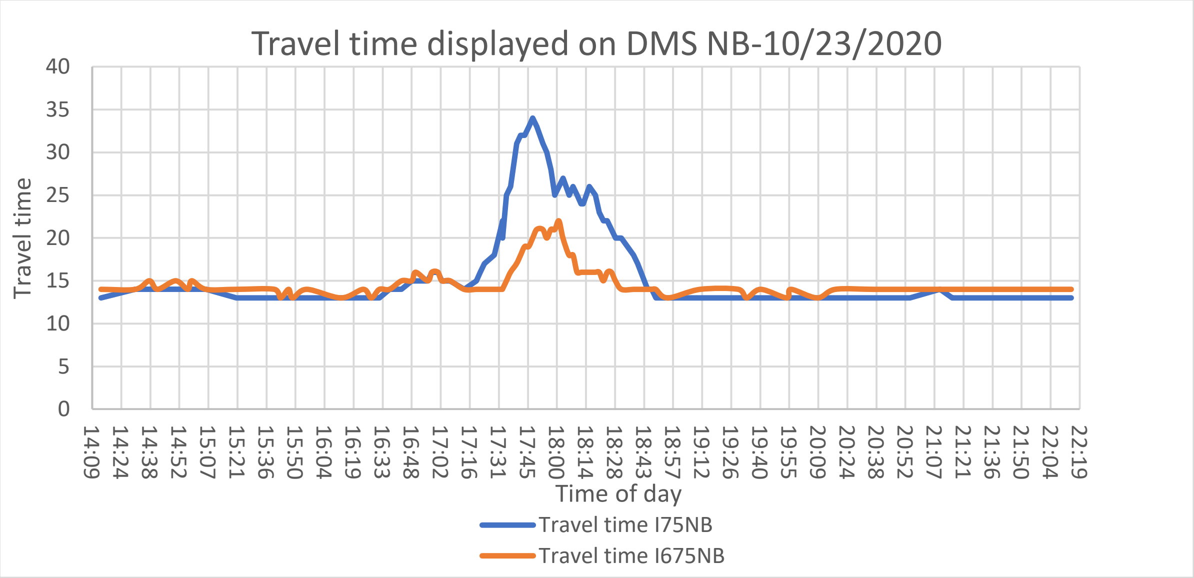


Figure 6.10. Travel time patterns during the incident on 10/23/2020

6.3.2 *Estimation of saving*

Traffic was counted manually, and using the Bluetooth sensor data, the minute-by-minute volume was used to create a function that showed the number of vehicles completing the trip by using the alternative route depending on the travel time. This function was used to link the DMS's displayed travel time during the incident to the number of cars that completed the trip on I-675 each minute. The final data contained the displayed DMS travel time for alternative routes and the number of complete trips for each minute during the incident. Analysis in the case study presented in Chapter 5 showed that an increase of one minute in travel time on the direct route (I-75) increased the likelihood of motorists taking the alternative route by 35 percent. The value of travel time calculated in the work zone analysis ($23.58/60 = $0.393/min for passenger car and $31.44/60 = $0.524/min for trucks) was adopted. MDOT provided the cost of DMS, which included installation cost ($72,000) and annual maintenance cost ($2,300).

6.3.3 *BCR analysis*

The cost of installing and operating a DMS was distributed throughout the 15-year service life of the DMS using the Equivalent Annual Uniform Worth (EAUW), which is written as follows:

$$EAUW = -C\left[\frac{i(1+i)^N}{(1+i)^N - 1}\right] - M \tag{6.4}$$

Where C = capital or initial cost (\$72,000); i = discount rate; N = service life of DMS (15 years), and M = annual maintenance/operating cost (\$2,300).

The yearly DMS benefits were determined based on the savings made during incidents per year. Knowing the number of incidents per year and the duration of incidents are necessary for sites where travel time in the alternative route becomes lower than that on the direct route only when an incident occurs. Also, the duration of incident is an important parameter associated with savings. The following formula was employed to calculate the saving during the incident duration:

$$DBI_i = \sum_{min=1}^{last\ min} VT \times V_a \times MF \times DF \tag{6.5}$$

Where DBI_i = total saving during a single incident i; VT = value of time per minute (\$0.393/minute); V_a = number of vehicles that complete the trip using the alternative route per minute; MF = difference in travel time between alternative and direct routes every minute; and DF = the probability of taking alternative route (0.35 in our study). Then, saving per year (DBY) can be estimated by summing the saving for all incidents (N) observed throughout the year as follows:

$$DBY = \sum_{i=1}^{N} DBI_i \tag{6.6}$$

The incident observed on 10/23/2020 took 39 minutes. Savings estimated based on the number of motorists who diverted in response to the message displayed on the DMS was \$183.327. The cost of DMS per 39 minutes estimated from the annual cost was determined to be \$0.618. These translated into a BCR of 296.56. However, a more realistic BCR could be calculated by accruing the benefits, say annually, to account for variations in incidents. To demonstrate this, after calculating the amount saved by DMS during this single event, the number of incidents per year along I-75 was determined using the average number of crashes observed along the route in the previous five years, which was found to be 46 incidents per year. Assuming these incidents had similar characteristics as the one observed on 10/23/2020, the annual saving can be estimated as: $BCR = \frac{DMS\ benefits}{DMS\ costs} = \frac{DBY}{Annual\ cost} = \frac{DBI \times N}{Annual\ cost} = \frac{\$183.327 \times 46}{8331.2} = 1.012$. However, incidents vary by many factors, including AADT, duration, and traffic distribution, to mention few. The next section discusses how to generalize the benefits.

6.3.4 Generalizing the BCR

Although the benefit-cost analysis of using DMS to display a travel time for an alternative route shows that the cost of DMS can be covered by using DMS during an incident, this BCR value was estimated based on specific location and incident characteristics such as AADT (53,819 veh/day), traffic distribution between alternative routes (60:40), and incident duration (39 minutes), all of which may influence the BCR value. As a result, these variables were simulated to see how they affected the BCR value and allow for a wider interpretation and application of the results from this analysis.

6.3.4.1 Impact of AADT

The amount of traffic the routes serve could be an important factor in determining savings. A sensitivity analysis was conducted using different AADT values (15000, 30000, 45000, 60000, and 75000) to identify its impact. Figure 6.11 shows a linearly increasing relationship between AADT and BCR value. The case study location had an AADT of 53,819 veh/day.

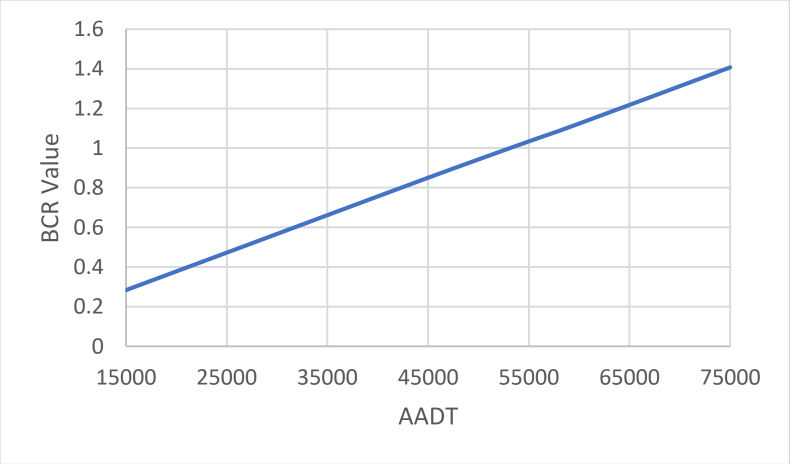


Figure 6.11. The impact of freeway AADT on BCR

6.3.4.2 Impact of incident duration

Simulating different incident durations with a 10-minute increase from the case study incident duration (39 minutes) up to 1.5 hours was used to assess the influence of incident duration on BCR value. The simulated travel times for the extension period were calculated using a moving average based on observed travel times. The corresponding number of vehicles per minute was then calculated using the volume-travel time formula previously generated. Figure 6.12 shows the impact of incident duration on the BCR when the travel time information is displayed on DMS. The figure depicts an increase in BCR value when the incident duration is long. Therefore, using DMSs can be even more beneficial if the incident requires a longer time to clear.

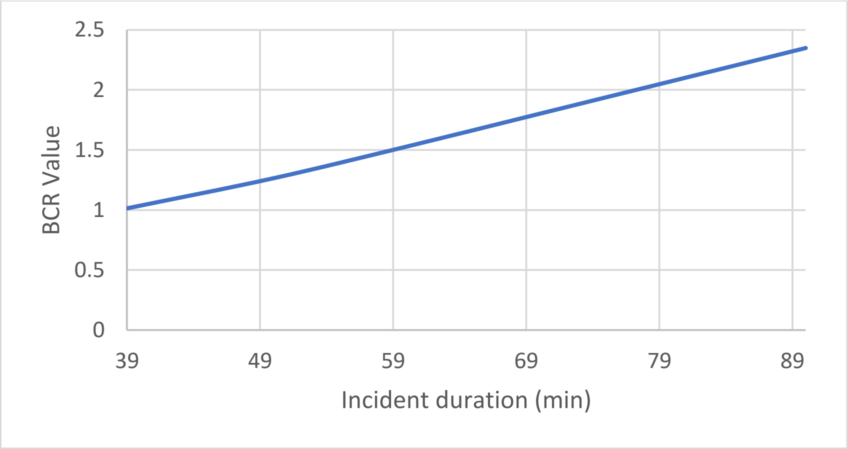


Figure 6.12. The impact of incident duration on BCR

6.3.4.3 Impact of traffic distribution

The likelihood of diverting from the direct route is associated with the original traffic split among the two alternative routes. The analyses above were carried out assuming the original traffic distribution in which the alternative route I-675 carries 40 percent of total traffic that travels from origin to destination under normal conditions. Therefore, several traffic distribution percentages (50, 30, and 20) were simulated on the alternative route to assess how the distribution percentage affects the amount of savings. As seen in Figure 6.13, an increase in the proportion of traffic using the alternative route is associated with higher savings.

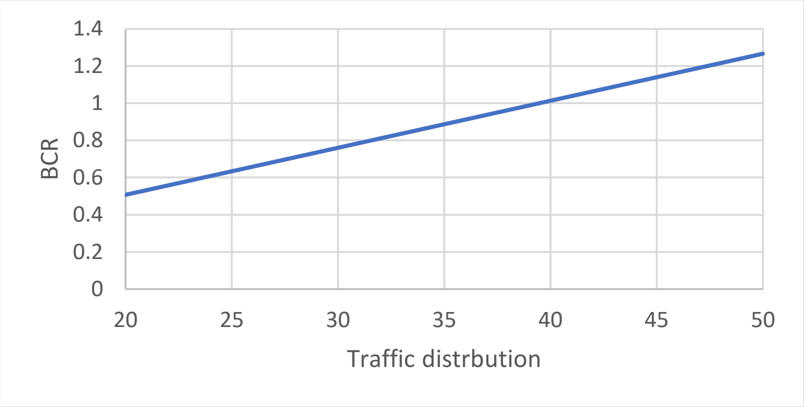


Figure 6.13. The impact of traffic distribution by alternative routes on BCR

6.3.4.4 Combined impact of AADT, incident duration and traffic distribution

Several parameters impact the saving amount associated with displaying travel time for alternative routes on a DMS. As such, the combined effect of various characteristics such as AADT, incident duration and traffic distribution, was simulated. Figure 6.14 shows a sample of the simulated combined impact on BCR for our case study, which had a 60:40 traffic distribution (graphs for other traffic distributions are in Appendix 9.11). The figure depicts a higher BCR value when the AADT at the DMS location is high, the traffic distribution on the alternate route is high, and the incident takes a long time to clear. These findings emphasize the usefulness of DMS on roadways with high traffic.

