Evaluation of Bridge Deck Winter Weather Warning Systems

FINAL REPORT

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16. Abstract
Warning signs are typically deployed at bridges to warn motorists of potential icy surface conditions on the bridge, although the effectiveness of these signs is questionable. One potential improvement is the bridge deck warning system (BDWS), which activates a flashing warning sign border or beacon based on real-time weather and bridge surface data. However, such systems have not been broadly implemented, and consequently, their effectiveness as a safety countermeasure is not well established. To address this knowledge gap, research was performed to evaluate BDWS strategies in terms of their impacts on driver behavior and safety performance during winter driving conditions, and to provide guidance to support future deployments of BDWS within Michigan. A series of winter field evaluations were performed along three freeway bridges in Michigan to assess the effectiveness of various BDWS strategies as a speed reduction countermeasure for motorists approaching a potentially icy bridge. The results showed that a BDWS with a flashing LED border reduced motorist speeds when encountering a bridge during winter weather conditions compared to the standard MUTCD W8-13 warning sign, and this effect was consistent between passenger cars and heavy trucks. Greater speed reductions were observed when the BDWS sign was combined with a dynamic speed feedback (DSFS) sign that displayed a "SLOW DOWN" or "ICY ROAD" message to approaching motorists, with the strongest effects observed when the message was pulsed at 1 hertz. Speed reductions were also observed when a "SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS" message was displayed on a full-size DMS located at the subject bridge. A preliminary analysis of crashes before and after installation of the current BDWS implementations in Michigan found that winter-season target crash frequencies were lower at 16 of the 20 sites after installation of the BDWS. Collectively, the findings of this research suggest that BDWS help improve driver behavior and safety performance at bridges during winter driving conditions in Michigan, and continued implementation and operation of BDWS is recommended. The research findings were utilized to develop guidelines and recommendations towards future implementation and operation of BDWS in Michigan, including selection of sites, sign types, warning alerts and messages, sensors and related equipment.

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EXECUTIVE SUMMARY

Michigan's transportation network includes more than 11,000 bridges, including 4,518 on highways under the jurisdiction of the Michigan Department of Transportation (MDOT). Bridge decks present a particular concern during winter travel conditions, as the surface typically freezes prior to the adjacent roadway pavement due to the open airflow underneath the bridge. Such pavement conditions can represent a significant safety hazard for road users, particularly when drivers encounter an unexpected reduction in friction at relatively high speeds and even more so when the bridge deck occurs on a horizontal curve or vertical downgrade.

In order to combat icy bridge decks, the *Manual on Uniform Traffic Control Devices* (MUTCD) provides the option for a BRIDGE ICES BEFORE ROAD (W8-13) sign to warn drivers of potential winter weather conditions downstream. While the seasonal installation of the W8-13 sign alone can help to provide a warning to drivers of potentially icy conditions on the bridge deck, their prolific use and ever-present message, regardless of conditions, often cause the signs to be ignored by drivers. Prior research has indicated that the effectiveness of static ice warning signs installed along roads or bridges is marginal, at best.

MUTCD W8-13 Sign

The conspicuity and message recognition of static winter weather warning signs may be improved by adding a flashing beacon or flashing LED sign border, but these systems have limited effectiveness if they flash continuously. To counter this, many agencies have begun to implement condition-responsive winter weather warning systems. This includes bridge deck warning systems (BDWS), which improve upon the "always-on" warnings by providing warning alerts or messages only when warranted based on sensors that provide real-time weather and pavement conditions on the bridge deck. Typically, the activated warning consists of an LED sign border or flashing beacon on standard warning signs or warning messages displayed on a dynamic message sign (DMS).

 Flashing LED Sign Border	 Flashing Overhead Beacon (Single)	 Flashing Ovehead Beacon (Dual)	 DMS Messages

Examples of Bridge Deck Warning Systems

Study Objectives

At the onset of this study, the Michigan DOT had implemented eight BDWS statewide, the majority of which were located on freeways. In each case, the BDWS consisted of a W8-13 sign with a flashing overhead beacon or flashing LED border that is connected to an environmental sensor station (ESS) located near the bridge. The flashing warning alert is activated based on data from a pavement sensor that includes both surface temperature and moisture conditions. However, due to the limited implementation of BDWS both within Michigan and nationwide, the effectiveness of these systems on driver behavior during potentially icy bridge conditions had not been well established. To this end, research was performed to determine the effectiveness of BDWS signing strategies in terms of driver behavior and safety performance and to provide guidance to support future implementation and operation of BDWS in Michigan. This included recommendations for sign types, warning alerts and messages, bridge site selection, sensors, and other related equipment.

Field Evaluation of Driver Behavior

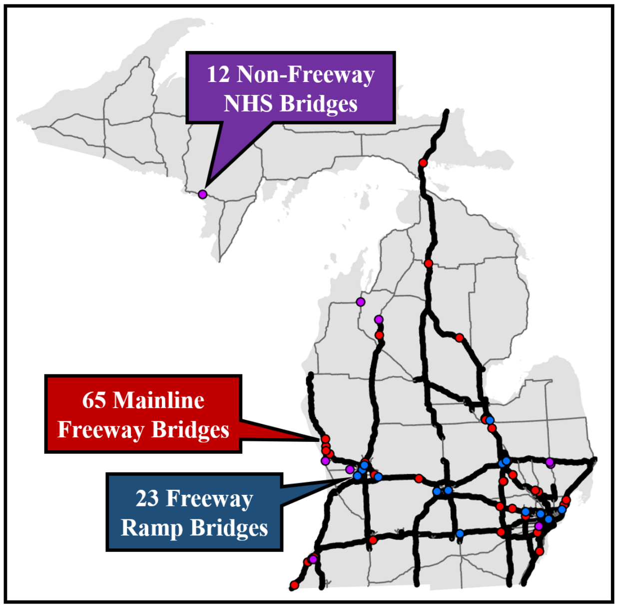
The impacts of BDWS on driver behavior were assessed through a series of field evaluations performed at existing BDWS installations on NB and SB US-131 near Cadillac, Michigan and a temporary BDWS installation on NB US-127 near Lansing, Michigan. The field evaluations were designed to measure the effectiveness of BDWS as a speed reduction countermeasure for motorists approaching a bridge during winter weather conditions compared to the standard warning signage. During the field evaluation, two types of BDWS were tested, which included a W8-13 warning sign with either a flashing LED border or a flashing amber beacon above the sign. Also evaluated in the field study were the incremental benefits provided by including a dynamic speed feedback sign (DSFS) panel in combination with the standard BDWS sign. The DSFS was programmed to display an on-demand “SLOW DOWN” or “ICY ROAD” message to approaching vehicles upon detection by the radar embedded within the sign panel. The field evaluation also included assessment of the effects of various winter weather warning messages on a DMS located near the bridge. Three DMS winter weather warning messaging strategies were tested, which included: “BRIDGE ICES BEFORE ROAD / REDUCE SPEEDS”; “SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS” and “SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS” displayed across two-frames (4-second per frame).

It was concluded that the flashing LED border BDWS had a statistically significant effect on motorist speeds when encountering a bridge during winter weather conditions. The magnitude of the speed reduction for the flashing LED border ranged between 0.7 mph and 1.1 mph for drivers of cars and large trucks, respectively, compared to when the LED border was not flashing. The flashing overhead beacon BDWS did not have a significant impact on speeds at the bridge compared to the inactive beacon. The inclusion of a radar-activated DSFS panel positioned beneath the BDWS sign provided even greater speed reductions, likely due to the increased conspicuity provided by the on-demand message activation as motorists approached the sign. The addition of the DSFS beneath the flashing LED border sign produced speed reductions of 1.9 mph compared to the inactive sign condition, and this effect was consistent for both cars and large trucks. The evaluation of DMS winter weather warning messages showed the strongest speed reduction effects to occur when the “SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS” message was displayed continuously on a single frame. With this message displayed, the speeds at the bridge were 0.6 mph lower for passenger cars compared to when travel time messages were displayed.

Analysis of Target Winter Bridge Crashes

Given the potential safety benefits associated with BDWS demonstrated by these speed reductions, a comprehensive analysis of target crashes occurring on MDOT bridges during periods of winter-season precipitation was performed. This analysis considered several bridge attributes, including historical traffic crash and volume data, roadway characteristics, and weather data. This dataset was used to benchmark safety performance on snowy or icy bridge decks in Michigan, as well as to conduct a network screening to identify candidate bridge decks that may benefit from future BDWS treatments. A total of 100 bridge locations on the MDOT trunkline NHS network were identified as candidates that could potentially benefit from the installation of a BDWS.

Additionally, this analysis identified several characteristics that influence bridge winter safety performance, including traffic volume, structure length, the frequency of winter-season precipitation, horizontal curvature, type of intersecting feature, and geographic region.



Map of 100 Candidate MDOT Bridges for Potential Future BDWS Implementation

A preliminary before-and-after crash data assessment was also conducted for the 20 bridge locations where BDWS had been installed for at least one winter-season period. It is critical to note that this assessment should be interpreted with caution as many of these systems are relatively new, greatly limiting the availability of post-installation data. Nevertheless, the results suggest that BDWS represent a promising option to potentially address crashes related to icy bridge deck conditions as 16 of the 20 sites experienced lower frequencies of target crashes after installation.

Preliminary Before-and-After Winter Crash Data for Existing MDOT BDWS Sites

Bridge Information		Winter Seasons		AADT		Target Crashes per Winter Season			Percent of Sites with Crash Reductions
Scenario	Count	Before	After	Before	After	Before	After	Percent Change	
Non-Freeway	1	9	4	23,216	23,728	1.89	1.00	-47.1%	100%
Flyover Ramp	1	8	5	28,186	24,490	1.88	1.00	-46.7%	100%
Big Bridge	4	44	4	20,595	19,108	5.98	3.50	-41.4%	100%
Freeway	14	120	48	10,594	12,410	0.89	0.73	-18.2%	71.4%

Recommendations for BDWS Implementation and Operation

Based on the findings from this study, a series of recommended guidelines were developed to support future implementation and operation of BDWS in Michigan. This included guidance towards selection of sign types, warning alerts and messages, future implementation sites, sensors, and other related equipment. Note that recommendations for future implementation sites, sensors, and other related equipment are detailed in the report and are not summarized here.

Sign Types and Flashing Warning Alerts

It is recommended that the BDWS include a MUTCD W8-13 sign with either a flashing LED border or dual top flashing amber beacons. The installation location for the BDWS sign with respect to the start of the bridge should be determined according to MDOT/MUTCD placement guidelines. If a single top flashing beacon is utilized, installation of BDWS signs on both sides of the road is recommended for freeways or other divided highways. If a flashing LED border is used, the LEDs should include an auto-dimming sensor to ensure that optimal brightness is achieved during both day and night. If such a sensor is not available, then the LED brightness should be set to achieve optimal brightness during daylight conditions. Doing so will help ensure that the flashing border is visible during daylight, darkness, and low visibility. Further, in areas that regularly experience heavy snowfall, MDOT should continue to use durable LED border signs with LEDs that are designed to withstand snow from passing plows. Finally, while the W8-13 sign is recommended due to its use in this study and broad implementation by MDOT, there may be other sign designs or messages strategies worth considering as a part of future deployments.

Messaging Strategies for Dynamic Speed Feedback Signs

To achieve optimal results, the BDWS should be combined with a radar-activated DSFS panel that is capable of displaying characters that are a minimum of 15-inches in height and mounted beneath the warning sign. The DSFS should be programmed to display a message such as “SLOW DOWN”, “ICY ROAD”, or simply “ICE”, and should be interconnected with the ESS/BDWS such that it is activated only during potentially slippery conditions on the bridge deck. To improve conspicuity, the message should be programmed such that it either pulses (i.e., dim to bright) or alternates between messages (e.g., ICE / SLOW DOWN) at a rate of 1 hertz. Note that the MUTCD does not allow flashing messages or strobes on DSFS or DMS displays. When active, the DSFS message should be displayed for all approaching vehicles, regardless of speed. These

DSFS messaging recommendations are based on signs manufactured by TraffiCalm that are commonly utilized by MDOT. Please check the manufacturer's specifications and programming capabilities if other DSFS panels are utilized. Although not evaluated here, MDOT may consider adding the DSFS panel as a standalone BDWS treatment beneath the standard W8-13 warning sign that do not include the flashing beacon or border. If such a standalone DSFS installation is implemented, it must be interconnected with the ESS such that it is activated only during potentially slippery conditions on the bridge deck.

Messaging Strategies for Dynamic Message Signs

At certain critical locations, MDOT should consider implementation of a DMS panel for BDWS messaging rather than the flashing LED border signs, flashing beacon signs, or DSFS. Although more expensive than traditional BDWS, the DMS panel would provide a larger, more visible display, in addition to greater messaging flexibility. DMS messaging for winter driving conditions should use "SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS" on a single frame, which is the message most commonly utilized by MDOT for warning of winter weather conditions. Splitting this message between two panels is not recommended. Discretion should be given towards the use of BDWS-specific DMS panels for other messaging purposes during the winter season, and it may be advisable to include additional flashing beacons on top of the DMS panel to emphasize winter weather warning alerts. MDOT should also continue to post winter weather warning messages on existing full-sized DMS located around the state, particularly those positioned near bridges. These messages may be posted automatically, if interconnected with an ESS, or manually by personnel at the traffic operations center when conditions warrant.