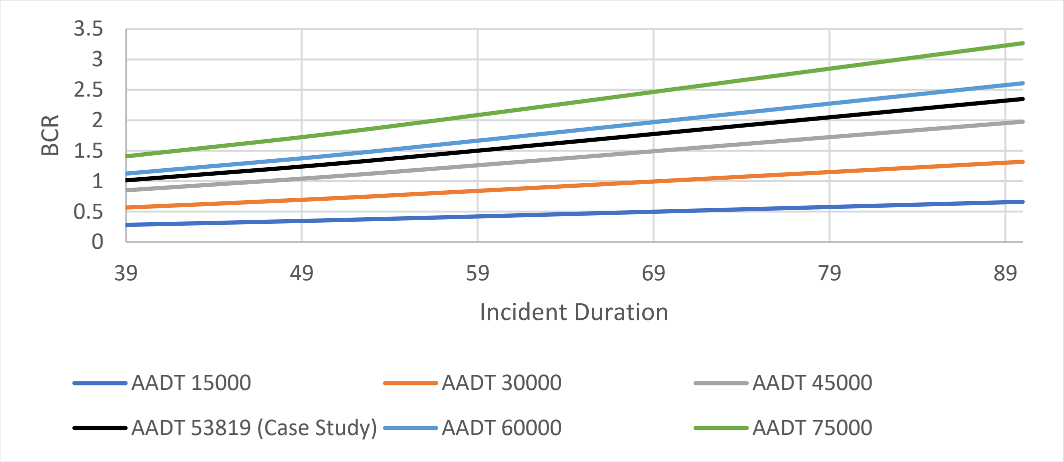


Figure 6.14. Combined BCR for different AADT and incident durations for traffic distribution of 60:40

7 CONCLUSIONS AND RECOMMENDATIONS

Digital Message Signs (DMSs) is a major part of the Michigan Department of Transportation (MDOT)'s advanced traveler information (ATIS) network. These DMSs are used to display real-time travel information to road users as well as other information focusing on improving the safety of the roadway network. Similar to other state DOTs, MDOT has Digital Message Sign Guidelines Manual which provides the general DMS operational guidelines. Although many state DOT's guidelines closely follow the Federal Highway Administration (FHWA)'s Changeable Message Sign Operation and Messaging Handbook, there exist a number of DMS operational practices that are unique to these states. Literature shows that several studies have examined the effectiveness and impacts of DMS on traffic flow in other states to guide their practices. Contrary, MDOT lacks such studies, although performances have been superficially examined as part of other studies conducted by MDOT. Therefore, this research intended to develop a data-driven methodology to assess the effectiveness of different DMS, message types and installation location in Michigan. The study also intended to generate necessary results to allow better allocation of MDOT's resources by investing in effective sign technologies for traffic improvement and improving overall DMS operational practices in Michigan.

To accomplish the objectives of this research, the research team methodically performed several tasks, including a literature review which uncovered practices and guidelines used by other states. It also revealed findings from past evaluations conducted in Michigan and elsewhere. The literature review was followed by a comprehensive survey of Michigan roadway users to determine their feedback on the DMSs. A series of field case studies were conducted to evaluate specific messages and DMS types, including a laboratory virtual reality (VR) simulation of alternative phasing designs for DMSs. Cost-Benefit analyses of selected cases were conducted to derive conclusions and recommendations on best and cost-effective practices.

7.1 Conclusions

The literature review indicated that the most important measure of DMS effectiveness is the motorists' compliance rate to the specific instructions being communicated (displayed) by the DMS. Although it is challenging to quantitatively measure specific driver responses to the DMS information in a complex driving environment, several methods such as surveys can be used to measure motorists' perceptions and responses that can then be connected with their socioeconomic and trip characteristics. Using empirical data analysis, field observations and laboratory simulations, DMS effectiveness and impacts on traffic flow can be quantified. The literature also indicated that it is very important to convey accurate information to the traveler to ensure the credibility of the DMS and enhance motorists' response and compliance. Factors that have been reported to reduce the credibility of DMS include the display of inaccurate, irrelevant, obvious, repetitive, trivial, erroneous, and poorly designed messages. The review also indicated differences in DMS guidelines among states, for example on prioritization of message requests, prohibited use of DMS, and the use of dynamic elements such as graphics on DMS.

Analysis of the survey of more than 900 users of Michigan roadways showed that, in general, drivers seek different types of trip/route information and use different sources to search for that information after they have started their journey. Traffic conditions and incident information are the travel information most often sought by drivers. Drivers also mostly use internet sources (e.g., smartphones) and DMS to search for different types of information. Guiding traffic during incidents and roadwork are the two road conditions during which drivers stated that DMSs are most useful. In addition, among other factors, understanding DMS content was identified as a significant factor affecting drivers' compliance with DMS messages. This makes perfect sense because compliance is impossible if a message is not understood. Specific DMS design and operation features and characteristics that need high priority in the effort to enhance understanding of DMs content include density of DMS, message phasing, clarity of message characters as well as text color. Although survey participants indicated other color preferences for specific conditions, the analysis showed that the use of yellow color on black background generally increased visibility of the DMS text. Also, participants suggested increasing clarity of messages conveying the location of an incident to avoid confusion.

In general, results from case studies conducted in this study indicated that specific DMS messages influence driver behaviors, consistent with survey results. Specifically:

- Assessment of the impact of the weather-related message on traffic speeds indicated that the message, “ROAD MAY BE SLIPPERY, REDUCE SPEED” resulted in a 5.66 mph reduction in speed on speeding drivers (those approaching the DMS at 80+ mph) just after seeing the message. Similarly, the messages reminding drivers about presence of snow or freezing rain resulted in speed reductions in the segments downstream of the DMS.
- Evaluation of the impact of displaying alternative routes’ travel times on motorists’ decisions found that the base likelihood of diverting to the alternative route increases by 35% when the alternative route is 1 minute faster than the preferred route. This value was obtained after accounting for drivers’ familiarity with the route and traffic volume condition. The finding aligns with the survey results, in which drivers stated that they were using the DMS to seek various information including travel time and they found the information provided by the DMS to be useful.
- Using Portable Changeable Message Sign (PCMS) to inform drivers of lane closure ahead helped traffic flow by increasing the percentage of drivers who merge to the open lane early. Specifically, the percent of vehicles merging early increased by 3.18 percent when the PCMS message about lane closure was on compared to when it was off. Also, due to drivers merging early when the PCMS message was on, there was an average of 5.54 percent reduction in travel time across the work zone compared to when the PCMS message was off.
- Comparison of field travel times observed in the field with those displayed on DMS showed that they were reasonably similar, especially for motorists driving within the speed limit.
- The analysis of overall travel times displayed on DMS indicated that travel time varies more in urban areas, especially areas with high traffic volume. The results also showed that more travel time variations are observed in the daytime since that is when traffic is more dynamic.

A simulation study was conducted using the Virtual Reality (VR) technique to investigate the impact of message phasing time and message length on readability and comprehension by motorists. In Michigan, the ATMS defaults to 4 second phase time and 0.3 seconds between phases when DMS messages are displayed in phases. While the results from the simulation study may not be conclusive due to the sample size of participants, they highlight important findings, specifically:

- There is an association between motorists' speed and the length of the messages displayed in phases on the DMS. The readability of both messages was lower for longer messages than for relatively shorter messages.
- Also, readability of both messages with a phasing time of 4 seconds was lower than when the phasing time was 2.5 seconds.

Analysis of the costs and benefits of DMS associated with changes in driver behavior in response to DMS messages observed through case studies was conducted. Among other findings, the results showed that:

- The travel time savings associated with using PCMS in the work zone to advise drivers of the upcoming lane closure outweigh the cost. The benefits are a function of the amount of traffic (AADT), distance from the PCMS to the beginning of the work zone, and the percentage of trucks in the traffic mix.
- Using DMS to inform drivers of the hazardous weather condition is a cost effective way to reduce potential crashes associated with speeding. The benefits can be realized instantly, especially if two or more weather-related crashes have been observed at the location.
- Displaying travel times of alternative routes saves road users' travel time. The saving benefits outweigh the cost of installing and operating DMS and are especially pronounced when there is an incident in one of the alternative routes.

7.2 Recommendations

The findings from this study are consistent with many previous studies evaluating the effectiveness and impact of DMS in traffic flow. However, a number of findings can lead to adjustments in current MDOT practices to maximize the effectiveness of DMSs. Specifically:

1. When conveying the location of an event (or incident) to drivers using DMS messages, street name suffixes (e.g., St, Rd, etc.) should be used to avoid confusing motorists who are unfamiliar with the location. If possible, include the distance to the incident. Almost 50 percent of survey respondents asked about the clarity of different messages used to convey the location of an incident stated that a message such "CONGESTION AFTER MARKET" was unclear compared to a message such as "CONGESTION AFTER MARKET AVE" or "CONGESTION AHEAD 1 MILE." Page 10 of the November 14, 2019 version of the MDOT Digital Message Sign Guidelines could be revised to reflect this.
2. MDOT should consider automating weather-related messages, in addition to travel times. The case study clearly demonstrated that it is possible to automate the display of weather-related messages using Environmental Sensor Stations (ESS) detections. However, further research should be conducted to identify other practical issues such as location of ESS compared to DMS and automation decision process (e.g., decision thresholds). Automation priority should be given to the messages that recommend specific actions to be taken by motorists based on the detected conditions, for example "ROAD MAY BE SLIPPERY, REDUCE SPEED."
3. Survey participants stated having difficulties reading messages when operated in phases. For example, the ability to read both messages from two screens when DMS message phasing is used was the most problematic DMS feature that drivers mentioned. Also, the simulation study confirmed the existence of potential issues associated with phasing time and message length. There is a need for MDOT to conduct an extensive study to test different phasing designs in the field and laboratory to identify the best designs to implement.

The effectiveness of DMS messages can be affected by driver characteristics, traffic patterns, and geographical area. Using survey results and case study results, the value matrices showing potential traffic-related message types to display by geographic area were created (Figure 7.1 and Figure 7.2). The vertical axis shows the potential effectiveness/usefulness/impacts of a specific message, while the horizontal axis gives the relative efforts/resources needed to collect and process data needed to generate and post the required message. The matrices are divided into four areas. The orange area shows messages that require relatively less effort and resources to generate, but also have relatively lower effectiveness/usefulness/impact. The red area shows messages with that require relatively high effort/resources to generate, but have less effectiveness. Messages in this area may not be necessary. At the top, the green area shows messages that require relatively low effort/resources to generate but have a high effectiveness/usefulness/impact. Messages in this area should be given more priority. Finally, the gray area shows messages that may require relatively high effort/resources to generate but have a very high impact/usefulness. MDOT should also invest in these types of messages. Figure 7.1 shows that in urban areas, work zone messages on PCMS, incident, congestion, weather, and travel time messages were all very useful and influential to motorists' behavior. However, displaying automated weather-related or travel time messages may require higher capital investments related to ESS sensor network and travel time measurements. Also, the results indicated a low impact of safety messages displayed on DMS. Figure 7.2 shows the value matrix for rural areas. As it can be seen, travel time messages may not be very useful because traffic patterns may not be dynamic in rural areas compared to urban areas. This is also true for congestion messages.

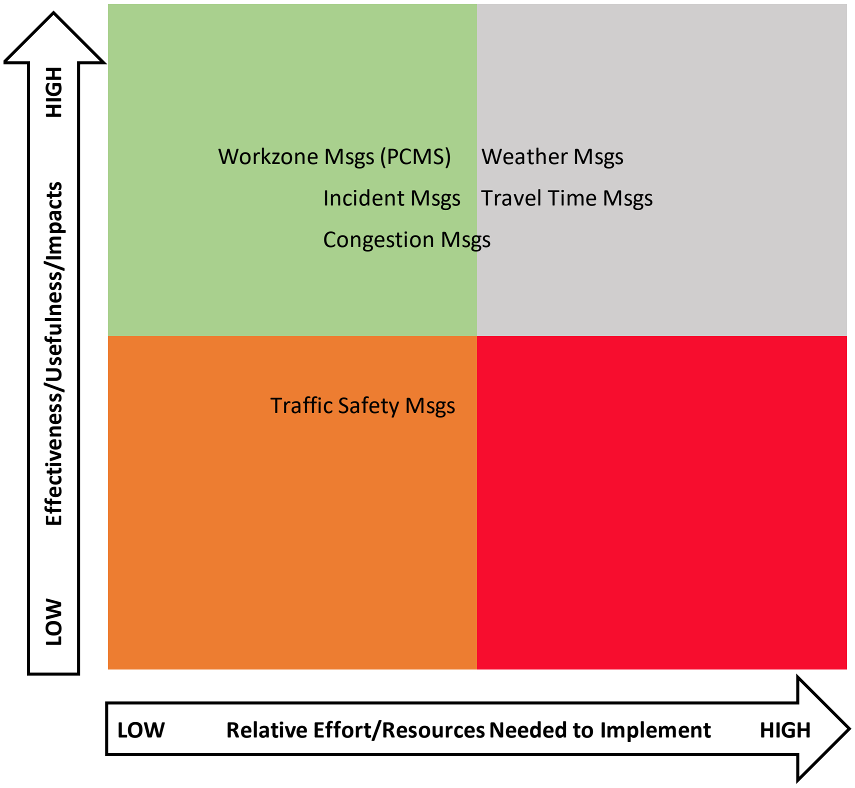


Figure 7.1. Value matrix for DMS use in urban areas

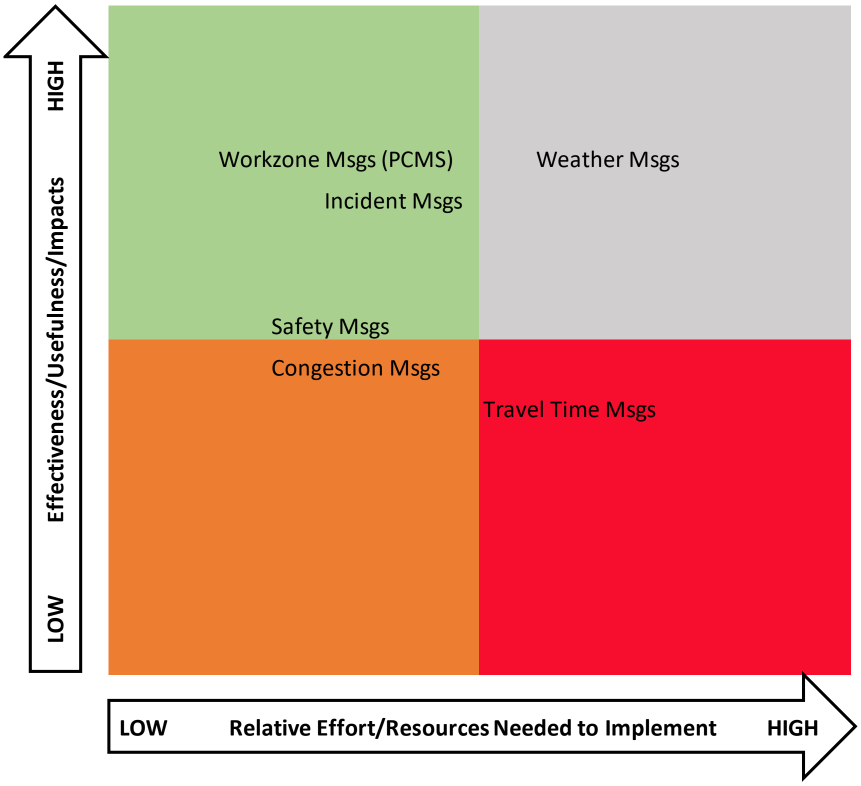


Figure 7.2. Value matrix for DMS use in rural areas

7.3 Study limitations and suggestions for future work

Driver response to DMS messages can be impacted by many factors, including the density of DMS, the message content and how it is presented, and other characteristics of DMS and drivers. Quantifying the impact of DMS may be more accurate if a high percentage (if not all) of DMSs are evaluated using operational and traffic data observed over a long period. MDOT maintains a good database of DMS operational data, such as messages posted at each DMS over time. However, the lack of historical traffic data, especially traffic volumes, makes it impossible to evaluate all DMSs over a long period of time. In this study, assessment of the usability of historical volume data collected by MVDS in the vicinity of DMSs and stored in the ATMS indicated that its accuracy is very low. Therefore, the study relied mostly on manually collected volume, limiting the number of cases that can be evaluated and the duration of evaluation. Therefore, it is recommended that MDOT perform a comprehensive evaluation of its data collection and storage programs to ensure the quality of stored data.

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9 Appendices

9.1 Prohibited message types and displaying techniques

STATE	PROHIBITED MESSAGE TYPES AND DISPLAYING TECHNIQUES
Federal (MUTCD)	•The display format shall not include animation, rapid flashing, or other dynamic elements that are characteristic of sports scoreboards or advertising displays
Alaska	•Public service announcements •Advertising •General security applications originated from homeland security
California	•Advertising messages •Detour motorists to arbitrary route •Message techniques such as fading, flashing, exploding, dissolving, or moving messages •The use of graphics with exception of full matrix sign which can mimic the approved MUTCD standard symbols and legends •Information that is obvious to the motorists •Public service announcements that would adversely affect the respect of the sign
Colorado	•Advertising, animation, rapid flashing, dissolving, exploding, scrolling, or other dynamic elements
Connecticut	•The message phase more than two frame •Legend-Reverse coloring(the only legend allowed is amber characters on a black background) •Advertising •Public Service Announcement (PSA) •Safety campaign messages, unless pre-approved by ConnDOT •Special event messages, unless pre-approved by ConnDOT •Messages containing telephone numbers or web addresses •Time and date only (i.e., not as part of a scheduled event message) •Holiday messages •Personal messages
Maine	•Advertising •General public announcements •Generic messages such as messages with slogans •Date/time/temperature •Normal static signing
Michigan	•Internet addresses and e-mail addresses •Overly simplistic or vague messages should not be displayed alone •Safety campaign messages must be consistent with MDOT policy •The display format shall not include advertising, animation, rapid flashing, dissolving, exploding, scrolling, or other dynamic elements. •Advertising messages shall not be displayed on DMS. •Avoid using messages that may encourage “gawking” by motorist. •Do not provide specific information such as “POLICE SITUATION”
Minnesota	•Diversion: CMS messages shall not divert motorists to specific alternative routes for partial closure of a road unless positive route guidance is available •Message displaying technique: Animation, rapid flashing, dissolving, exploding, scrolling or other dynamic elements
Missouri	•Advertising, animation, rapid flashing, dissolving, exploding, scrolling
Montana	•Flashing-It significantly increase the amount of time required to read the sign
New Mexico	•Static message •Advertising message •General public service announcement (PSA)

	•Contact information •Date and time
New York	•Display format like advertising displays •Animation, rapid flashing, fading, exploding, dissolving or moving messages
Oregon	•Fading, exploding, dissolving, or scrolling shall not be used. The text of messages shall not flash. Arrows can be flashed. Arrows and chevrons may be used. •Graphics not allowed •Advertising messages
Virginia	•Traffic diversion- Avoiding giving hard detours to divert motorists to specific alternate routes unless positive route guidance is available. •Generic congestion message •Advertising •Public service announcements •Contact information •Date/time •Static signing
Wisconsin	•Flashing messages •Graphic, symbols and animation •General weather reports •Slogans in safety messages

9.2 DMS message prioritization by state

STATE	MESSAGE PRIORITY
Alaska	1.Emergencies 2.AMBER alerts 3.Road closure 4.Road surfaces(ice, mud, water, pavement failure, etc..) 5.Weather 6.Events 7.Safety campaigns 8.Construction (Non-closure events)
California	1. Incident Ahead 2. Lane Closures/Work Zones 3. Weather-Related 4. Special Events 5. AMBER Alert 6. Blue Alert 7. Future Lane/Ramp Closures 8. Travel Times 9. Safety Campaigns 10. Emergency Security Message(varies depending on other co-occurring events)
Colorado	1. Safety Messages (Road Closed, Accident Ahead, Merge Right 2. Regulatory (Chain Laws) 3. Amber Alert 4. Travel Times/Chain Station location (Where applicable) 5. Public Service Messages. (Parking ahead, Click it or Ticket etc.)
Michigan	1.High impact events (Full freeway closure, ramp closures, lane closure, blocking incidents) 2.Medium impact (congestion/ramp backups, short-term work zone, weather condition and NWS alerts) 3.Public service announcement(AMBER, weather, safety messages) 4.Travel times
Minnesota	1.Incident management 2.Work zone applications 3.Travel times 4.Adverse weather, environmental or roadway condition 5.Special events 6.Abducted child alert 7.Traffic safety campaigns 8.Test messages
Missouri	1. Emergencies, such as evacuations or closures 2. Hazardous and/or uncommon road conditions 3.Traveler information and suggested alternative routes for delay 4. AMBER or Blue Alerts originating in the local area 5.Travel times 6.AMBER or Blue Alerts originating outside the local area 7.Ozone alerts 8.Advance data or time notice for scheduled events 9.Public service messages that improve highway safety and reduce congestion 10. Safety messages

Montana	1.Roadway and Ramp Closures 2.Traffic Incidents/Accidents 3.Road Weather Advisories 4.AMBER Alert 5.Public Safety Messages (during campaign periods) 6.Test Messages 7.Blank
New Mexico	1.Roads or lanes(s) or ramp closures 2.Incidents and crashes 3.Adverse weather or environmental conditions 4.AMBER alerts 5.Emergency security messages 6.Special events traveler information 7.Construction or maintenance operations 8.Travel time and travel-related information 9.Special public safety messages 10.Test messages
Oregon	1. Drawbridge operations, road or ramp closures, and emergency situations; 2. Incident or crash; 3. Adverse weather or environmental conditions and related regulations such as chain restriction information; 4. Construction or maintenance operations; 5. Amber Alert message (see Supplement D); 6. Traffic operations information associated with special events such as car shows or sports events; 7. Travel time information; 8. Special public safety messages approved by the State Traffic Engineer; 9. Travel-related information directed at individual vehicles such as commercial trucks, 10. Public Service Announcements approved by the State Traffic Engineer.
Virginia	1.Event impacting a lane (traffic incidents and crashes, debris, road/ramp closures, traffic detour etc..) 2.Dedicated lane control(Reversible roadway critical signs, active traffic management, hard shoulder running, HOV lanes) 3.Lane control 4.Travel advisory messages 5.Events not impacting a lane (traffic incidents and crashes) 6.Weather warnings 7.Special event management(soft diversion) 8.Emergency alert(AMBER, Senior, Leo) 9.Future impacts 10.Environmental messages 11.Campaign messages 12.Public service announcements
Wisconsin	1.Incident/Weather/Emergency 2.Amber Alert or Silver Alert 3.Roadwork (construction and maintenance) 4.General traffic flow conditions 5.Current travel times 6.Current special events 7.Future occurrences (according to chronological date) 8.Transportation-related messages such as safety messages

9.3 Motorists survey questionnaire

1- Are you a licensed driver?

○ Yes

○ No

2- Have you ever seen roadway message signs like these at freeway in **<u>Michigan while driving</u>**? *They are called* ***Dynamic Message Signs (DMS).***

○ Yes

○ No

○ I am not sure

Trip Characteristics

Please answer the following questions about your general experience when making any freeway trip in Michigan

3- What type of vehicle do you usually drive?

○ Passenger Car (e.g. Sedan, Van, SUV, Small Pickup, etc.)

○ Commercial Vehicle (e.g. Bus, Truck, etc.)

○ Motorcycle

4- How frequently do you seek and/or use the following trip and route information (if available) **after** starting the journey?