Site Selection for Future BDWS Treatments

The list of 100 candidate locations (details provided within the report) represent potential suitable locations for MDOT to consider when expanding the BDWS program. In all cases, a more detailed engineering study should ultimately be performed during site selection, considering those factors that were found in the safety performance analysis to influence bridge deck winter safety performance, including: traffic volume, structure length, frequency of winter-season precipitation, horizontal curvature, type of intersecting feature, and geographic region, in addition to the presence of existing ESS technology near the bridge.

1. INTRODUCTION AND BACKGROUND

1.1 Background

Michigan's transportation network incorporates more than 11,000 bridges, including 4,518 maintained by the Michigan Department of Transportation (MDOT). Safely maintaining these bridge structures (**Figure 1**) represents one of the core responsibilities of MDOT (Michigan Department of Transportation, n.d.-b). Consistent with MDOT's Bureau of Bridges and Structures mission to support "the efficient and innovative design, construction, and active preservation of transportation structural assets, inspired by safety, resiliency, and mobility," proactive solutions to improve the safety performance of these bridge structures is a key consideration for the department (Michigan Department of Transportation, n.d.-a). Further, the improvement of engineering infrastructure is one of four emphasis areas identified as a part of Michigan's Strategic Highway Safety Plan (SHSP) (Governor's Traffic Safety Advisory Commission, 2019). The use of innovative traffic control devices and related connected vehicle technologies represents an opportunity to improve Michigan's engineering infrastructure toward achieving the state's long-term *Towards Zero Death* vision (Governor's Traffic Safety Advisory Commission, 2019).

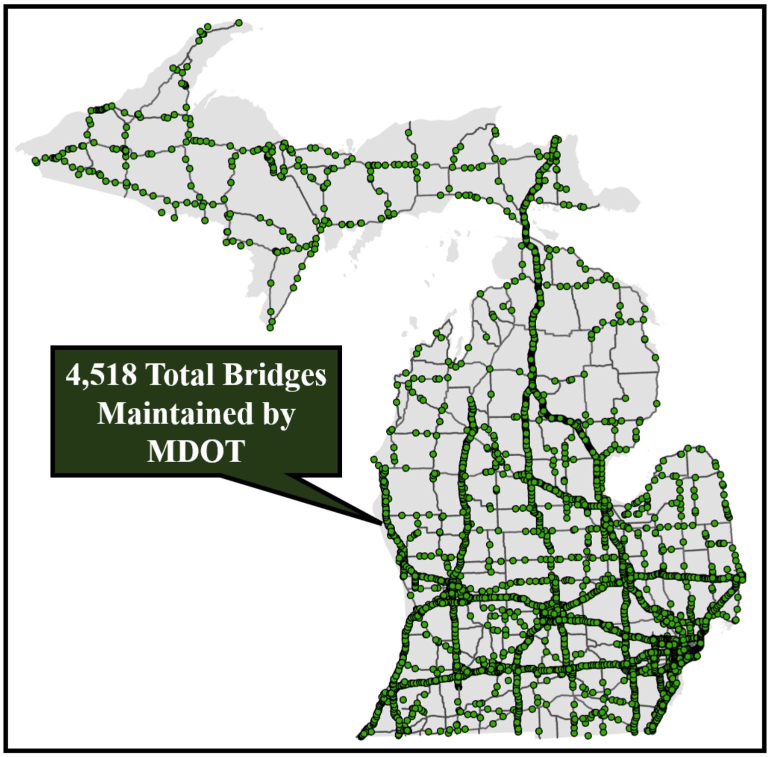


Figure 1. Map of MDOT Bridges

Weather conditions significantly affect road safety since these not only impact the driver's visual perception in terms of visibility distance (width of field of view, perception of shapes, colors, and motions) but also impact pavement friction and visibility of road elements (pavement markings, road signs, and other road safety elements). In the United States, approximately 21 percent of all crashes are weather-related, occurring during adverse weather conditions (i.e., rain, sleet, snow, fog, severe crosswinds, or blowing snow/sand/debris) or on slick pavement (i.e., wet pavement, snowy/slushy pavement, or icy pavement (Federal Highway Administration (FHWA), n.d.). Though the majority of the weather-related crashes occur during rainfall, a significant portion occurs during winter conditions, including 18 percent during snow or sleet, 13 percent on icy pavement, and 16 percent on snowy or slushy pavement (Federal Highway Administration (FHWA), n.d.). An average of approximately 156,000 crashes occur along icy pavement annually in the United States, resulting in 42,000 injuries and more than 500 fatalities (Federal Highway Administration (FHWA), n.d.).

A particular concern during winter travel conditions is bridge surfaces, which often freeze prior to the adjacent pavement due to the open airflow underneath the bridge deck. When precipitation occurs, this condition often leads to the bridge deck icing prior to the adjacent roadway (Roosevelt et al., 2004). This can lead to a potentially hazardous situation where drivers operating along the roadway that has not iced over may not expect the slippery pavement upon encountering the bridge deck (Barrett & Pigman, 2001). Such pavement conditions can represent a significant safety hazard for road users, particularly when drivers encounter an unexpected reduction in friction at relatively high speeds and even more so when the bridge deck occurs on a horizontal curve or vertical downgrade. The Great Lakes region of the U.S. is particularly susceptible to winter weather conditions that contribute to bridge decks prematurely icing prior to the adjacent roadway surface. This region is generally characterized as a wet-freeze climate, where winter weather events are frequent and numerous freeze-thaw cycles occur throughout the winter. Such conditions contribute to situations where the bridge deck is susceptible to icing prior to the adjacent roadway surface.

1.2 Problem Statement and Objectives

In order to combat icy bridge decks, the *Manual on Uniform Traffic Control Devices* (MUTCD) provides the option for a BRIDGE ICES BEFORE ROAD (W8-13) sign (**Figure 2**), which "may be used in advance of bridges to advise bridge users of winter weather conditions" (Federal

Highway Administration (FHWA), 2009). MDOT's *Traffic Sign Design, Placement, and Application Guidelines*, notes the use of W8-13 signs at "all bridges and overpass structures 50' or more in length with posted speeds of 45 mph or higher. Where posted speeds are less than 45 mph the sign is optional. For 3 or more lanes, dual signs may be used."

Figure 2. MUTCD W8-13 Sign

While the seasonal installation of the W8-13 sign alone can help to provide a warning to drivers of potentially icy conditions on the bridge deck, their prolific use and ever-present message, regardless of conditions, often cause them to be ignored by drivers. The overall driver awareness of road signs is generally under 50 percent (Babić et al., 2017; Macdonald & Hoffmann, 2007; Milosevi & Gajic, 2007), and they mainly respond to the signs which are relevant to the current or upcoming situation. Several older studies have also shown that static warning signs with messages related to an icy bridge, such as "ICY BRIDGE," "WATCH FOR ICE ON BRIDGE," or "REDUCE SPEED-ICE ON BRIDGE," have varying impacts on drivers and thus on road safety (Hanscom, 1975; Stewart & Sequeira, 1971). Moreover, an analysis by Carson and Mannering (Carson & Mannering, 2001) of 8,176 crashes involving icy conditions on the road found that the presence of ice warning signs does not have a significant impact on the reduction of ice-related crashes or their severity.

The aforementioned studies indicate that the effectiveness of static ice warning signs installed along roads or bridges is, at best, marginal and may not have a desired cost-benefit ratio, even when considering the relatively low implementation costs. The conspicuity and message recognition of static winter weather warning signs may be improved by adding a flashing beacon or flashing LED sign border, but these systems have limited effectiveness if they flash continuously, regardless of the weather conditions. To counter this, many agencies have begun to implement condition-responsive winter weather warning systems. This includes bridge deck warning systems (BDWS), which improve upon the "always-on" warning messages by providing warning alerts or messages only when warranted based on sensors that provide real-time weather and pavement conditions on the bridge deck. Typically, the activated warning consists of an LED sign border or flashing beacon on standard warning signs (e.g., W8-13), although warning messages may also be displayed on a dynamic message sign (DMS). Examples of BDWS alerts and messaging strategies are displayed in **Figure 3**. Through the use of condition-responsive warning alerts, BDWS are designed to reduce motorist speeds prior to encountering the potentially low-friction conditions on the bridge deck, thereby reducing the frequency and severity of crashes.

Flashing LED Sign Border	Flashing Overhead Beacon (Single)	Flashing Ovehead Beacon (Dual)	DMS Messages

Figure 3. Examples of Bridge Deck Warning Systems

At the onset of this study, the Michigan DOT had implemented eight BDWS statewide, the majority of which were located on freeways. In each case, the BDWS consisted of a W8-13 sign with a flashing overhead beacon or flashing LED border that is connected to an environmental sensor station (ESS) located near the bridge. The flashing warning alert is activated based on data from a pavement sensor that includes both surface temperature and moisture conditions. However, due to the limited implementation of BDWS both within Michigan and nationwide, the effectiveness of these systems on driver behavior during potentially icy bridge conditions had not been well established.

To this end, research was performed to determine the effectiveness of BDWS signing strategies in terms of driver behavior and safety performance and to provide guidance to support future deployments of BDWS within Michigan. The specific objectives of this research were as follows:

- Perform a review of literature and state agency practices specific to bridge deck warning messaging strategies and associated system components.
- Conduct an evaluation of MDOT's existing BDWS installations to assess the effectiveness of BDWS signs on driver behavior and safety performance.
- Identify suitable bridge locations within Michigan for potential future BDWS deployment.
- Develop guidelines and related materials to support future installation and operation of BDWS in Michigan, including recommendations for implementation locations, sign types, warning alerts and messages, sensors and other related equipment.

1.3 Report Structure

In order to achieve the above-stated research objectives, the following tasks were performed. A detailed description of these tasks has been provided in the subsequent chapters of this report.

- **Chapter 2**: Review of Literature and Agency Practice
- **Chapter 3**: Field Evaluation Methodology
- **Chapter 4**: Field Evaluation Results
- **Chapter 5**: Traffic Crash Analysis and Network Screening for Future BDWS Deployments
- **Chapter 6**: Recommended BDWS Equipment Specifications
- **Chapter 7**: Conclusions and Recommendations for BDWS Implementation and Operation

2. REVIEW OF LITERATURE AND AGENCY PRACTICE

Traffic signs are a basic means of communication between road authorities and road users, and as such, they represent important road infrastructure elements that are used to facilitate efficient and safe travel for all road users. Their functions range from warning road users of upcoming situations, regulating traffic by defining obligations and prohibitions, providing visual guidance and route-finding, and providing road users with information. In order to fulfill the aforementioned functions, traffic signs must meet certain requirements. According to Elvik (2010), traffic signs must:

- *conspicuous* – attract attention to be noticed by drivers;
- *legible* – be legible and recognizable in all conditions and at relevant distances;
- *comprehensible* – be easily understood by all road users; and
- *credible* – be able to convince road users to act according to the message/information provided by the sign.

The aforementioned requirements have a hierarchical order in order for traffic signs to be effective and beneficial for road safety. Several studies have shown that readability, comprehensibility and in the end compliance with the message, are influenced by a number of factors such as sign type, design of the sign, placement of the signs, visibility (day/night), weather and traffic conditions, as well as other driver-related factors such as motivation, understanding, age, cultural background, or familiarity (Ben-Bassat, 2019; Ben-Bassat & Shinar, 2015; Jamson & Mrozek, 2016; Shinar et al., 2003; Shinar & Vogelzang, 2013; Zwahlen et al., 1999). Overall, a vast body of literature highlighted the positive impact of traffic signs (especially warning, mandatory or obligatory signs) on drivers' behavior and thus road safety in different road situations/locations, such as curves, intersections, exit ramps, as well as other risky situations (construction zones, downgrades, location with possible animal-vehicle interaction, locations with potential for icey-crash, etc.) (Babi´c et al., 2021; Brimley et al., 2016; Carson & Mannering, 2001; Choi et al., 2020; Gates et al., 2004; S. Hallmark et al., 2020; Khalilikhah & Heaslip, 2017; Montella & Alfonso, 2009; Moomen et al., 2018; Ré et al., n.d.; Rose & Carlson, 1918; Y. Wu et al., 2013, 2016; Zhao, Wu, et al., 2015). They are particularly important in low visibility and night-time conditions, during which drivers show much less visual adaptation, shorter sight distance, reduced peripheral vision, lower contrast sensitivity and vision clarity, and poorer perception of motion and color. In the aforementioned conditions, traffic signs must meet minimal retroreflective properties. Studies have shown that traffic signs that do not meet minimal retroreflective properties per kilometer increase the rate of all crashes (material damage, death, or injury) during night-time conditions (Fereko et al., 2019; Šarić et al., 2018; Xu et al., 2018).