	Always	Most of the time	About half the time	Sometimes	Never
Travel Time	○	○	○	○	○
Direction	○	○	○	○	○
Weather	○	○	○	○	○
Traffic Condition (e.g. Congestion and Backup)	○	○	○	○	○
Incidents (e.g. Work zone and Crash)	○	○	○	○	○
Other (please specify)	○	○	○	○	○

5- Which source(s) would you likely use (if available) for trip and route information **after** starting the journey?

	Extremely likely	Somewhat likely	Neither likely nor unlikely	Somewhat unlikely	Extremely unlikely
Dynamic Message Signs	○	○	○	○	○
Smart Phone or Tablet App/Internet (e.g., Mi Drive, Google Map, Waze, etc.)	○	○	○	○	○
Car Navigation (i.e., GPS)	○	○	○	○	○
Radio	○	○	○	○	○
Telephone	○	○	○	○	○
Other (please specify)	○	○	○	○	○

Drivers' Behavior Towards Dynamic Message Signs (DMS)

6- Please, indicate how much you agree with the following statements about Dynamic Message Signs **while driving in Michigan**

	Strongly agree	Somewhat agree	Neither agree nor disagree	Somewhat disagree	Strongly disagree
I often notice one or more Dynamic Message Signs on a trip.	○	○	○	○	○
I usually can read the entire message on Dynamic Message Signs.	○	○	○	○	○
I usually understand the Dynamic Message Sign's content.	○	○	○	○	○
The characters on Dynamic Message Signs are usually clear.	○	○	○	○	○
The yellow color used for Dynamic Message Signs characters increase the visibility of the message.	○	○	○	○	○
I prefer the overhead location for the Dynamic Message Signs rather than at the side of the road.	○	○	○	○	○
The travel time information on the Dynamic Message Signs is reasonably accurate.	○	○	○	○	○

7- Please provide your reasons for disagreeing with the following statements

-
- I often notice one or more Dynamic Message Signs on a trip ____
-
- I can read the entire message on Dynamic Message Signs ____
-
- I usually understand the Dynamic Message Sign's content ____
-
- The characters on Dynamic Message Signs are usually clear ____
-
- The yellow color used for Dynamic Message Signs characters increases the visibility of the message ____
-
- I prefer the overhead location for the Dynamic Message Sign rather than at the side of the road ____
-
- The travel time information on the Dynamic Message Sign is reasonably accurate ____

8- In your opinion, how useful are the Dynamic Message Signs in providing guidance to traffic in the following events in **Michigan roadway**?

	Extremely useful	Very useful	Moderately useful	Slightly useful	Not at all useful
Congestion/ Ramp Back-ups	○	○	○	○	○
Lane closure due to roadwork	○	○	○	○	○
Full roadway closure due to roadwork	○	○	○	○	○
Roadway blockage because of an incident (e.g. Crash, Broken vehicle, etc.)	○	○	○	○	○
Lane blockage because of an incident (e.g. Crash, Broken vehicle, etc.)	○	○	○	○	○
Inclement weather that affect traffic and safety	○	○	○	○	○
Real travel time or delay information	○	○	○	○	○
Traffic safety message (e.g. Reduce speed on wet pavement)	○	○	○	○	○

9- Given a specific roadway event in Michigan roadway, if there is a Dynamic Message Sign displaying a message with a recommended action for drivers to take (underlined in the messages below), how likely would you take the recommended action?

Event: Congestion/ Ramp Back-ups

	Extremely likely	Somewhat likely	Neither likely nor unlikely	Somewhat unlikely	Extremely unlikely
Heavy congestion ahead **<u>Watch for backups</u>**	○	○	○	○	○
Slow traffic Ahead **<u>use caution</u>**	○	○	○	○	○
Slow traffic Ahead **<u>Reduce speed</u>**	○	○	○	○	○

Event: Lane closure due to roadwork

	Extremely likely	Somewhat likely	Neither likely nor unlikely	Somewhat unlikely	Extremely unlikely
LEFT LANE CLOSED AT US-10 EXIT 162 **WATCH FOR BACKUPS**	○	○	○	○	○
RAMP CLOSED TO M-6 EAST **SEEK ALTERNATE ROUTE**	○	○	○	○	○
EXIT CLOSED TO COOPER ST EXIT 139 **FOLLOW DETOUR**	○	○	○	○	○
RIGHT 2 LANES CLOSED AHEAD **USE CAUTION**	○	○	○	○	○
ROAD WORK AHEAD **BE PREPARED TO STOP**	○	○	○	○	○
LEFT LANE CLOSED AFTER EXIT 98 **BE ALERT FOR WORKERS**	○	○	○	○	○

Event: Lane blockage because of incident (e.g. Crash, Broken Vehicle, etc)

	Extremely likely	Somewhat likely	Neither likely nor unlikely	Somewhat unlikely	Extremely unlikely
LEFT 2 LANES BLOCKED AT MILLER RD EXIT 117 **USE I-475 NORTH EXIT 111**	○	○	○	○	○
RIGHT LANE BLOCKED AHEAD **USE CAUTION MERGE LEFT**	○	○	○	○	○
ONLY CENTER LANE OPEN **USE CAUTION**	○	○	○	○	○
LEFT LANE BLOCKED AHEAD **WATCH FOR BACKUPS**	○	○	○	○	○
RIGHT LANE BLOCKED AT LEE RD EXIT 58 **BE PREPARED TO STOP**	○	○	○	○	○

Event: Inclement weather that affects traffic

	Extremely likely	Somewhat likely	Neither likely nor unlikely	Somewhat unlikely	Extremely unlikely
EXTREME COLD STARTS TODAY **<u>PLAN AHEAD</u>**	○	○	○	○	○
SLIPPERY ROAD CONDITIONS **<u>REDUCE TRAVEL SPEEDS</u>**	○	○	○	○	○
SNOW SQUALL ADVISORY **<u>USE EXTREME CAUTION</u>**	○	○	○	○	○
WINTER WEATHER ADVISORY IN EFFECT **<u>INCREASE FOLLOWING DISTANCE</u>**	○	○	○	○	○
REDUCE SPEED ON WET PAVEMENT **<u>AVOID USING CRUISE CONTROL</u>**	○	○	○	○	○
WINTER WEATHER ADVISORY IN EFFECT **<u>STAY ALERT</u>** DON'T GET CAUGHT OFF GUARD	○	○	○	○	○
IN WINTER WEATHER **<u>REDUCE SPEED CRASHES 2X AS LIKELY</u>**	○	○	○	○	○

10- Suppose you are driving on I-196 in east direction (indicated by the red arrow) shown in the figure below. A Dynamic Message Sign (shown by the red circle) is information intended to inform drivers about the current congestion at the segment between Market intended to inform drivers about the current congestion at the segment between Market Ave SW and Butterworth St (shown by blue color).

How clear are the following Dynamic Message Signs messages in conveying the location of this congestion?

	Extremely clear	Somewhat clear	Neither clear nor unclear	Somewhat unclear	Extremely unclear
CONGESTION AFTER MARKET	○	○	○	○	○
CONGESTION AFTER MARKET AVE	○	○	○	○	○
CONGESTION AHEAD	○	○	○	○	○
CONGESTION START AFTER MARKET AVE	○	○	○	○	○
CONGESTION AHEAD 1 MILE	○	○	○	○	○
CONGESTION BEYOND MARKET AVE	○	○	○	○	○
CONGESTION AFTER NEXT EXIT	○	○	○	○	○
CONGESTION MARKET AVE TO BUTTERWORTH ST	○	○	○	○	○

11- Do you use smartphone apps for navigation purpose (e.g. Google Map, Waze, etc.) while driving?

○ Yes, I use almost always.

○ Yes, I use only when I need.

○ No, I have a smartphone, but do not use because I do not need it.

○ I have a smartphone and want to use, but I do not know how.

○ No, I do not use because I do not have a smart phone.

12- Please provide any other opinion/suggestion/concern about Dynamic Message Signs in Michigan.

____

____

____

____

____

Demographic Information
Please provide the following information:

13- Home Postcode:

____

14- Work/Typical Destination Postcode:

____

15- Gender

○ Male

○ Female

○ Other ____

○ Prefer Not to Say

-

16-Age Group:

○ 16 – 20 Years

○ 21 – 24 Years

○ 25 – 40 Years

○ 41 – 59 Years

○ 60 – 64 Years

○ 65 Years and Older

○ Prefer Not to Say

17-Years of Driving Experience:

○ 0 – 5

○ 6 - 10

○ 11 - 15

○ More than 15

9.4 Impact of age on drivers’ survey responses

Age	Unlikely	Neutral	Likely
Source of information drivers used to seek trip/route information			
Internet sources (X^2 =27.295 ; P = 0.001**)			
Young drivers	3%	8%	89%
Middle age drivers	8%	4%	88%
Older drivers	18%	6%	75%
Telephone (X^2 = 15.442 ; P = 0.051*)			
Young drivers	74%	9%	17%
Middle age drivers	70%	15%	15%
Older drivers	59%	16%	25%
Compliance with recommended actions during congestion related messages			
Slow traffic ahead use caution (X^2 =20.319 ; P = 0.009**)			
Young drivers	8%	11%	82%
Middle age drivers	7%	10%	83%
Older drivers	6%	6%	88%
Slow traffic ahead reduce speed (X^2 =29.097 ; P = 0.000**)			
Young drivers	5%	21%	74%
Middle age drivers	9%	9%	83%
Older drivers	5%	9%	87%
Compliance with recommended actions during lane closure due to roadwork			
Watch for backups (X^2 =26.097 ; P = 0.001**)			
Young drivers	3%	8%	89%
Middle age drivers	5%	5%	90%
Older drivers	3%	3%	94%
Use caution (X^2 =27.295 ; P = 0.002**)			
Young drivers	3%	5%	92%
Middle age drivers	3%	6%	90%
Older drivers	3%	5%	92%
Be prepared to stop (X^2 =18.197 ; P = 0.001**)			
Young drivers	8%	8%	84%
Middle age drivers	7%	7%	86%
Older drivers	3%	6%	91%
Be alert for workers (X^2 =15.240 ; P = 0.055*)			
Young drivers	5%	11%	84%
Middle age drivers	6%	8%	86%
Older drivers	3%	7%	90%
Compliance with recommended actions during lane blockage because of incident			
Use caution/Merge left (X^2 =13.450; P = 0.097*)			
Young drivers	0%	0%	100%
Middle age drivers	3%	4%	93%

Older drivers	2%	4%	94%
Use caution (X^2 =15.157 ; P = 0.056*)			
Young drivers	0%	3%	97%
Middle age drivers	4%	7%	89%
Older drivers	3%	4%	93%
Watch for backups (X^2 =23.127 ; P = 0.003**)			
Young drivers	3%	3%	95%
Middle age drivers	5%	6%	88%
Older drivers	3%	6%	90%
Be prepared to stop (X^2 =17.784; P = 0.023**)			
Young drivers	3%	3%	95%
Middle age drivers	4%	6%	90%
Older drivers	3%	4%	93%
Compliance with recommended actions during inclement weather that affects traffic			
Stay alert (X^2 =15.379 ; P = 0.052*)			
Young drivers	8%	14%	78%
Middle age drivers	25%	21%	54%
Older drivers	21%	18%	61%

9.5 Impact of gender on drivers’ responses

Types of trip/route information drivers sought before start of the journey			
Gender	Never	At least once	
Traffic condition **(X^2 = 7.819 : P = 0.098*)**			
Male	6%	94%	
Female	4%	96%	
Incident **(X^2 = 16.723 : P = 0.002**)**			
Male	5%	95%	
Female	4%	96%	
Usefulness of DMS to guide traffic during different road conditions and scenarios			
	Not useful	Useful	
Congestion and ramp back-ups **(X^2 = 11.531 : P = 0.021**)**			
Male	5%	95%	
Female	1%	99%	
Lane closure due to roadwork **(X^2 = 14.74 : P = 0.005**)**			
Male	4%	96%	
Female	1%	99%	
Full road closure due to roadwork **(X^2 = 12.279 : P = 0.015**)**			
Male	3%	97%	
Female	0%	100%	
Lane blockage because of an incident **(X^2 = 8.104 : P = 0.088*)**			
Male	4%	96%	
Female	1%	99%	
Inclement weather that affects traffic and safety **(X^2 = 21.039 : P = 0.000**)**			
Male	8%	92%	
Female	4%	96%	
Real travel time or delay information **(X^2 = 11.234 : P = 0.024**)**			
Male	8%	92%	
Female	4%	96%	
Traffic safety messages **(X^2 = 39.132 : P = 0.000**)**			
Male	20%	80%	
Female	10%	90%	
Drivers opinions on DMS design and operation features and characteristics			
	Disagree	Neither agree nor disagree	Agree
Ability to read both messages from two screen (two phases) **(X^2 = 10.201 : P = 0.037**)**			
Male	24%	16%	61%
Female	34%	12%	54%
Source of information drivers use to seek trip/route information			
	Unlikely	Neutral	Likely
DMS **(X^2 = 8.531 : P = 0.074*)**			

Male	14%	7%	79%
Female	9%	6%	85%
Telephone (X^2 = 27.607 : P = 0.000**)			
Male	11%	6%	83%
Female	12%	3%	85%
Compliance with recommended actions during congestion/Ramp back-ups			
Heavy congestion ahead watch for backups (X^2 = 20.808 : P = 0.000**)			
Male	5%	6%	89%
Female	2%	3%	94%
Slow traffic ahead use caution (X^2 = 51.513: P = 0.000**)			
Male	7%	10%	83%
Female	4%	6%	90%
Slow traffic ahead reduce speed (X^2 = 45.006 : P = 0.000**)			
Male	8%	12%	80%
Female	4%	4%	92%
Compliance with recommended actions during lane closure messages due to roadwork			
Watch for backups (X^2 = 17.069 : P = 0.002**)			
Male	5%	4%	91%
Female	2%	5%	93%
Seek alternative route (X^2 = 12.204 : P = 0.016**)			
Male	6%	4%	90%
Female	2%	5%	93%
Follow detour (X^2 = 16.380 : P = 0.003**)			
Male	5%	4%	91%
Female	2%	5%	93%
Use caution (X^2 = 14.971 : P = 0.005**)			
Male	4%	6%	90%
Female	2%	5%	93%
Be prepared to stop (X^2 = 32.696 : P = 0.000**)			
Male	7%	7%	86%
Female	2%	6%	92%
Be alert for workers (X^2 = 31.019 : P = 0.000**)			
Male	6%	10%	84%
Female	3%	4%	94%
Compliance with recommended actions during lane blockage because of incident			
Use I-475/North/Exit 111 (X^2 = 14.792 : P = 0.005**)			
Male	6%	5%	90%
Female	2%	2%	96%
Use caution/Merge left (X^2 = 21.324 : P = 0.000**)			
Male	4%	4%	93%
Female	1%	2%	97%
Use caution (X^2 = 29.168 : P = 0.000**)			

Male	4%	6%	90%
Female	2%	5%	93%
Watch for backups (X^2 = 26.692 : P = 0.000**)			
Male	5%	7%	88%
Female	3%	4%	93%
Be prepared to stop (X^2 = 15.829 : P = 0.003**)			
Male	4%	6%	90%
Female	2%	4%	94%
Compliance with recommended actions during inclement weather that affects traffic			
Plan ahead (X^2 = 21.563 : P = 0.000**)			
Male	31%	28%	40%
Female	20%	26%	55%
Reduce travel speeds (X^2 = 65.515 : P = 0.000**)			
Male	16%	17%	67%
Female	7%	7%	87%
Use extreme caution (X^2 = 33.823 : P = 0.000**)			
Male	14%	12%	74%
Female	5%	8%	87%
Increase following distance (X^2 = 45.898 : P = 0.000**)			
Male	16%	20%	63%
Female	9%	10%	81%
Avoid using cruise control (X^2 = 52.284 : P = 0.000**)			
Male	24%	22%	53%
Female	12%	12%	76%
Stay alert (X^2 = 28.967 : P = 0.000**)			
Male	25%	23%	52%
Female	16%	15%	70%
Reduce speed crashes 2x as likely (X^2 = 33.202 : P = 0.000**)			
Male	28%	23%	49%
Female	16%	18%	66%

9.6 Message automation matrix using ESS data (Grand Region)

Precipitation type	NTCIP	Visibility (mile)	Wind (mph)	Auto Response Name	Library Message Name	Priority	Phase 1	Phase 2
Light Snow	7	>0.9		GRAND ESS 92nd-1	GRAND ESS 92nd-1	Low	LIGHT SNOW DETECTED AT M-179(EXIT 61)	
Moderate Snow	8	>0.9		GRAND ESS 92nd-2	GRAND ESS 92nd-2	Medium	MODERATE SNOW DETECTED AT M-179(EXIT 61)	
Heavy Snow	9			GRAND ESS 92nd-3	GRAND ESS 92nd-3	Medium	HEAVY SNOW DETECTED AT M-179(EXIT 61)	
Moderate Snow	8	<1	Gust>25	GRAND ESS 92nd-4	GRAND ESS 92nd-4	Medium	BLOWING SNOW DETECTED AT M-179(EXIT 61)	
Heavy Snow	9	<1	Gust>25	GRAND ESS 92nd-4.1	GRAND ESS 92nd-4.1	Medium	BLOWING SNOW DETECTED AT M-179(EXIT 61)	
Light Snow	7	<1	Gust>25	GRAND ESS 92nd-4.2	GRAND ESS 92nd-4.2	Medium	BLOWING SNOW DETECTED AT M-179(EXIT 61)	
Heavy Rain	12			GRAND ESS 92nd-5	GRAND ESS 92nd-5	Low	HEAVY RAIN DETECTED AT M-179(EXIT 61)	REDUCE SPEED ON WET PAVEMENT
Light Freezing Rain	13			GRAND ESS 92nd-6	GRAND ESS 92nd-6	Medium	FREEZING RAIN DETECTED AT M-179(EXIT 61)	KEEP A SAFE FOLLOWING DISTANCE
Moderate Freezing Rain	14			GRAND ESS 92nd-6.1	GRAND ESS 92nd-6	Medium	FREEZING RAIN DETECTED AT M-179(EXIT 61)	KEEP A SAFE FOLLOWING DISTANCE
Heavy Freezing Rain	15			GRAND ESS 92nd-6.2	GRAND ESS 92nd-6	Medium	FREEZING RAIN DETECTED AT M-179(EXIT 61)	KEEP A SAFE FOLLOWING DISTANCE
No Precipitation	3	<1		GRAND ESS 92nd-7	GRAND ESS 92nd-7	Low	LOW VISIBILITY DETECTED AT M-179(EXIT 61)	HEADLIGHTS ON BE SAFE BE SEEN
Light Unidentified	4			GRAND ESS 92nd-8	GRAND ESS 92nd-8	Low	SLEET DETECTED AT M-179(EXIT 61)	KEEP A SAFE FOLLOWING DISTANCE
Moderate Unidentified	5			GRAND ESS 92nd-8.1	GRAND ESS 92nd-8	Low	SLEET DETECTED AT M-179(EXIT 61)	KEEP A SAFE FOLLOWING DISTANCE
Heavy Unidentified	6			GRAND ESS 92nd-8.2	GRAND ESS 92nd-8	Low	SLEET DETECTED AT M-179(EXIT 61)	KEEP A SAFE FOLLOWING DISTANCE

9.7 TMC segments used for speed data analysis

Segment	County	Distance (miles)	Zip Code	Start Latitude	Start longitude	End Latitude	End Longitude
1	Kent	0.298	49548	42.83307	-85.67569	42.82904000	-85.67360000
2	Kent	0.339	49548	42.82904	-85.67360	42.82448000	-85.67115000
3	Kent	0.686	49548	42.82448	-85.67115	42.81478000	-85.66901000
4	Kent	0.360	49315	42.81478	-85.66901	42.80957000	-85.66894000
5	Kent	1.676	49315	42.80957	-85.66894	42.78531000	-85.66834000
6	Kent	0.343	49315	42.78531	-85.66834	42.78037000	-85.66884000
7	Kent	0.736	49315	42.78037	-85.66884	42.76991002	-85.67155999
8	Kent	0.122	49315	42.76991	-85.67156	42.76818000	-85.67200000
9	Allegan	0.267	49323	42.76818	-85.67200	42.76438000	-85.67299000
10	Allegan	2.568	49323	42.76438	-85.67299	42.72726000	-85.67311000
11	Allegan	0.297	49323	42.72726	-85.67311	42.72311000	-85.67162000
12	Allegan	3.339	49348	42.72311	-85.67162	42.67701000	-85.66116000
13	Allegan	0.368	49328	42.67701	-85.66116	42.67169000	-85.66152000
14	Allegan	2.687	49348	42.67169	-85.66152	42.63281000	-85.66240000
15	Allegan	0.293	49344	42.63281	-85.66240	42.62857000	-85.66245000

9.8 Intermediate questionnaire for simulation study

Did you notice the Dynamic Message Sign?

☐ Yes ☐ No ☐ I am not sure (DMS1)
☐ Yes ☐ No ☐ I am not sure (DMS2)
☐ Yes ☐ No ☐ I am not sure (DMS3)
☐ Yes ☐ No ☐ I am not sure (DMS4)

Were you able to read the entire message displayed on subsequent screens of the Dynamic Message Sign?

☐ Yes ☐ No ☐ I am not sure (DMS1)
☐ Yes ☐ No ☐ I am not sure (DMS2)
☐ Yes ☐ No ☐ I am not sure (DMS3)
☐ Yes ☐ No ☐ I am not sure (DMS4)

- **If the answer is Yes (was able to read the entire message): Can you recall it?**

☐ Yes ☐ No ☐ I am not sure (DMS1)
☐ Yes ☐ No ☐ I am not sure (DMS2)
☐ Yes ☐ No ☐ I am not sure (DMS3)
☐ Yes ☐ No ☐ I am not sure (DMS4)

If the answer is Yes (can recall): **What did the messages say?**

-- (DMS1)

-- (DMS2)

-- (DMS3)

-- (DMS4)

If the answer is No/ I am not sure (cannot recall):

Please choose the reason why you cannot recall them?

	DMS1	DMS2	DMS3	DMS4
The DMS's messages were complicated.				
The display time for DMS's messages was too short.				
The display time for DMS's messages was too long.				
Other (please specify)				

If the answer is No/ I am not sure (was not able to read the entire message on two screens):

Were you able to read the message on one of the screens?