Although traffic signs carry important messages for the safety of road users, due to a number of reasons mentioned in the previous paragraph, they are often not visually perceived and/or comprehended by drivers. In general, studies have reported that drivers' awareness of traffic signs varies widely from 2 percent to 75 percent, with most of them reporting that overall awareness is under 50 percent (Babić et al., 2019; MacDonald & Hoffmann, 1991; Milosevi & Gajic, 2007). Even if they are visually perceived and comprehended by the drivers, drivers often do not comply or adjust their behavior according to the message traffic signs are conveying. Therefore, in specific situations and conditions that demand higher attention from drivers and change in their driving behavior, road authorities often use two strategies: a) the use of enhanced static traffic signs or b) the use of dynamic message signs (DMS).

2.1 Active Warning Signs

2.1.1 *Static Traffic Sign with Flashing Lights*

A survey conducted among 28 state roadway agencies (Al-Kaisy, 2006) identified two main methods for enhancing the conspicuity of static warning signs: static signs with unconventional design and static signs with flashing lights (i.e., active advanced warning signs). Approximately 20 percent of agencies reported the use of static signs with unconventional designs, which include signs that are of a different size, color, or enhanced with reflectors or any other altered feature from the standard MUTCD warning signs, while 43 percent of agencies reported the use of static signs with flashing lights. According to the questionnaire responses, 64 percent of these agencies reported the aforementioned enhancements to be effective, while for 21 percent of them, the signs were ineffective. A body of literature supports this survey results and indicates that such enhancements are effective for advance detection in specific situations such as intersections, pedestrian crossings, curves, and railway level crossings, as a measure for reduction of wrong-way driving, work zones, etc.

Previous studies have highlighted that active (flashing) advance warning signs are effective in reducing crashes and traffic conflicts on high-speed approaches to signalized intersections (Pant & Xie, 1995; Sayed et al., 1999). However, it should be noted that some studies indicated that the effect of the aforementioned signs is mixed or inconsistent (Klugman et al., 1992; Sayed et al., 1999). For instance, Gates et al. (2004) evaluated the effect of blinking LED stop signs at intersections and found a significant effect on daytime and nighttime stopping compliance (both blow-throughs and roll-throughs) compared with standard stop signs. Furthermore, Weidemann et al. (2011) investigated the effect of an advanced LED warning system (ALWS) at a rural through–stop intersection and reported that after the installation of the ALWS, speed slightly increased during daytime periods but significantly decreased during nighttime periods. The difference in speed reduction between day and night, as the authors stated, suggests that the brightness of LEDs is important during daylight periods. Similarly, Simpson & Troy (2013) evaluated the safety effectiveness of “VEHICLE ENTERING WHEN FLASHING” intersection conflict warning systems at stop-controlled intersections and found a reduction in severe injury crashes.

With respect to horizontal curves, Montella et al. (2015) found a significant crash reduction in total, night-time, daytime, rainy, non-rainy, run-off-road, and property damage-only crashes when curves were marked with “dangerous curve” warning signs, chevron signs, and sequential flashing beacons along the curve. Overall, the authors estimated that such measures may reduce crashes by 47.6 percent. The same author and his colleagues tested ten different measures for increasing safety when approaching and driving through horizontal curves on rural roads (Montella et al., 2015). The measures ranged from advance warning signs to perceptual and delineation measures. Although analysis showed that perceptual markings (dragon teeth, colored strips, and medians) have a significant effect on driver behavior, both in the approach tangent and inside the curve, it was highlighted that by adding flashing beacons on curve warning signs and chevrons approaching speed can be significantly reduced compared to the case in which signs are without flashing beacon. Moreover, the literature highlights the positive impact of visibility enhancements of static traffic signs at railway level crossings and as a wrong-way driving reduction measure (Larue et al., 2019; Kayes et al., 2018). Although beneficial to road safety, conspicuity aids for traffic signs have to be planned and limited to high-risk traffic situations since their effectiveness may drastically decrease if overused. Examples of described measures are presented in **Figure 4**.

One of the more common application of flashing warning beacons is at pedestrian crossings. In 2015, the Texas Transportation Institute tested several methods for emphasizing the presence of pedestrian crossings, among which were additional traffic signs with beacons or embedded light-emitting diodes (Fitzpatrick et al., 2015). The study evaluated what characteristics of rapid-flashing beacons affected drivers' ability to detect people or objects, as well as drivers' likelihood of yielding to a pedestrian. Results show that drivers were more than three times more likely to yield to pedestrians when a beacon has been activated than when it has not been activated.

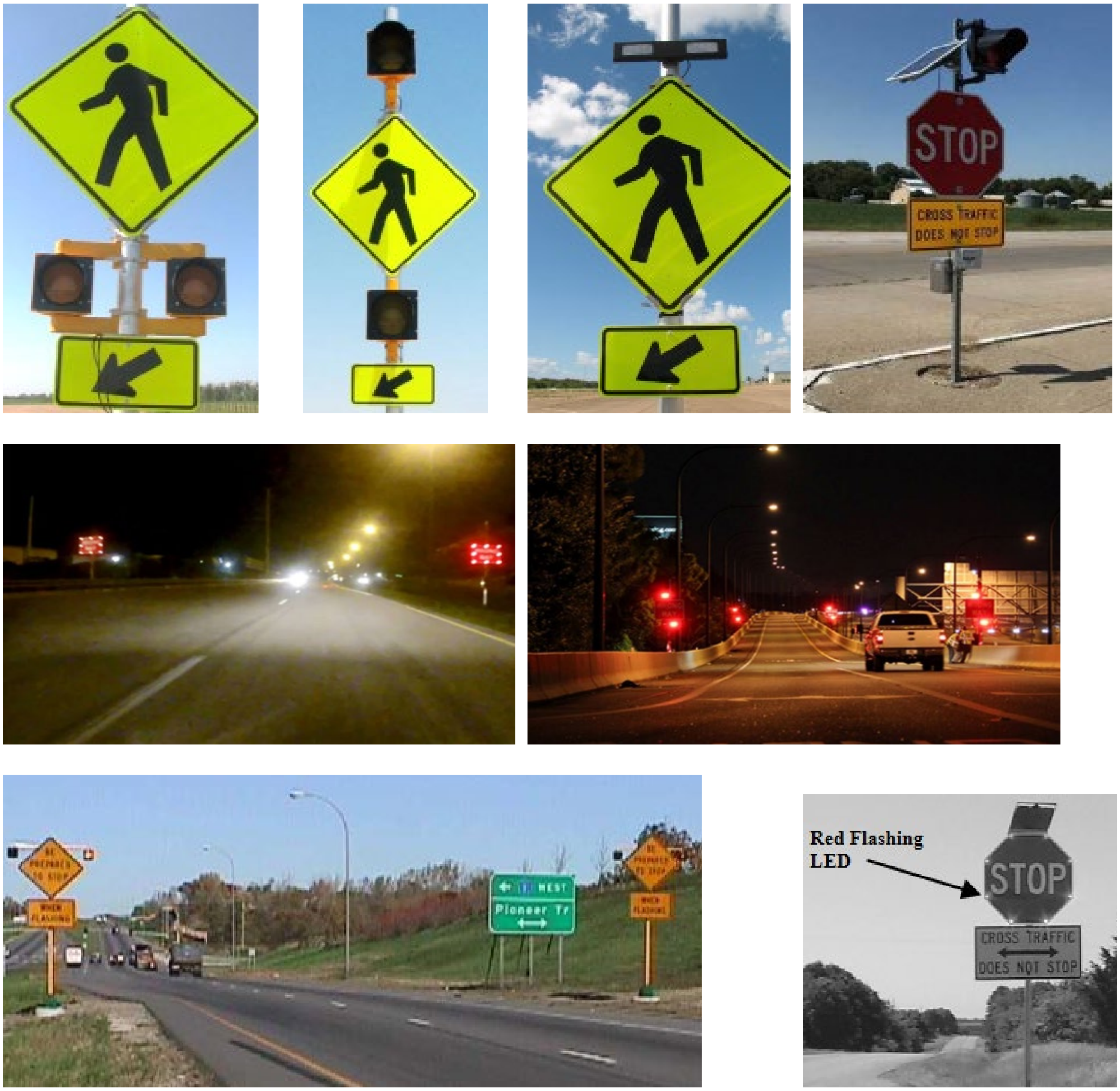


Figure 4. Examples of Different Types and Uses of Flashing Traffic Signs (Farraher et al., 1999; Fitzpatrick et al., 2015; S. L. Hallmark et al., 2018; Kayes et al., 2018)

Similarly, systems are used by agencies to warn drivers about adverse weather conditions that may impact their safety. Collins & Pietrzyk (2001) developed an automated, dynamic motorist warning system to attract attention to the advisory speed limit signs and thus encourage motorists to reduce vehicle speed (Collins & Pietrzyk, 2001). A pavement sensor embedded in the roadway activated two flashing beacons located above the signs whenever moisture was detected. In California and Utah, fog detection system uses speed and visibility detectors to assess road conditions, traffic management software to process data and control the field devices, and changeable message signs to provide information to the traveling public (Berman et al., 2009; Perrin, 2003). In Oregon, Idaho, and Wyoming, automated wind warning systems were designed in such a way that wind gauges were connected to static signs with flashers or dynamic message signs, which are activated when adverse wind speeds reach predetermined threshold levels and warn drivers to pull over and wait until weather conditions improved or take an alternate route (Kumar & Strong, 2006; Kyte et al., 2000; Young et al., 2010).

2.1.2 *Dynamic Message Signs*

Dynamic message signs (DMS), also known as variable message signs (VMSs) or changeable message signs (CMSs), are programmable electronic signs typically located along highways and provide real-time information to drivers. They have been in use for nearly 70 years and represent essential components of numerous ITS and traffic management strategies aimed at regulating, routing or re-routing, warning, and managing traffic (Banerjee et al., 2020; Kassens-Noor et al., 2021a). DMS are widely used throughout the US, where the majority of states have written guidelines or policies on DMS design and operation (National Academies of Sciences, 2008a).

Dynamic message signs (DMS) must convey meaningful and easy to understand messages that are timely and accurately comprehended by the driver. DMS possess a large number of applications related to messaging for warning or safety purposes, including adverse weather conditions, geometric warning situations, speed control, incident management and route diversion, among others (FHWA, 2009). Therefore, when implementing a DMS for warning or safety messaging purposes, is important to consider the specific safety problem, the content of the displayed message, its length, format of the message and units of information, placement of DMSs, as well as target groups and general characteristics of the drivers. In Michigan, the most common messages are related to safety and are primarily focused on four driving behaviors: speeding (24 percent), work zone safety (17 percent), lane discipline/compliance (11 percent), and turn signal use (6 percent), while other messages, such as adverse weather messages, warnings about drunk driving, tailgating, and cell phone use while driving represent less than 5 percent (Kassens-Noor et al., 2021a). Drivers tend to respond more often and more quickly to warning messages and high-risk messages on DMS compared to informative and regulatory messages on DMS (Fallah Zavareh et al., 2017; Song et al., 2016).

The content of the message must provide information relative to the driver's needs. A DMS message should present the “advice” and the “reason.” “Advice” may be “REDUCE SPEED,” “SLOW DOWN,” “EXIT AND TAKE OTHER ROUTES,” etc., while the “reason” in most cases is the problem such as “MAJOR ACCIDENT,” “ACTIVE WORK ZONE,” or “LEFT 2 LANES CLOSED”. Drivers expect this information to appear first in a DMS message but also prefer to know where the problem occurred, and this should be provided to them in the next line of the DMS message (National Academies of Sciences, 2008a). Jindahra & Choocharukul (2013) investigated the route-changing propensity of different DMSs in Bangkok (Thailand) and found that qualitative delay and suggested route information are the most important components of messages intended for route diversion management (Jindahra & Choocharukul, 2013).

In previous studies, different types of messages were tested on DMSs to analyze the driver's behavior by measuring the change in traffic flow, volume, and speed of the vehicles. A study in Montana found that average speeds were reduced when “SLOW DOWN, ANIMAL” advisory messages were shown instead of travel time messages (Hardy et al., 2006). DMS have also been found to reduce speeds in freeway work zones by up to 3.65 mph (Edara et al., 2014). Further, Haghani et al. (2013) assessed the effect of DMS on traffic flow using traffic volume and speed data collected from probe-based sensors in Maryland. Three different types of DMS messages were tested, including danger/warning, informative/common, and regulatory/non-traffic related messages. The results show that drivers responded more to the warning messages and subsequently reduced their speed.

Several studies have also tested DMS messages related to adverse weather conditions. Rama and Kulmala (2000) investigated the effect of VMS on driver behavior in Finland. A before and after study was performed to test warning signs for slippery road conditions and a minimum headway sign at three different sites covering two winter seasons. The results showed that the slippery road condition sign reduced the mean speed on slippery roads by 1-2 km/h (0.6–1 mph) in addition to the decrease in speed caused by the adverse road conditions (Rama & Kulmala, 2000).

Overall, several studies have shown that drivers tend to read and react positively to messages displayed on DMS (Boyle et al., 2014; Kassens-Noor et al., 2021a; Tay & De Barros, 2008). However, the relationship between traffic crashes and the frequency with which various types of safety messages are displayed did not show any effect on total crashes (Johari et al., 2022).

2.2 Weather Warning Systems

2.2.1 ***Traditional Winter Weather Warning Signs***

To address issues with unexpected reductions in friction on bridge decks during winter weather conditions, the MUTCD provides the optional use of the W8-13 "BRIDGE ICES BEFORE ROAD" in advance of bridges to advise bridge users of winter weather conditions. This sign may be removed or covered during seasons of the year when its message is not relevant (Federal Highway Administration (FHWA), 2009). While the seasonal installation of the MUTCD W8-13 sign alone can help to provide a warning to drivers of potentially icy conditions on the bridge deck, their efficiency is questionable. As described in the above subsection, drivers' overall awareness of traffic signs is, in general, under 50 percent (Babić et al., 2019; MacDonald & Hoffmann, 1991; Milosevi & Gajic, 2007) and drivers primarily respond to the signs which are relevant for the current or upcoming situation. Since the aforementioned warning signs carry the ever-present message regardless of condition, drivers often disregard them and do not adjust driving behavior.

Several older studies show that static warning signs with messages related to icy bridges, such as "ICY BRIDGE," "WATCH FOR ICE ON BRIDGE," or "REDUCE SPEED-ICE ON BRIDGE," have varying impacts on drivers and thus road safety (Dillhoff & Culp, 1970; Stewart & Sequeira, 1971). In addition to the above studies, it is worth noting that Carson & Mannering (2001) analyzed the general impact of ice warning signs on the reduction of frequency and severity of ice-related crash in Washington (Carson & Mannering, 2001). In total, 8176 crashes involving ice conditions, which occurred from January 1993 to December 1995, were included in the analysis. Results show that the presence of ice warning signs was not a significant factor in reducing ice-related crash frequency or severity.

Overall, from the above, it can be concluded that the effectiveness of static ice warning signs, regardless of whether they are implemented on the road or bridge, is marginal and may not have the desired cost-benefit ratio when looking at the placement and maintenance costs and their potential for reducing crashes. However, the conspicuity and message recognition, and thus their effectiveness, may be improved by adding different conspicuity elements, such as flashing beacon or flashing LED sign border, till such systems may have limited effectiveness if they flash at all times. Therefore, warning alerts/messages have to be present only when warranted based on real-time weather and pavement conditions. In general, such systems rely on real-time measurement of pavement surface conditions and other weather data from a nearby ESS or other road weather information system (RWIS) technology.

2.2.2 *Policies and Guidelines for BDWS and Application for "Icy Road" Warnings*

A number of state departments of transportation (DOTs) have implemented winter weather warning systems to improve driver speed selection during low-friction conditions, subsequently reducing the frequency and severity of crashes. In 2001, the Wyoming Department of Transportation installed an ice warning system on a curved bridge prone to icing in Nugget Canyon, located on U.S. Route 30 (southwest Wyoming). Prior to the bridge, there was a lengthy tangent stretch of roadway where head-on crashes were common due to the high speeds at which drivers would approach the bridge, causing an unexpected loss of control when the bridge was icy (Veneziano et al., 2014). The basic system included an in-pavement sensor used in conjunction with atmospheric sensors and in-field processing equipment to interpret the sensor data. Based on conditions, the system would determine if ice or frost was present and activate flashing beacons on a static ice warning sign. Overall, it was found that driving speeds dropped by 5 to 10 mph when the beacons were activated, although it is likely that these speed reductions were affected by variations in weather conditions between the beacon-off and beacon-on conditions. Additionally, before implementation, at least one fatal crash occurred, while in four years after the implementation, there were no fatal crashes.

Oregon DOT deployed an ice warning system along a segment of Oregon Highway 140 in 2005 (Veneziano & Ye, 2011). The system employed an ESS at an elevation of 5,100 feet and two static "WATCH FOR ICE WHEN LIGHTS FLASH NEXT 20 MILES" warning signs equipped with beacons that flash when threshold conditions are met (**Figure 5**). After installation, driving speeds were significantly reduced by 9.5 mph on average (eastbound dropped by 10.4 mph and westbound by 8.4 mph). However, the researchers noted that it could not be conclusively determined from the collected data whether the beacons caused drivers to slow down or if poor road conditions caused motorists to drive more cautiously, as there were no control sites. Crash data were also analyzed using the data from 2003 to 2008, which included two years before system implementation and three years after implementation. Crash frequency trends showed that before implementation, an average of 43 crashes per season occurred, while after implementation, an average of 51 crashes occurred. Although this suggests that the implemented system is counterproductive, it has to be highlighted that the length and severity of winter conditions vary from year to year, which might be the reason for such crash frequency. Finally, researchers indicated that there is strong public acceptance and confidence in the implemented system. Most of the respondents to the driver survey stated that they are aware of the system, especially the beacons, and that this prompted them to reduce their speed and help them to be more attentive.

Figure 5. Ice Warning Signs with Flashing Beacons Used in Oregon (Veneziano & Ye, 2011)

In 2014, the Oklahoma Department of Transportation developed a prototype decision support system with the aim of predicting and detecting a thin coating of glazed ice on roadways or other transportation surfaces called “black ice.” Due to high transparency, “black ice” has an identical appearance to pavement and wet roads, and therefore, it’s very difficult to be seen by drivers. The main reason for developing such a system was that static warning signs with the message “ICE MAY FORM ON BRIDGE” did not draw enough attention from drivers. Overall, the system consists of a weather sensor system which detects ice formation and a wireless-controlled module which activates yellow lights on the ice-warning sign and/or red lights in case of lane closure (Liu et al., 2014a).

Veneziano et al. (2014) published a study in which they evaluated the speed impacts of an icy curve warning system (ICWS) on a five-mile segment of SR 36 in Lassen County, California. The system consisted of using pavement sensors to detect icy conditions (in total, five sensors for two locations), in combination with dynamically activated signage (two in each direction of travel), to warn drivers of icy conditions through a message stating "ICY CURVES AHEAD" when icy conditions were detected or predicted by one of the ice and environmental sensor station sensors. Speed data were measured by radar units mounted to each of the implemented signs and aimed at the lanes of approaching traffic. Overall, the results suggest that vehicle speeds were lower when the ICWS was on compared to the situation when it was off. Mean speeds were significantly reduced by greater than 5 mph during wet weather during both day and night. However, when ice was present but unexpected (e.g., clear, cold, and dry), mean speed reductions during the day and at night were between 3 and 5 mph when the system was active.

Similar systems have also been implemented outside of the United States. One example in British Columbia, Canada, involved multi-year implementation of automated RWIS connected with variable message signs, which has been continuously expanding since 2011 (Sengupta & Walker, 2020a). Each system includes an ESS connected to two variable message signs, one in each travel direction. The RWIS system consists of a number of sensors (including weather sensors, air temperature and humidity sensors, optical pavement sensors, and anemometers) which collect and analyze weather and road conditions every 15 minutes and automatically post a real-time condition message to the road users. The message is displayed on both VMSs in a flashing/alternating format to draw drivers' attention. The messages may be overridden by operators in the traffic management center to post other priority messages based on operational requirements.

2.2.3 *Types of Warning Sign Message Displays for* BDWS

Two main types of BDWS have been used by roadway agencies: static warning signs with various conspicuity aids (e.g., flashing beacons or borders) and DMS.

2.2.3.1 Enhancements to Traditional Static Warning Signs

DOTs have historically utilized various alternative messages on static warning signs to warn motorists of potential icy bridge conditions. These messages include the current MUTCD standard message "BRIDGE ICES BEFORE ROAD" as well as other variations such as "ICY BRIDGE", "WATCH FOR ICE ON BRIDGE", "BRIDGE MAY BE ICY", "REDUCE SPEED-ICE ON BRIDGE", or "ICE MAY FORM ON BRIDGE".

To improve sign conspicuity, the aforementioned signs are usually combined with flashing beacons or LED lights above the sign or implemented in the signs (around sign borders), which are activated when specific weather and pavement conditions are met, typically using one or more environmental sensors. In Oregon, a slightly different approach was used. Instead of standard diamond warning signs, rectangular static signs with the message "WATCH FOR ICE WHEN LIGHTS FLASH NEXT 20 MILES" equipped with flashing beacons were used (**Figure 5**).

2.2.3.2 Dynamic Message Signs

Dynamic message signs are also often implemented as a part of BDWS. According to a survey conducted among state DOTs, several agencies deploy road weather-related warnings for winter storms, high wind, dense fog, freezing rain, and blizzard conditions using DMSs (Rolland & Kline, 2019). Messages are typically delivered through a manual process in the majority of states, although a combination of manual and automated processes is used in eight states (Alabama, Maine, Maryland, Michigan, Mississippi, Nevada, Virginia, and Wisconsin). Also, the majority of survey respondents create messages using a combination of standard message templates and custom messages. Examples of such messages are presented in **Table 1**.

Table 1. Examples of Weather-Related Messages Displayed on DMS (Rolland & Kline, 2019)

State	Examples of the DMS message
Colorado	• HEAVY SNOW/ICY CONDITIONS EXPECTED THURSDAY THROUGH SATURDAY • HEAVY SNOW/ICY CONDITIONS EXPECTED AFTER 10 PM • SNOW FORECAST AFTER 8 AM/EXPECT CHANGING CONDITIONS • HEAVY SNOW/HIGH WINDS OVERNIGHT/VISIBILITY MAY BE LIMITED
Indiana	• WINTER WEATHER/ADVISORY - REDUCE YOUR SPEED/DO NOT TAILGATE
New York	• HEAVY SNOW EXPECTED - AVOID TRAVEL • POOR DRIVING CONDITIONS - REDUCE SPEED
Tennessee	• WET CONDITIONS/ICY CONDITIONS/ICE AND SNOW POSSIBLE - USE CAUTION/TAKE IT SLOW • POSSIBLE ICE ON BRIDGES - USE CAUTION • ICE AND SNOW/ICY/ICE AND SNOW COVERED ROADWAY CONDITIONS - TAKE IT SLOW AHEAD/USE CAUTION/HEADLIGHTS ON WHEN SNOWING
Vermont	• WINTER WEATHER - WATCH YOUR SPEED
Virginia	• WINTER STORM – WARNING – TONIGHT • BLACK ICE – POSSIBLE - USE CAUTION
Michigan	• BLIZZARD/ FREEZING/ICE/ICY/SLIPPERY

Messages are most commonly displayed on DMS before a storm event (Maine, Missouri, New York, Pennsylvania, and South Dakota). In Delaware and Mississippi, messages are displayed at event onset, while in Vermont, during the event. British Columbia, Canada posts various weather and surface condition DMS messages that are selected based on condition. Examples of these messages are presented in **Table 2**.

Table 2. Weather-Specific DMS Messages (Sengupta & Walker, 2020a)

Message	Condition
Road Icy/Slow Down	Snowy or icy surface with extreme low level of grip.
Slippery Sections/Use Caution	Slushy, frosty, snowy, or icy surface with moderate level of grip.
Heavy Snowfall/Use Caution	Snowfall with acceptable level of grip.
Water Pooling on Road/Use Caution	Rainfall with surface temperature above freezing.
Standard Safety Messaging (static, not flashing)	Absence of triggering conditions for the higher priority messages.

2.2.3.3 Dynamic Speed Feedback Signs

Dynamic speed feedback signs (DSFS), also known as speed feedback signs or dynamic speed display signs, are small full-matrix DMS panels that provide active information to the drivers on a digital display after detecting the speed of approaching vehicles. The signs can be programmed to display the speed of the approaching vehicle or warning messages, such as "SLOW DOWN," "YOU ARE SPEEDING SLOW DOWN," "HIGH SPEED SLOW DOWN," and "EXCESSIVE SPEED SLOW DOWN." DSFS have been found to reduce speeds across various highway speed-reduction contexts, including work zones, sharp horizontal curves, freeway exit ramps, speed transition zones, high-speed arterials, school zones, and residential neighborhoods. Previous studies have shown that DSFS has a significant impact on reducing crashes of both passenger cars and heavy vehicles (S. L. Hallmark, Qiu, et al., 2015; Tribbett et al., 2000). However, speed feedback signs have not previously been evaluated for weather warning messaging purposes.

2.2.4 ***BDWS Sensors***

Activation of weather-related messages or warning alerts on BDWS typically rely on data obtained from an ESS at the bridge deck. The ESS includes a suite of sensors that gather and transmit weather and pavement data to a processor where the warning alerts may be activated or messages selected, either automatically or manually, depending on the jurisdiction.

A standard ESS configuration used to support winter maintenance activities usually consists of an air temperature/relative humidity sensor, wind sensor, precipitation sensor, surface sensor, sub-surface sensor, and processing units (Milosevi & Gajic, 2007). Also, many agencies may include several additional sensors to meet specific needs or interests, such as biometric pressure sensors, visibility sensors, solar radiation sensors, net radiometer sensors, snow depth sensor, IP surveillance systems (CCTV), and traffic monitoring devices (In-pavement sensor and Microwave vehicle detection system) (Milosevi & Gajic, 2007).