☐ Yes ☐ No ☐ I am not sure (DMS1)
☐ Yes ☐ No ☐ I am not sure (DMS2)
☐ Yes ☐ No ☐ I am not sure (DMS3)
☐ Yes ☐ No ☐ I am not sure (DMS4)

If the answer is Yes (was able to read one message): **Can you recall it?**
☐ Yes ☐ No ☐ I am not sure (DMS1)

☐ Yes ☐ No ☐ I am not sure (DMS2)
☐ Yes ☐ No ☐ I am not sure (DMS3)
☐ Yes ☐ No ☐ I am not sure (DMS4)

If the answer is Yes (can recall): **What did the message say?**
--- (DMS1)
--- (DMS2)
--- (DMS3)
--- (DMS4)

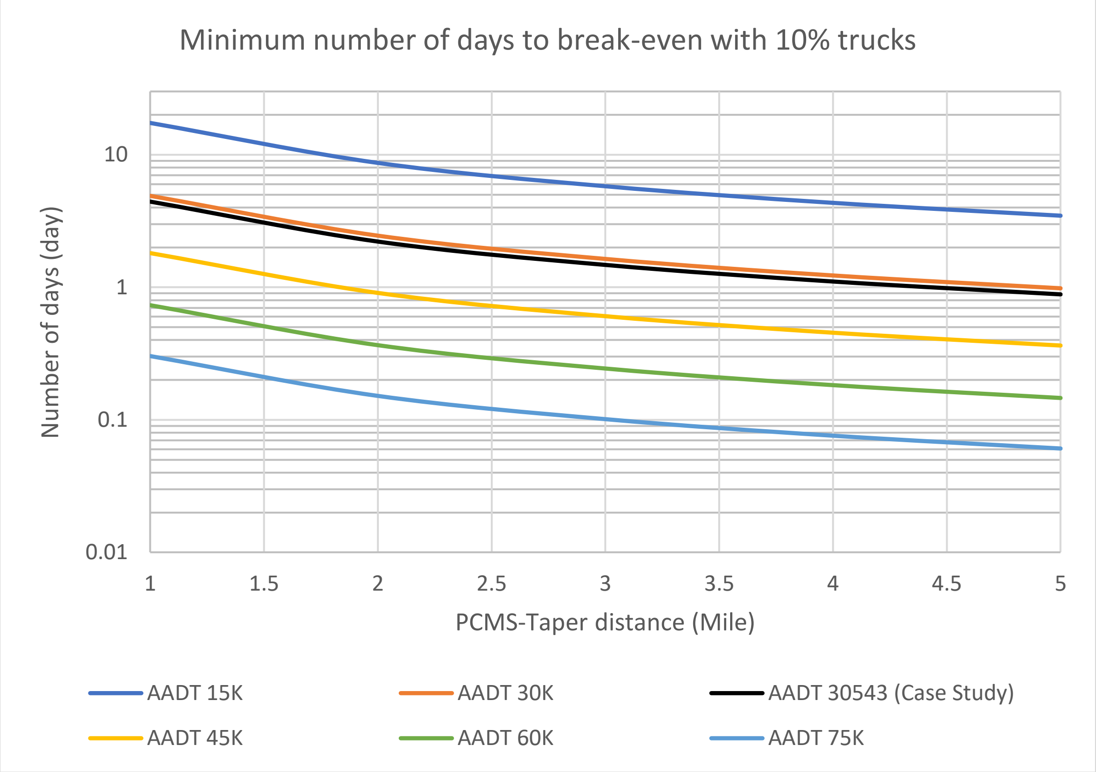
If the answer is No/ I am not sure (cannot recall): **Please choose the reason why you cannot recall it?**

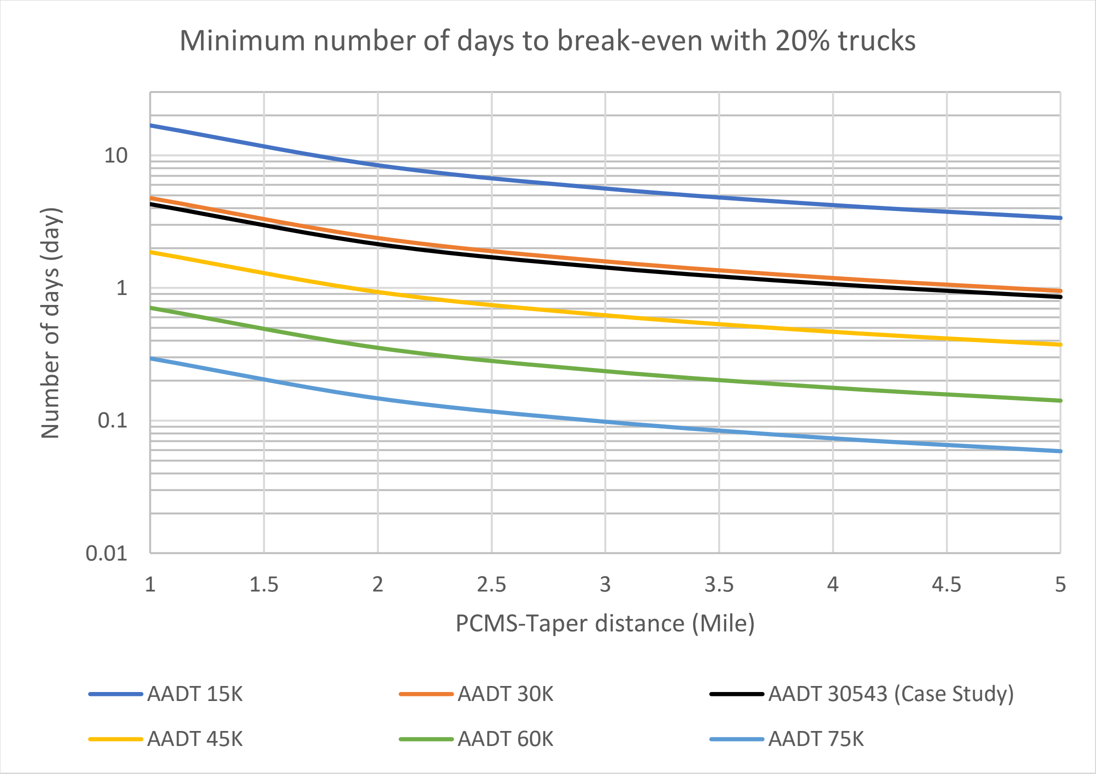
	DMS1	DMS2	DMS3	DMS4
The DMS's messages were complicated.				
The display time for DMS's messages was too short.				
The display time for DMS's messages was too long.				
Other (please specify)				

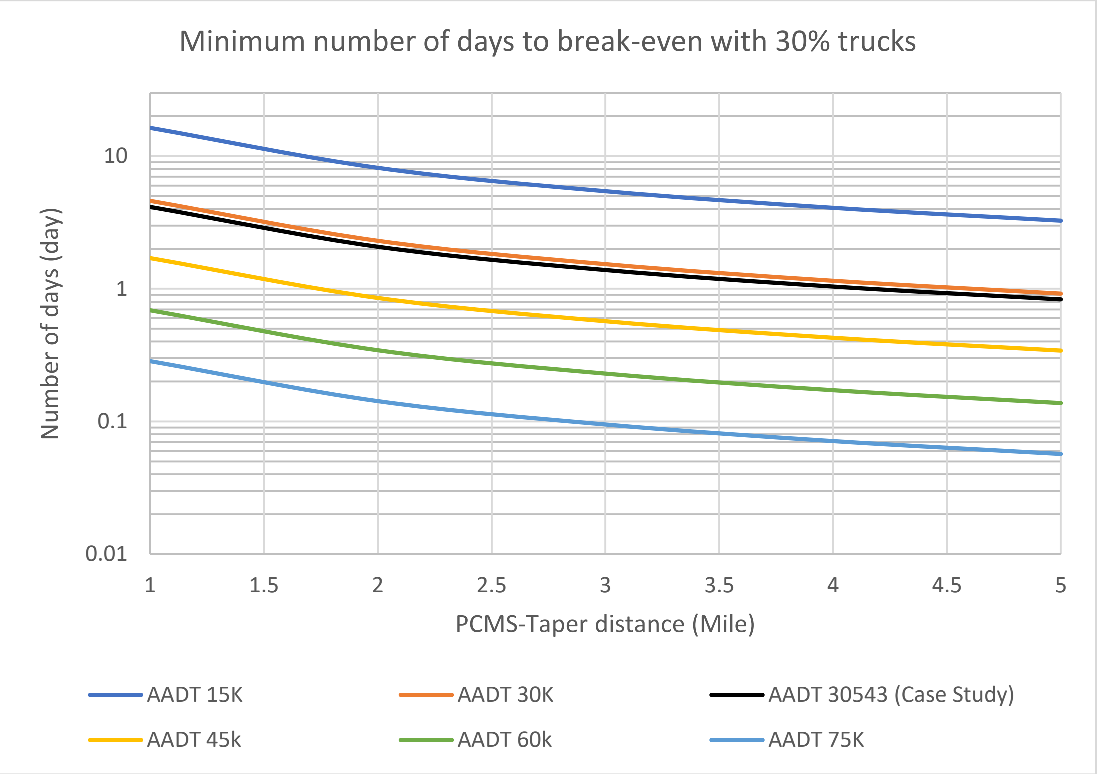
If the answer is No/ I am not sure (was not able to read one message):
Why you were not able to read the DMS message?
Please choose the reason why you cannot recall them?

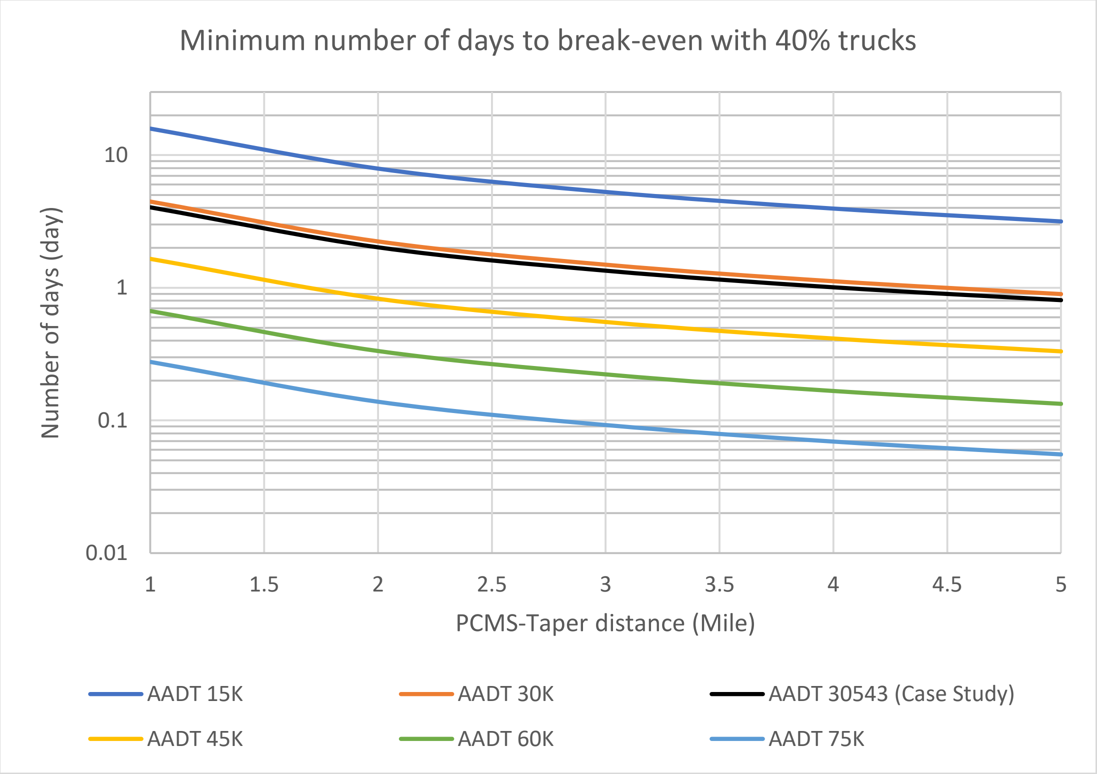
	DMS1	DMS2	DMS3	DMS4
The DMS's messages were complicated.				
The display time for DMS's messages was too short.				
The display time for DMS's messages was too long.				
Other (please specify)				