2.2.4.1 Atmospheric Sensors for Detecting Frost Conditions

Although a variety of sensors are used on an ESS, the most critical sensors for predicting unexpected icy conditions on bridges include those used to detecting and predict frost condition. Traditionally, to determine a frost condition, a combination of atmospheric sensors as well as surface and subsurface sensors are necessary (Al-Kaisy, 2006). Atmospheric sensors mainly collect data related to air temperature, relative humidity, dew temperature, air pressure, and precipitation (Gibby et al., 1992). Air temperature and relative humidity sensors are used in combination to determine the ambient air temperature and the amount of moisture in the atmosphere. The key parameter derived from an air temperature/RH sensor is the dew point temperature, which, when used with pavement temperature, is a critical factor in determining the potential for frost and dew at an ESS location. Air pressure plays an important role in calculating the prediction algorithm for any icing on the road (Gibby et al., 1992). Typically, aneroid barometers are used in meteorological applications to measure the air pressure. Such barometers contain an aneroid cell - a sealed, flexible metal box or pair of thin circular disks - that expands or contracts as atmospheric pressure changes (Sayed et al., 1999). Precipitation is measured based on optical and radar-based sensors, which provide accurate estimates of the precipitation type and intensity during normal precipitation events. However, both sensors exhibit a tendency to overestimate the amount of precipitation when wind speeds are in excess of 30 mph due to turbulence that impacts the rate of fall of snow or water droplets (Milosevi & Gajic, 2007).

2.2.4.2 Surface and Subsurface Sensors for Detecting Frost Conditions

Surface and subsurface sensors measure pavement conditions (e.g., temperature, dry, wet, ice, freeze point, chemical concentration) and subsurface or soil conditions. There are two basic types of surface sensors: active and passive.

<u>Passive Sensors:</u> Passive pavement condition sensors detect energy radiating from an external source and do not change the chemical or thermal conditions of the layer of snow, ice, water, and chemicals they are measuring (Sayed et al., 1999). They provide information related to the pavement temperature, pavement condition status (dry, wet, trace moisture, etc.), the chemical concentration, and factors derived from surface condition and chemical concentration. Although they are most commonly used for collecting pavement data, their disadvantage is the fact that they are invasive, i.e., they need to be physically installed in the highway pavement (typically on the outside edge of the wheel track closest to the shoulder) (Milosevi & Gajic, 2007).

<u>Active Sensors:</u> Active sensors generate and emit a signal and measure the radiation reflected by a targeted surface and are used to measure freeze point temperature. Typically, active pavement sensors heat and cool the mixture of snow, ice, water, and chemicals back and forth through the freezing point of the mixture. Since active sensors head and cool the surface, therefore, they are coupled with a passive sensor, which measures the pavement temperature. The ESS controller can

use the combined input from the two sensors to provide a good estimate of the chemical characteristics of the surface layer (percentage of ice and chemical concentration) and the surface condition. Active sensors are installed in the pavement using techniques similar to passive sensors (Milosevi & Gajic, 2007; Sayed et al., 1999).

2.2.4.3 Contact Free Sensors

Recently, a contact-free technology was introduced. Such technology uses non-invasive sensors mounted to the side or above the road surface. They use infrared optics, and in contrast to the bottom-up measuring process of invasive sensors, these sensors work top-down from an average distance of 20-50 feet above the road. Since the water molecule absorbs IR energy differently when it occurs as water, ice, or snow, contact-free sensors measure the amount of energy in specific wavelengths and use the energy levels in these wavelength bands to determine the depth of snow, ice, and water in the surface layer. Furthermore, they measure the amount of radiation in the full IR spectrum to determine the temperature of the top surface of the pavement or the top of the layer of snow, ice, and water on the pavement. These sensors "see" the road conditions like a camera or a scanner and rate the "grip" of the surface (i.e., friction) on a scale of zero to one. The higher the grip value, the more traction a vehicle will get during wet or icy conditions (Milosevi & Gajic, 2007). An example of a non-intrusive system is presented in **Figure 6**.

Figure 6. Non-Invasive Ice Detection and Warning System (Klugman et al., 1992)

2.2.4.4 Mobile Sensors

Mobile sensors involve the integration of sensors and other systems onto vehicle platforms. Such systems combine sensors with vehicle location and data communications technologies to sense both pavement conditions (e.g., temperature, friction) and atmospheric conditions (e.g., air temperature) (Weidemann et al., 2011). Although less widespread than fixed sensors, several state transportation agencies, such as Iowa, Michigan, and Minnesota, have deployed maintenance vehicles equipped with mobile environmental sensors to determine pavement freeze point temperature. The freeze point sensor is composed of a receptacle that collects liquid from tire spray, and a computer system calculates the freeze point of the liquid (Sayed et al., 1999). In addition to these efforts by state agencies, a Connected Vehicle Program that could be widely deployed on light and heavy vehicles has the potential to dramatically increase the number of mobile sensor systems across the United States. (Weidemann et al., 2011).

2.2.5 ***Benefits Associated with BDWS***

As described earlier, the driver behavior and traffic safety benefits of standard static ice warning signs are questionable. Even when these signs are combined with additional conspicuity elements (e.g., flashing beacon or flashing LED sign border), they may not have a desired cost-benefit ratio when considering their installation and maintenance costs versus their potential for crash reduction. Systems which provide warnings based on real-time weather and pavement conditions tend to be viewed more positively in terms of alerting motorists of potentially slippery conditions, eliciting appropriate response from motorists, and subsequent safety benefits.

Although the literature lacks broader evidence of safety benefits associated with BDWS, a select number of BDWS implementations have shown some evidence of positive impacts on driver behavior in terms of reduced driving speed and crash reductions. Wyoming DOT's ice warning system on Nugget Canyon bridge found driving speeds to have dropped 5 to 10 miles per hour when the systems were active, although it is likely that these speed reductions were affected by variations in weather conditions between the beacon-off and beacon-on conditions. Additionally, four years after the implementation, no fatal crashes had occurred compared to the years prior to systems implementation in which at least one fatal crash occurred annually. In addition, Oregon and California's example of icy road warnings indicated that such warning reduces driving speed between 3 and 10 mph and that such systems may provide a monetary benefit of $1.7 million per winter season through reduced crashes (Veneziano et al., 2014).

Overall, when BDWS is integrated with an ESS, one could expect significant positive safety related benefits. Case studies from different US states clearly highlight that RWIS implementation is an efficient investment and that potential benefits include reduced travel time, crash reduction during adverse weather, and operating cost savings through more efficient use of winter maintenance resources. MDOT has previously evaluated the benefits and costs of deploying RWIS in four regions finding benefit-cost ratios between 2.8 and 7.0, with travel time savings providing a significant proportion of the benefits (Murphy, 2012). Similar conclusions were found in the British Columbia, Canada study, where such a system was used for warnings in severe winter conditions. Crash data showed a reduction of over 30% after systems implementation, while economic evaluation showed that the systems led to a benefit-cost ratio of 4.8 and an overall net present value of more than $12 million (Esawey et al., 2019).

2.2.6 ***Screening Methods to Identify Potential BDWS Implementation Locations***

The primary method used for identifying bridges for implementation of BDWS is most commonly based on some combination of winter crash frequency, approach road geometry, and high speeds approaching the bridge, in addition to the frequency of icy conditions on the bridge. For example, the Nugget Canyon bridge was selected for implementation of the ice warning system by the Wyoming DOT due to the bridge being on a horizontal curve, in an area that was prone to icing, and possessing a long tangent stretch of roadway leading to up the bridge where travel speeds were typically 75 to 80 miles per hour, which led to a high frequency of head-on crashes at the bridge during icy conditions (Veneziano et al., 2014). In Canada, BDWS is implemented on rural highways that experience extreme winter weather conditions and poor safety performance (Sengupta & Walker, 2020b). The Oklahoma DOT suggested identifying bridges in areas that are susceptible to “black ice,” which has a similar appearance to wet pavement making it difficult for drivers to detect (Liu et al., 2014b).

2.3 State Agency Survey

To supplement the literature review, the MSU research team also conducted a national-level survey of transportation agencies with experience in the deployment and operation of BDWS, including ESS/RWIS. The main objectives of the survey were to:

- Obtain policies, guidelines, and other strategies utilized by agencies for site selection and installation of BDWS or other similar motorist alert systems that rely on RWIS technology to activate weather warning messages.
- Determine details related to the BDWS or other road weather warning systems, including system specifications and associated costs, types of messages or warnings displayed, type of environmental sensor and communication protocols and peripherals, data and decision algorithm used for posting warning messages, speed data collection components, mounting equipment and procedures, installation location with respect to the bridge, sign durability and maintenance, connected vehicle/V2I communication components, and details regarding communication with operations centers.
- Obtain information pertaining to any published or internal evaluations of the safety, operational, and/or economic benefits associated with the use of BDWS or other road weather warning systems. This includes details related to site selection, field data collection and analysis, findings, and recommendations.

The questions (found in **Appendix A**) were focused on identifying details related to deployment and operation of RWIS/ESS across the U.S. The survey included questions related to the use of RWIS/ESS for the activation of BDWS, DMS/VMS, and warning sign/flashing beacon to provide weather-related messages at the bridge, the number of RWIS/ESS deployed in a state, and also the utilization of ESS data in conjunction with a connected vehicle, V2I type of application.

Initially, the survey was sent to 44 agencies that experience winter weather throughout the United States. The list of agencies was compiled by the research team based on prior communication and an internet search for appropriate personnel. Next, the survey was distributed to members of the Aurora winter operation program (Iowa State University, 2022) to circulate the survey to their member agencies, which ultimately increased the number of responses. A total of 12 responses were received from eight states. The use of RWIS/ESS in those states are summarized in **Table 3** with detailed survey responses provided in **Appendix A**. A total of four of the responding states were noted as utilizing RWIS/ESS for weather related messaging, although only Michigan, Wisconsin, and Illinois utilized the systems for weather messages at bridge overpasses, and only Michigan and Wisconsin used warning systems that were specific to bridges.

Table 3. Summary of Key Findings from Survey

State	Summary and Key Findings
Michigan	• More than 50 RWIS/ESS are deployed • RWIS/ESS are connected to DMS/VMS and activated warning sign or flashing beacon to display weather related messages • Activated warning sign or flashing beacon are deployed to display weather related messages at bridge or overpass • Crash analysis was done to select the critical location of RWIS connected active warning sign
Wisconsin	• More than 50 RWIS/ESS are deployed • RWIS/ESS are connected to DMS/VMS messaging system through TMC operator • DMS/VMS are deployed to display weather related messages at bridge or overpass
Illinois	• 11 to 20 RWIS/ESS are deployed • RWIS/ESS are connected to DMS/VMS to display weather related messages at bridge or overpass • Sites are selected based on ability to monitor weather conditions for the overall Illinois Tollway system as well as critical locations that have high numbers of crashes in inclement weather.
Washington	• More than 50 RWIS/ESS are deployed • RWIS are only used to display weather conditions and camera views • None of these RWIS are deployed at the bridge
Rhode Island	• 11 to 20 RWIS/ESS are deployed • None of them are used to display weather related messages • Use for dashboard for viewing • RDOT has a project where RWIS data is utilized in conjunction with a connected vehicle. For that DOT have 13 trucks in the fleet.
Indiana	• More than 50 RWIS/ESS are deployed • None of them are used to display weather related messages • Purpose of RWIS is not mentioned in the survey
Arizona	• 11 to 20 RWIS/ESS are deployed • RWIS are used for winter operations such as forecasting, images, and deployments • Looking at DMS activation through RWIS
Ohio	• More than 50 RWIS/ESS are deployed • TOC operator reviews RWIS data and manually enters messages as needed • snow and ice control/VSL corridor

2.4 State of the Practice Summary

During the winter season, bridges often freeze prior to the adjacent pavement. This may lead to a potentially hazardous situation since drivers often do not expect slippery pavement upon encountering the bridge deck. To tackle this problem, most DOTs that experience winter weather use static warning signs to convey winter weather warning messages at bridges. These messages include MUTCD standard “BRIDGE ICES BEFORE ROAD” as well as other variations such as “ICY BRIDGE,” “WATCH FOR ICE ON BRIDGE,” “REDUCE SPEED-ICE ON BRIDGE,” or “ICE MAY FORM ON BRIDGE”. However, the effectiveness of such signs is questionable due to the frequency of the signs and ever-present messages, and consequently, such signs may not provide the desired safety benefits.

To improve effectiveness of winter weather warning strategies, several agencies have implemented BDWS, which consist of ESS equipped with various atmospheric and pavement sensors that collect the data related to the air temperature, relative humidity, dew temperature, air pressure, precipitation, and other pavement conditions. Based on the data collected by these sensors, the system determines if ice or frost is present and activates either flashing elements on warning signs or a DMS message. Although the literature lacks broader evidence of safety benefits associated with BDWS, a select number of BDWS implementations have shown some evidence of positive impacts on driver behavior in terms of reduced driving speed and crash reductions. Although agencies typically do not employ formal screening processes for identification of bridge locations for BDWS implementation, selection of bridges for BDWS implementation is typically based on a combination of the following factors: 1.) frequency of target winter crashes; 2.) road geometry at the bridge; 3.) speed approaching the bridge; 4.) frequency of icy conditions on the bridge.