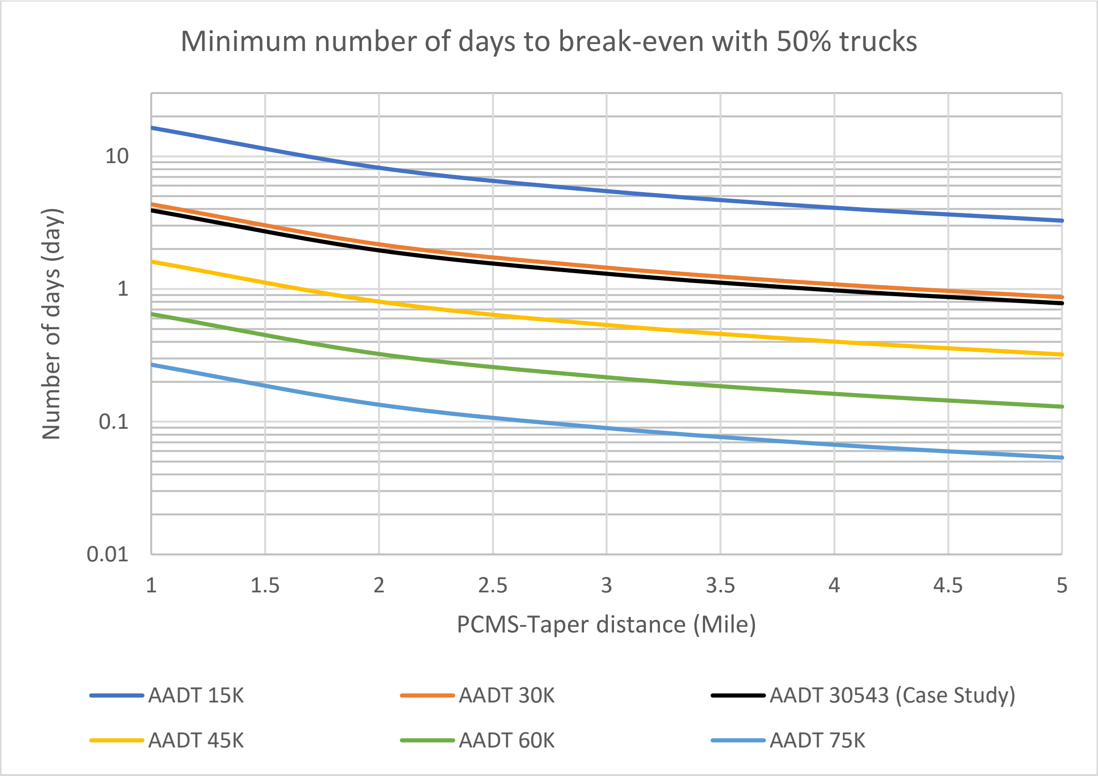
9.9 Work zone BCR for different truck percentages



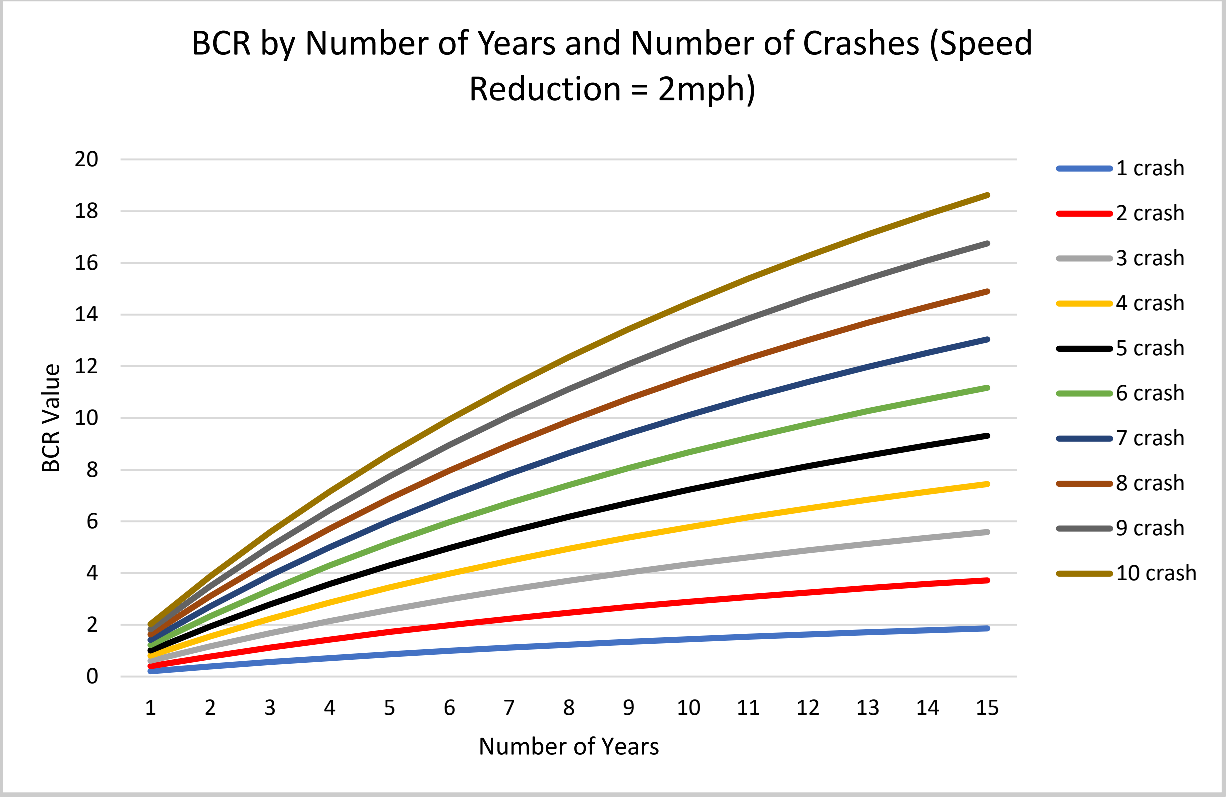


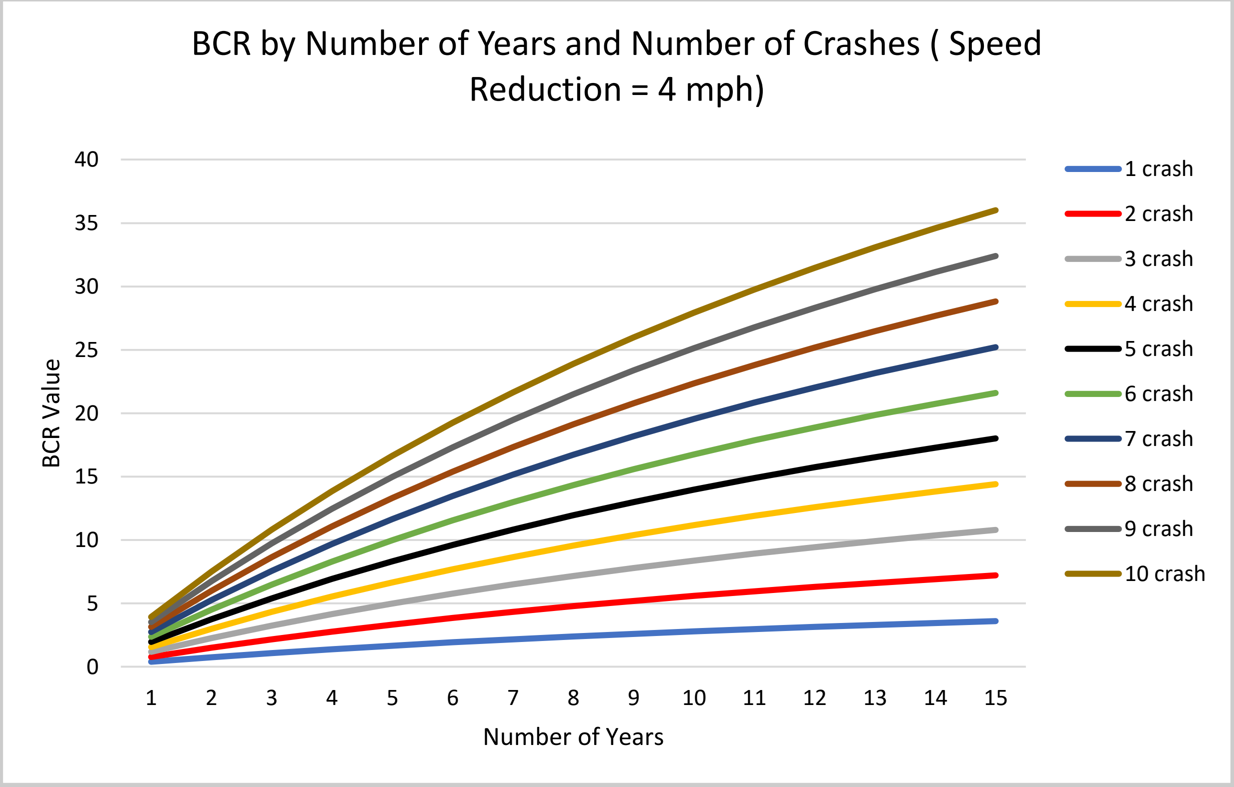

Minimum number of days to break-even with 30% trucks
Number of days (day)
10
1
0.1
0.01
1
1.5
2
2.5
3
3.5
4
4.5
5
PCMS-Taper distance (Mile)
AADT 15K
AADT 30K
AADT 30543 (Case Study)
AADT 45k
AADT 60k
AADT 75K

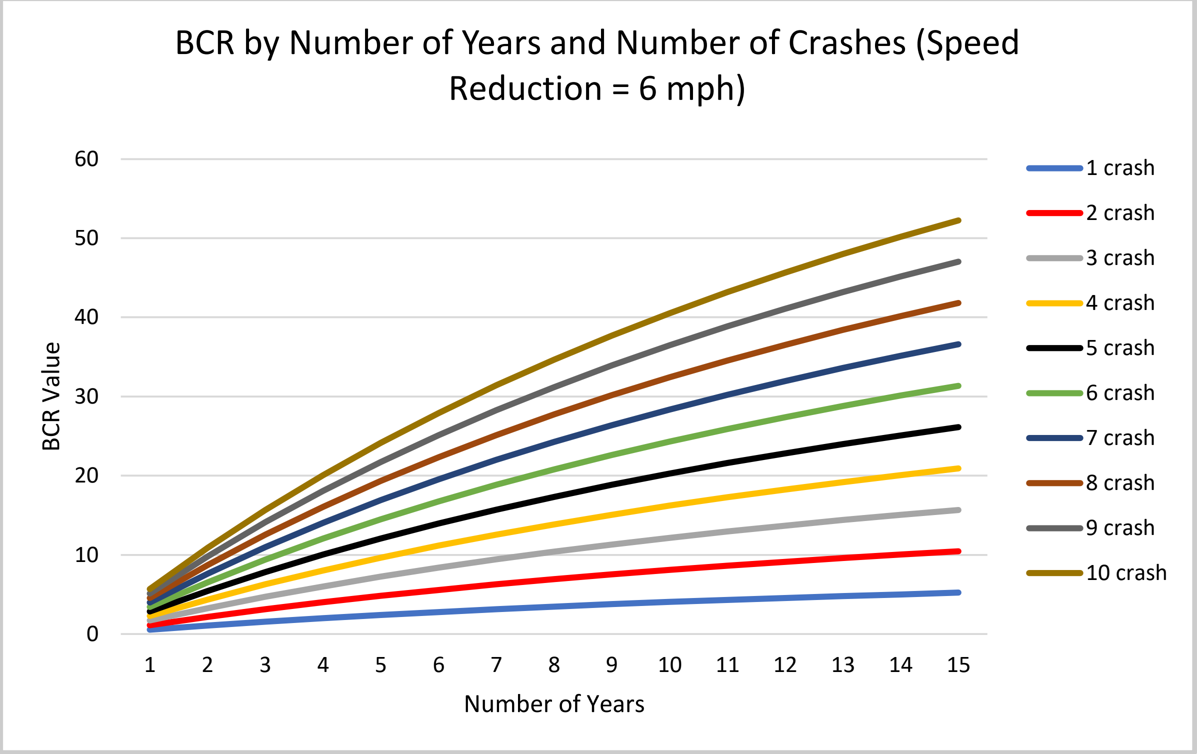

Minimum number of days to break-even with 40% trucks
Number of days (day)
10
1
0.1
0.01
1
1.5
2
2.5
3
3.5
4
4.5
5
PCMS-Taper distance (Mile)
AADT 15K
AADT 30K
AADT 30543 (Case Study)
AADT 45K
AADT 60K
AADT 75K