However, due to the limited implementation of BDWS nationwide, the effectiveness of these systems on driver behavior and safety performance during winter driving conditions is not well established in the literature. Thus, research was performed to determine the effectiveness of BDWS in terms of driver behavior and safety performance and to provide guidance to support future deployments of BDWS within Michigan and nationwide.

3. FIELD EVALUATION METHODOLOGY

A series of field evaluations were performed at freeway BDWS locations to evaluate the impact of the BDWS on driver behavior while approaching bridges during winter weather conditions. The field evaluations were performed across various roadway, weather, and pavement conditions. The results of these field evaluations were ultimately intended to select the optimal warning alert strategy for future BDWS deployments at critical locations across Michigan. The following subsections provide a summary of the field evaluation methods, including site selection, sign test conditions, field data collection, measures of effectiveness, and analytical methods. Specific details related to the field evaluations are provided in subsequent chapters.

3.1 Preliminary Site Investigations

During the initial planning stages for the field evaluations in Fall 2021 a total of eight BDWS installations were operational as a part of MDOT's RWIS network. Seven of these eight BDWS installations were bi-directional, which gave a total of 15 directional BDWS locations, which are listed in **Table 4**. Each site was reviewed using satellite and street-view imagery, and as a result, seven of the 15 available sites were deemed potentially suitable for data collection. Thereafter, a series of site visits and preliminary data collection was performed at each of these seven sites, as noted in **Table 4**.

After a thorough evaluation, only two sites, NB and SB US-131 at E-50 Road near Cadillac, Michigan were deemed to be suitable for further evaluation. These sites were selected primarily because it included a nearby upstream bridge overpass with a standard MUTCD W8-13 warning sign and no BDWS that could serve as a control site. This study design would allow for the speeds of individual vehicles to be tracked through both the control site and BDWS study site, thereby isolating of the effects of the BDWS treatment across various conditions. A comprehensive field evaluation was performed at these two locations during the initial (i.e., 2021/2022) winter season.

Travel challenges for data collection during the initial winter season made it desirable for selection of a site closer to MSU's campus for the field evaluations performed during the second (i.e., 2022/2023) winter season. After consultation with the MDOT project team, NB US-127 over Willoughby Rd near Lansing, Michigan was utilized for field evaluations occurring during the 2022/2023 winter season. This site was selected due to proximity and because as it was on a straight segment and with broad shoulders and a flat roadside, which made it suitable for field data collection. Further details pertaining to the selected sites and field data collection procedures are explained in the sections that follow.

Table 4. List of Available MDOT BDWS sites and Field Data Collection Potential

Site No	Area	Location	Data Collection Potential	Data Collection Dates
1	Cadillac	NB US-131 at E-50 Rd	Possible	Dec 2021 to Mar 2022
2	Cadillac	SB US-131 at E-50 Rd	Possible	Dec 2021 to Mar 2022
3	Cadillac	NB US-131 at M-115	Possible	Nov 16 and 23, 2021
4	Cadillac	SB US-131 at M-115	Possible	Nov 22 and 23, 2021
5	Cadillac	NB US-131 at S-43 Mile Rd	Possible	Nov 23, 2021
6	Cadillac	SB US-131 at S-43 Mile Rd	Possible	Nov 16 and 23, 2021
7	Cadillac	NB US-131 at Railroad	Not Possible	
8	Cadillac	SB US-131 at Railroad	Not Possible	
9	Escanaba	WB US-2 at Escanaba River	Not Possible	
10	Escanaba	EB US-2 at Escanaba River	Not Possible	
11	Gaylord	NB I-75 at Charles Brink Rd	Not Possible	
12	Gaylord	SB I-75 at Charles Brink Rd	Possible	Nov 19, 2021
13	Gaylord	NB I-75 at Trowbridge Rd	Not Possible	
14	Gaylord	SB I-75 at Trowbridge Rd	Not Possible	
15	Pontiac	NB I-75 at Square Lake Rd	Not Possible	

Note: SB = Southbound, and NB = Northbound

3.2 Field Evaluation Sites

3.2.1 ***Site 1: NB US-131 Cadillac***

The first BDWS site utilized for field evaluation during the 2021/2022 winter season was NB US-131 over E-50 Rd near Cadillac, Michigan. A satellite view of the site is shown in **Figure 7**. The site was located on a limited-access freeway with a speed limit of 75 mph for passenger cars and 65 mph for heavy vehicles. As mentioned earlier, this site was specifically selected as it included a nearby upstream bridge that did not include BDWS signs, thereby allowing for a case-control study design. The control bridge, which was over White Pine Recreational Trail, was approximately 0.85 miles (4,500 feet) to the south of the BDWS bridge and was similar in length to the E-50 bridge.

Figure 7. Study Site Layout at NB US-131 over E-50 Rd in Cadillac, Michigan

The base sensor suite at the ESS site at US-131 in Cadillac (sites 1 and 2), shown in **Figure 8**, includes a camera, wind sensor, precipitation sensor, air temperature sensor, humidity sensor, visibility sensor, surface pavement sensor, and a sub-surface temperature probe. A field controller remote processing unit (RPU) is connected to the array of ESS sensors, allowing for the transfer of the data from the field controller to MDOT's central server, where the data are processed and the LED sign border is automatically activated when slippery conditions are detected on the bridge.

The sign activation algorithms allow consideration of a number of factors to activate the flashing sign border, including air temperature, dew point temperature, bridge deck temperature, freezing point, surface status, precipitation type, and surface friction. However, after preliminary testing, MDOT modified the activation algorithm to utilize only bridge deck surface temperature and surface friction to activate the flashing LED border, which only occurred when the bridge deck surface temperature was less than 0°C, and the bridge deck surface friction coefficient was less than 0.4.

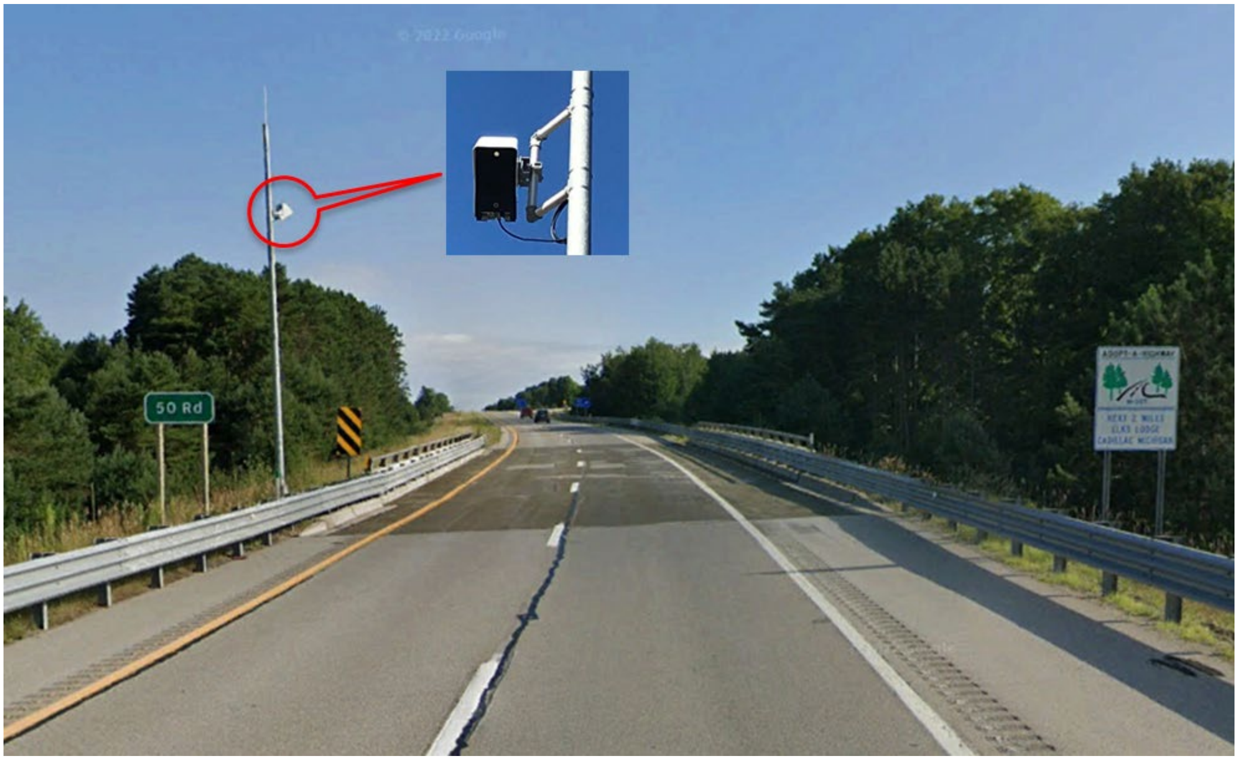


Figure 8. Environmental Sensor Station, US-131 Bridge over E50 Rd in Cadillac, Michigan

3.2.2 *Site 2: SB US-131 Cadillac*

The SB US-131 bridge over E-50 Rd in Cadillac was also utilized for field evaluation during the 2021/2022 winter season. The site layout is shown in **Figure 9**. The bridge was also the overpass bridge on E-50 Rd but in the opposite traffic direction to site 1. The site did not have a control bridge upstream of the BDWS bridge; therefore, only the BDWS site was utilized for the field evaluation. This site was selected due to being suitable for speed data collection using LiDAR guns, as there was no obstruction of the guardrail, broad shoulders, and a flat roadside. Furthermore, given the combination of low traffic volume and its suitability for LiDAR data collection, this location also afforded the opportunity for conducting nighttime data collection. Similar to site 1, this site contains an existing BDWS connected to the ESS installed at the E-50 bridge overpass.

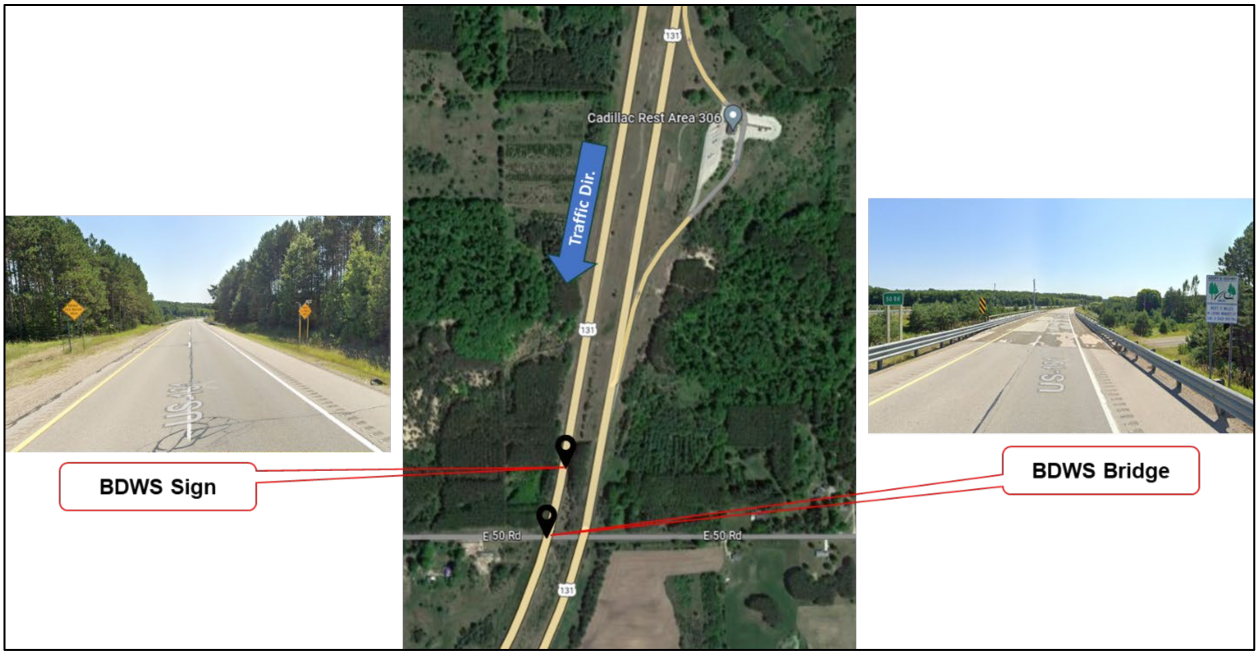


Figure 9. Study Site Layout at SB US-131 over E-50 Rd in Cadillac, Michigan

3.2.3 *Site 3: NB US-127 Lansing*

As noted previously, travel challenges during the initial winter season made it desirable for the selection of a site closer to MSU's campus for the field evaluations performed during the second winter season. NB US-127 over Willoughby Rd near Lansing, Michigan, was utilized for field evaluations occurring during the 2022/2023 winter season, which is shown in **Figure 10.** This site was specifically selected due to its proximity and because it was on a straight segment with broad shoulders and a flat roadside, which made it suitable for field data collection. This site was also selected due to the presence of a DMS prior to the bridge, which allowed for evaluation of icy bridge related warning messages posted on the DMS, in addition to the traditional BDWS. It should be noted that this site did not include an existing BDWS, which required the installation of a manually enabled BDWS for the field evaluation, as no ESS existed within the proximity of the bridge. Furthermore, although this location did not include an upstream control bridge, it was possible to begin tracking vehicle speeds far upstream of the BDWS sign. The site was also located on a limited-access freeway with a speed limit of 70 mph for passenger vehicles and 65 mph for heavy trucks and buses.

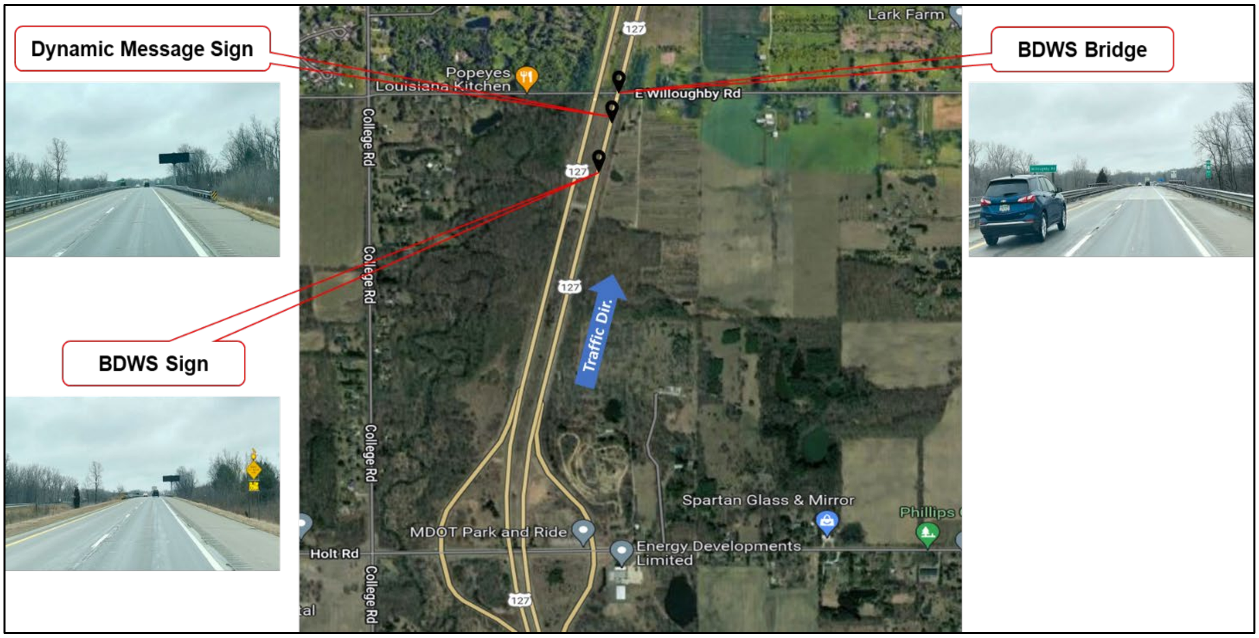


Figure 10. Study Site Layout at NB US-127 over Willoughby Rd in Lansing, Michigan

3.3 Sign Test Conditions

The BDWS test conditions, which varied between the three evaluation sites, are described in the following subsections.

3.3.1 *Site 1: NB US-131 Cadillac*

As previously stated, the US-131 site included an existing MDOT BDWS that was on both sides of the highway and connected to an ESS located at the bridge. The BDWS was a 48-in by 48-in "BRIDGE ICES BEFORE ROAD" warning sign (W8-13) with eight flashing LEDs along the sign border and was located 535 ft upstream of the bridge. During normal operation, the flashing LED border was activated based on the ESS data when the bridge deck surface temperature was below 0°C and the bridge deck surface friction coefficient was less than 0.4. However, during the field evaluation, the flashing LED border was periodically manually activated during the field evaluation by MDOT at the request of the researchers when the pavement was wet and the temperature was below freezing, which was similar to the sensor activation conditions. Due to the unpredictability of winter weather conditions, this manual activation of the BDWS was important to allow for data to be collected in an efficient manner across the various test conditions.

In addition to testing BDWS by itself, a DSFS display panel was installed beneath the BDWS sign on the right side as a means of providing an additional driver warning alert. The DSFS consisted of a full-matrix amber LED feedback panel capable of displaying characters up to 18 inches in height with a maximum of two lines of text. The DSFS panel contained an embedded radar for detection of approaching vehicles, possessing a typical detection range of approximately 400 feet for passenger cars, extending beyond 600 feet for trucks. The DSFS remained dark until the radar sensor detected an approaching vehicle, at which point a "SLOW DOWN" message was displayed on the panel which was programmed to pulse between high and low intensity at a rate of 1 hertz. The DSFS was battery powered and only activated during data collection. A representative image of the active BDWS and DSFS at the NB US-131 study site is displayed in **Figure 11.**

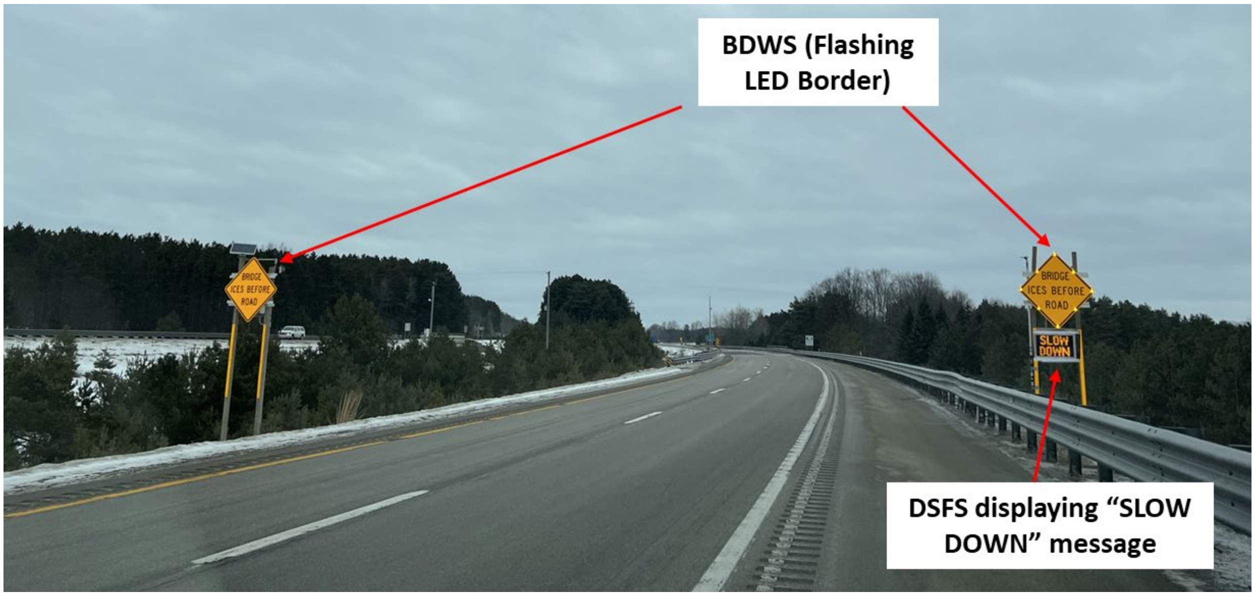


Figure 11. Example of Active BDWS and DSFS at NB US-131 Cadillac Site

During the evaluation at NB US-131 in Cadillac, three bridge deck warning sign conditions were tested at the BDWS site, which are described as follows and displayed in **Figure 12**.

- <u>Inactive Sign:</u> In this condition, the LED border of the W8-13 and the DSFS panel were off (dark). Thus, the sign was not functionally different from the standard MUTCD W8-13 sign located at the control site.
- <u>Flashing LED Border</u>: In this condition, the LED border of the W8-13 sign was flashing while the DSFS panel remained off (dark).
- <u>Flashing LED Border plus DSFS with Pulsing "SLOW DOWN" Message</u>: In this condition, the LED border of the W8-13 sign was flashing, and the DSFS displayed a *pulsing* "SLOW DOWN" message upon detection of an approaching vehicle.

The upstream control site on NB US-131 included a standard 48-in by 48-in MUTCD W8-13 sign without any warning lights or alerts, which remained unchanged during the field evaluation.

Figure 12. Field Evaluation Layout and Sign Test Conditions at NB US-131 Cadillac Site

3.3.2 *Site 2: SB US-131 Cadillac*

Similar to Site 1 (NB US-131), an existing BDWS sign was present at the SB US-131 Cadillac site as shown in **Figure 13**. The BDWS sign was located on the right side of the road, approximately 545 ft upstream of the bridge, and was connected to the ESS as the NB bridge (Site 1). Along with a BDWS sign on the right, an additional static W8-13 sign was also present on the left side, as shown in **Figure 13**. Also similar to Site 1, in addition to testing BDWS by itself, a DSFS display panel was installed beneath the BDWS sign as a means of providing an additional driver warning alert. The tested BDWS and DSFS signs were identical to the signs tested at site 1 (NB US-131 Cadillac). Further, the sign test conditions were also identical to site 1. However, as mentioned earlier, due to the unavailability of the control site upstream of the BDWS site, the speed data were collected at the BDWS site only. The field evaluation layout and sign test conditions at SB US-131 over E-50 Rd in Cadillac is displayed in **Figure 14**. Note that a limited amount of data were collected during dark conditions, in addition to daylight conditions.

Figure 13. Example of Active BDWS and DSFS at SB US-131 Cadillac Site

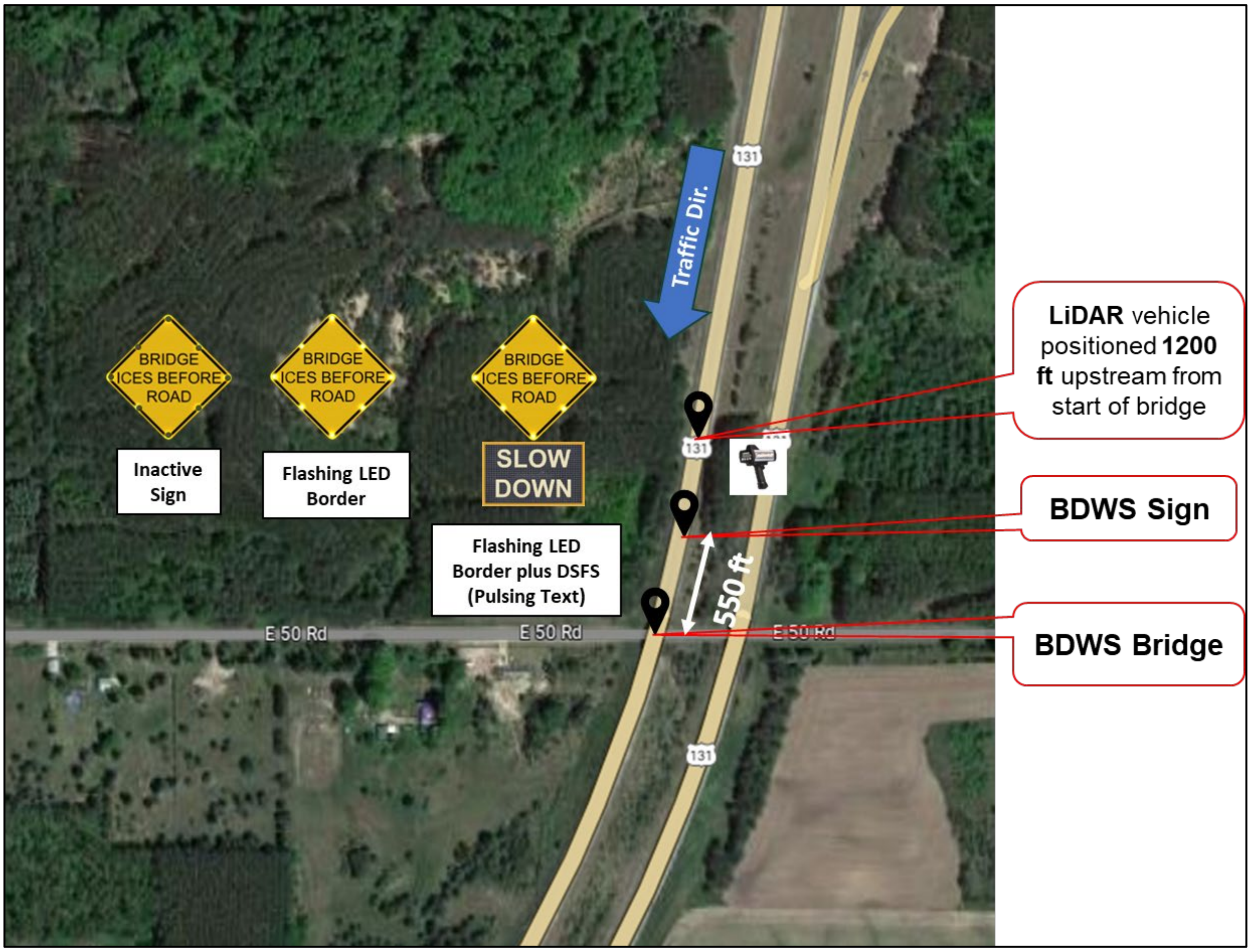


Figure 14. Field Evaluation Layout and Sign Test Conditions at SB US-131 Cadillac Site

3.3.3 *Site 3: NB US-127 Lansing*

3.3.3.1 BDWS and DSFS signs

The BDWS sign tested at the US-127 Lansing site consisted of a MUTCD standard 12-inch diameter amber beacon affixed to the top of the existing W8-13 sign that was 720 ft upstream of the bridge. When activated, the beacon would flash at a rate of 1 hertz. The flashing beacon was selected as an alternative to the flashing LED border sign that was tested during the prior winter season at US-131 in Cadillac. The beacon was installed by MDOT for this field evaluation one week prior to the start of field data collection. As no ESS existed at this location, the beacon was activated and deactivated manually during data collection using a switch, which provided flexibility to evaluate the sign test conditions across various weather conditions. Similar to the US-131 site, the DSFS was again installed beneath the W8-13 sign but had been re-programmed by the manufacturer to include an additional "ICY ROAD" message in addition to the previously used "SLOW DOWN" message. While the "SLOW DOWN" message could be set to alternate between steady and pulsing, the "ICY ROAD" message could only be given as a steady display. The DSFS was battery-powered and only activated during data collection. A representative image of the active BDWS and DSFS at the NB US-127 study site is displayed in **Figures 15 and 16**. Five different bridge deck warning sign test conditions were tested at the NB US-127 Lansing site, which are described as follows and are displayed in **Figure 17**.