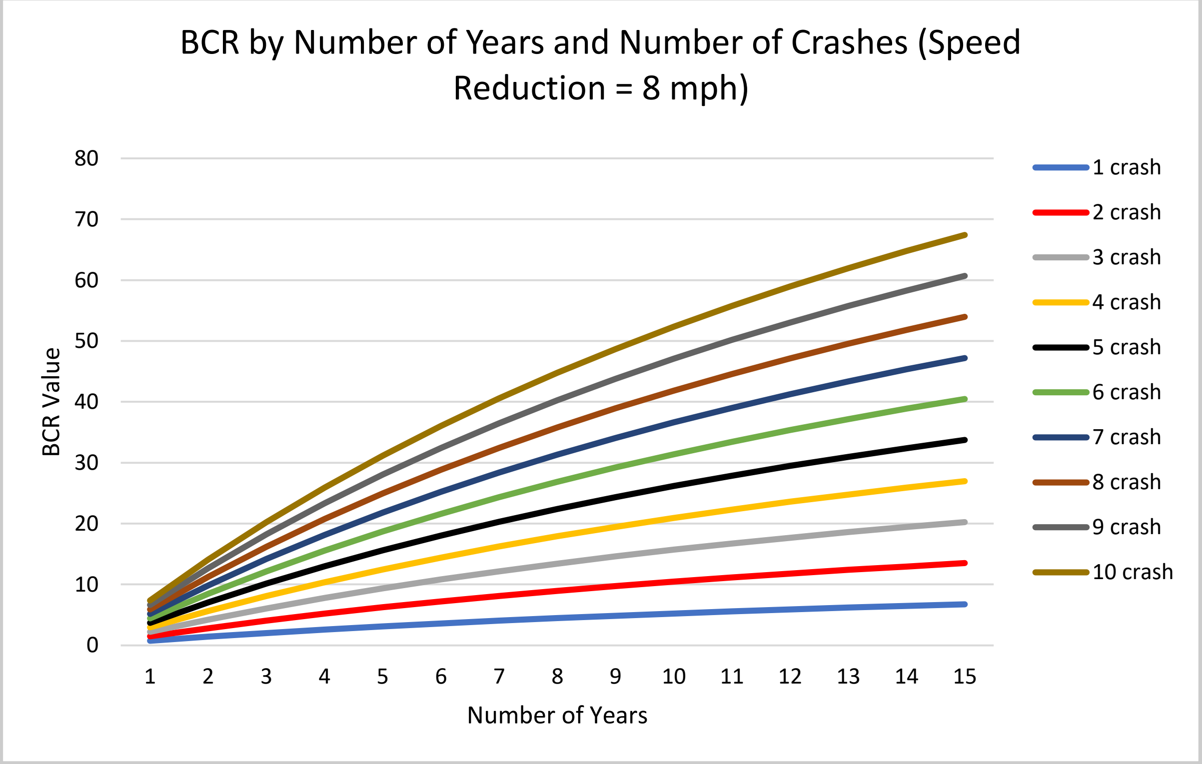

Minimum number of days to break-even with 50% trucks
Number of days (day)
10
1
0.1
0.01
1
1.5
2
2.5
3
3.5
4
4.5
5
PCMS-Taper distance (Mile)
AADT 15K
AADT 30K
AADT 30543 (Case Study)
AADT 45K
AADT 60K
AADT 75K

9.10 BCR by different speed reductions associated with weather-related message.

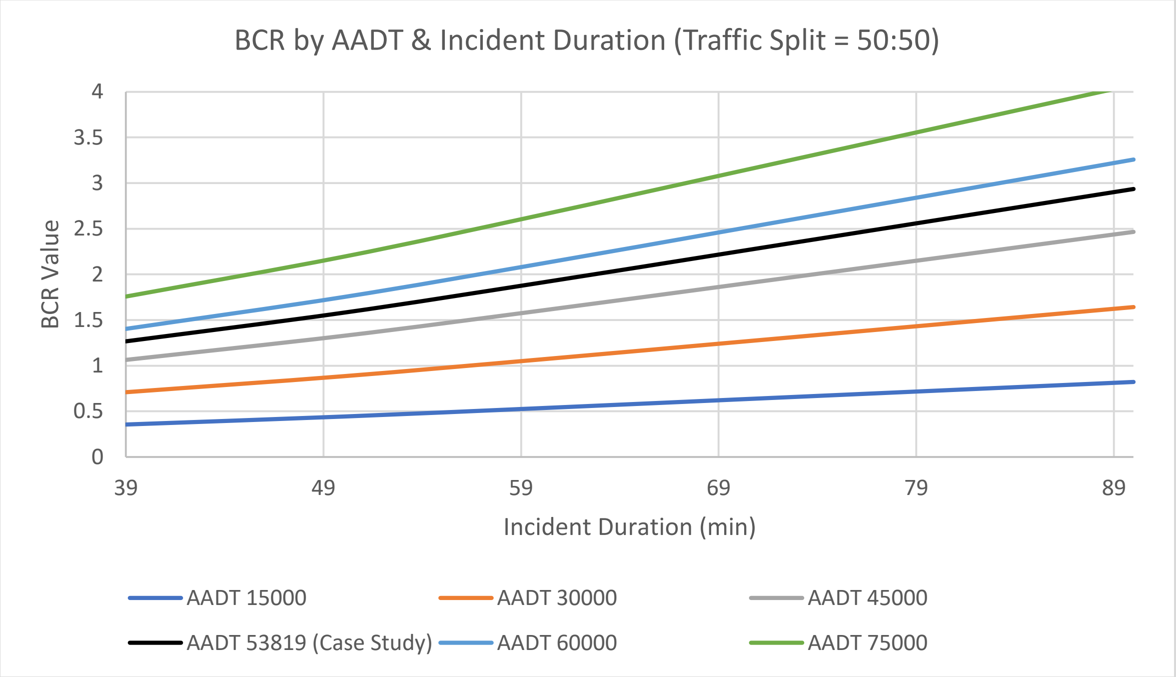


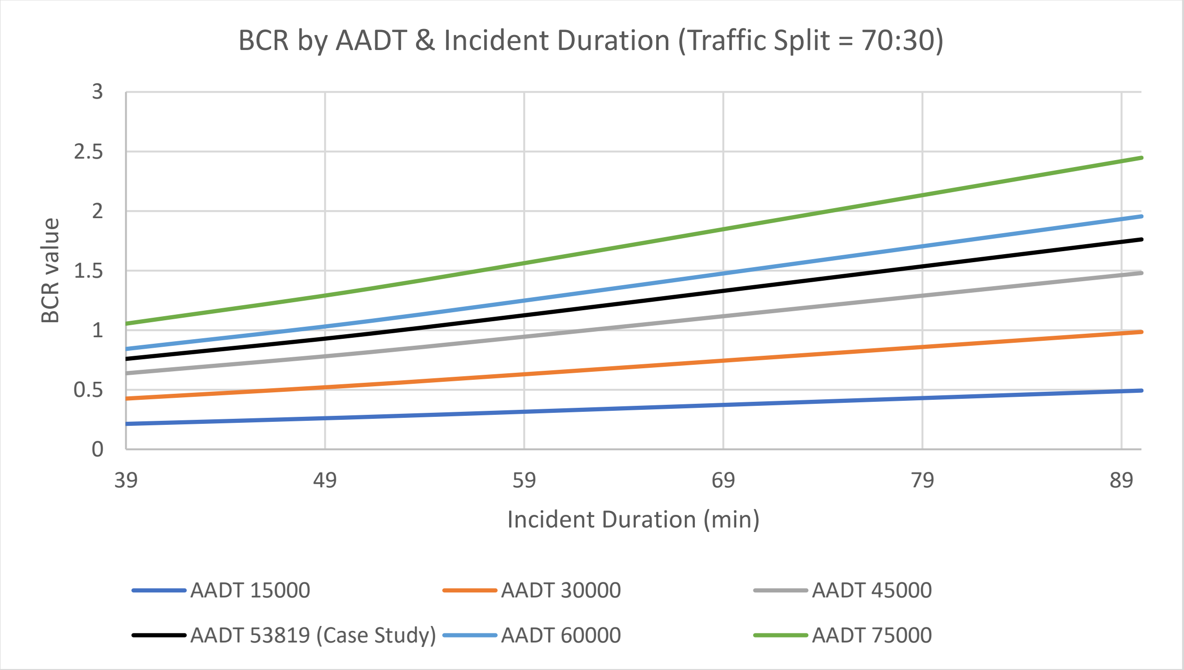


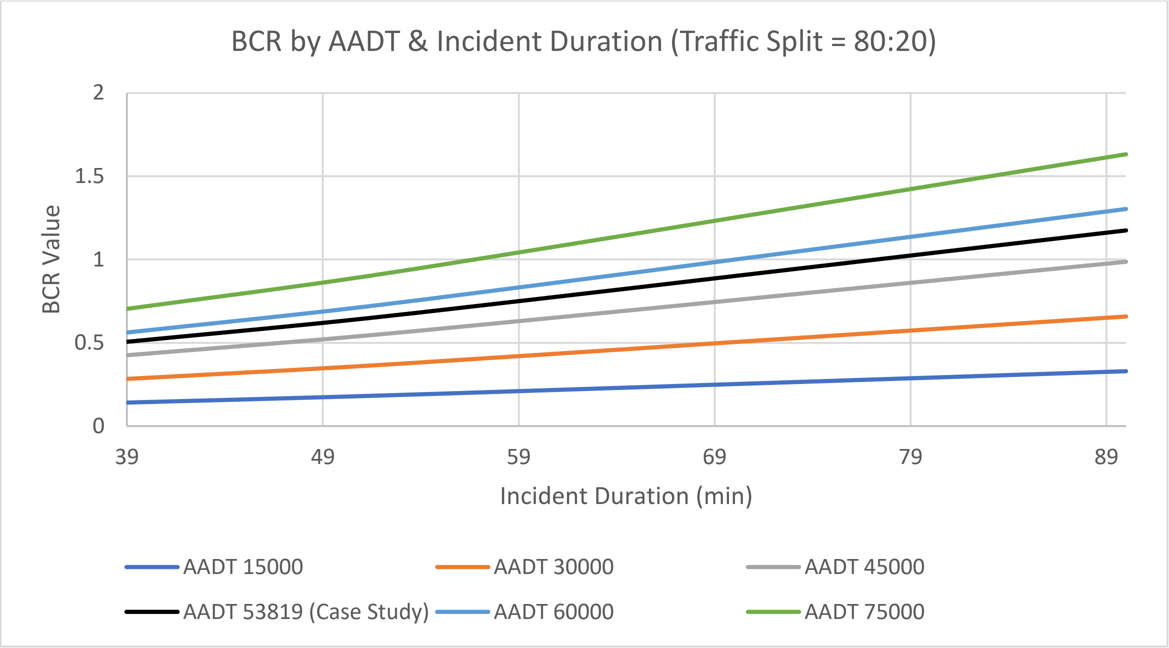

BCR by Number of Years and Number of Crashes (Speed Reduction = 6 mph)
BCR Value
0
10
20
30
40
50
60
Number of Years
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
1 crash
2 crash
3 crash
4 crash
5 crash
6 crash
7 crash
8 crash
9 crash
10 crash


BCR by Number of Years and Number of Crashes (Speed Reduction = 8 mph)
BCR Value
0
10
20
30
40
50
60
70
80
Number of Years
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
1 crash
2 crash
3 crash
4 crash
5 crash
6 crash
7 crash
8 crash
9 crash
10 crash

9.11 Impact of different traffic distributions on the savings associated with displaying alternative travel time for optional routes






BCR by AADT & Incident Duration (Traffic Split = 80:20)
BCR Value
2
1.5
1
0.5
0
39
49
59
69
79
89
Incident Duration (min)
AADT 15000
AADT 30000
AADT 45000
AADT 53819 (Case Study)
AADT 60000
AADT 75000