- Inactive Sign: In this condition, the beacon above the W8-13 and the DSFS panel were off (dark). Thus, the sign was not functionally different from a standard MUTCD W8-13 sign.
- Flashing Beacon: In this condition, the beacon above the W8-13 sign was flashing while the DSFS panel remained off (dark).
- Flashing Beacon plus DSFS with Pulsing "SLOW DOWN" Message: In this condition, the beacon above the W8-13 sign was flashing, and the DSFS displayed a *pulsing* "SLOW DOWN" message upon detection of an approaching vehicle.
- Flashing Beacon plus DSFS with Steady "SLOW DOWN" Message: In this condition, the beacon above the W8-13 sign was flashing, and the DSFS displayed a *steady* "SLOW DOWN" message upon detection of an approaching vehicle.
- Flashing Beacon plus DSFS with Steady "ICY ROAD" Message: In this condition, the beacon above the W8-13 sign was flashing, and the DSFS displayed a *steady* "ICY ROAD" message upon detection of an approaching vehicle.

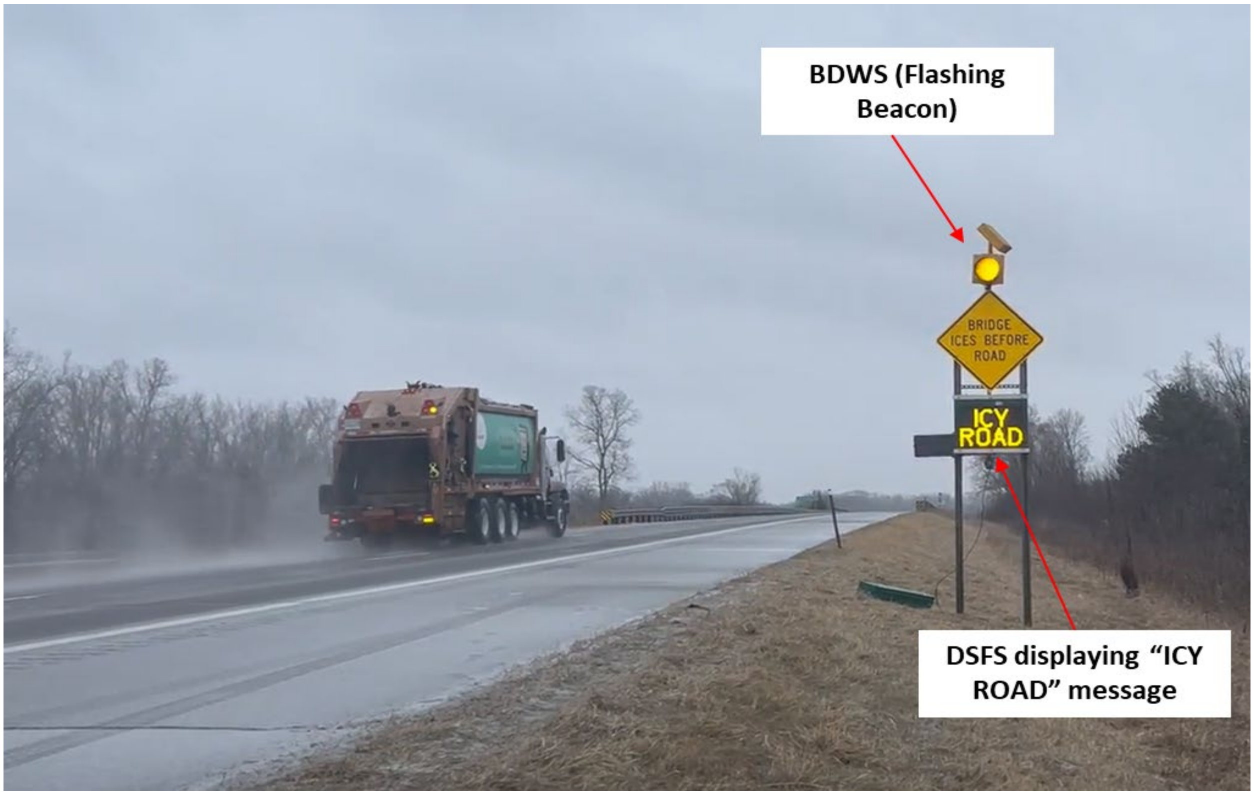


Figure 15. Example of Active BDWS and DSFS with "ICY ROAD" Message at NB US-127 Lansing Site

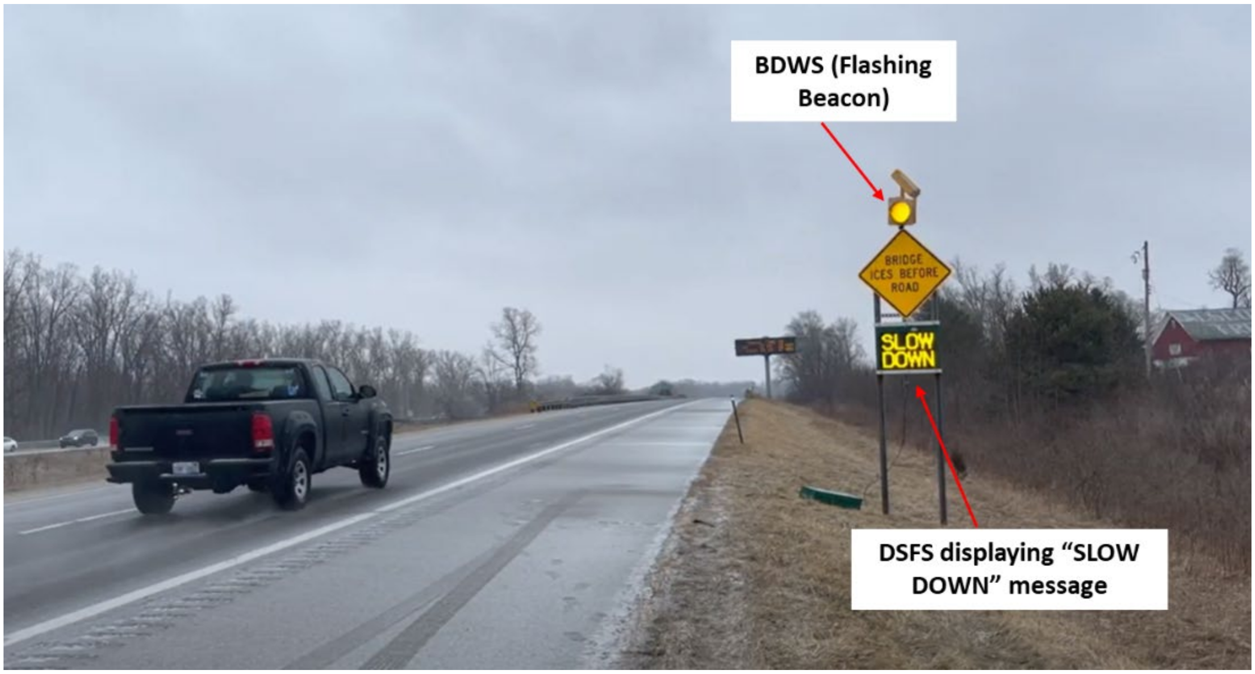


Figure 16. Example of Active BDWS and DSFS with "SLOW DOWN" Message at NB US-127 Lansing Site

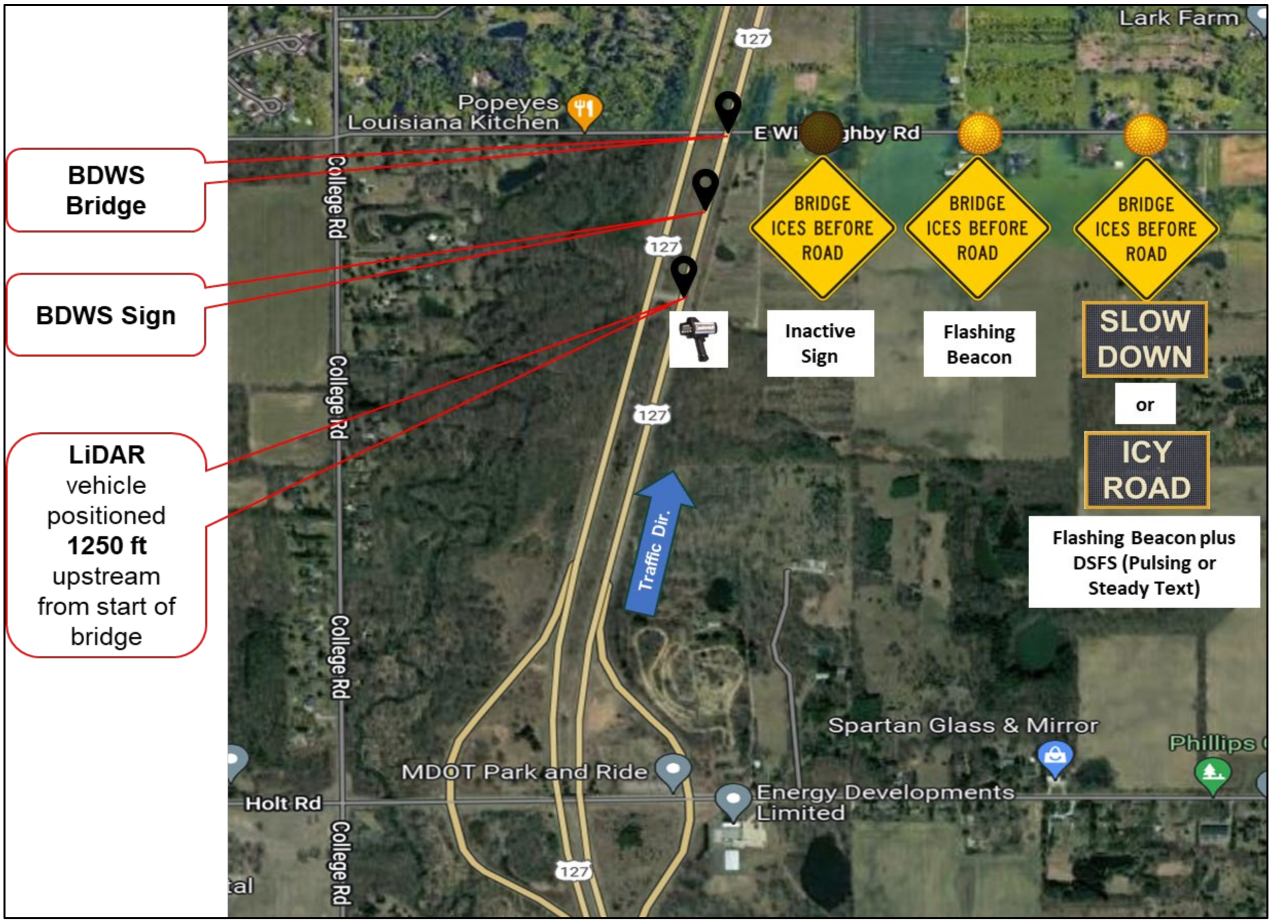


Figure 17. Field Evaluation Layout and Sign Test Conditions at NB US-127 Lansing Site

3.3.3.2 Dynamic Message Sign (DMS)

As noted previously, a permanent DMS located 150 feet upstream of the bridge was also present at the US-127 Lansing site, which was utilized to test the effectiveness of various warning messages during winter weather conditions. This DMS, shown in **Figure 18,** was a full matrix amber LED panel that was 29.33 ft wide by 8 ft tall and capable of displaying 25 alphanumeric characters of 13 inches wide by 18.2 inches tall in up to three rows. The DMS was controlled by the MDOT Statewide Transportation Operation Center (TOC) located in Lansing. The message content, message length, aspect ratio of alphanumeric characters, phases of messages, and unit information were selected in consultation between the research team, MDOT project team, and MDOT statewide operations center personnel.

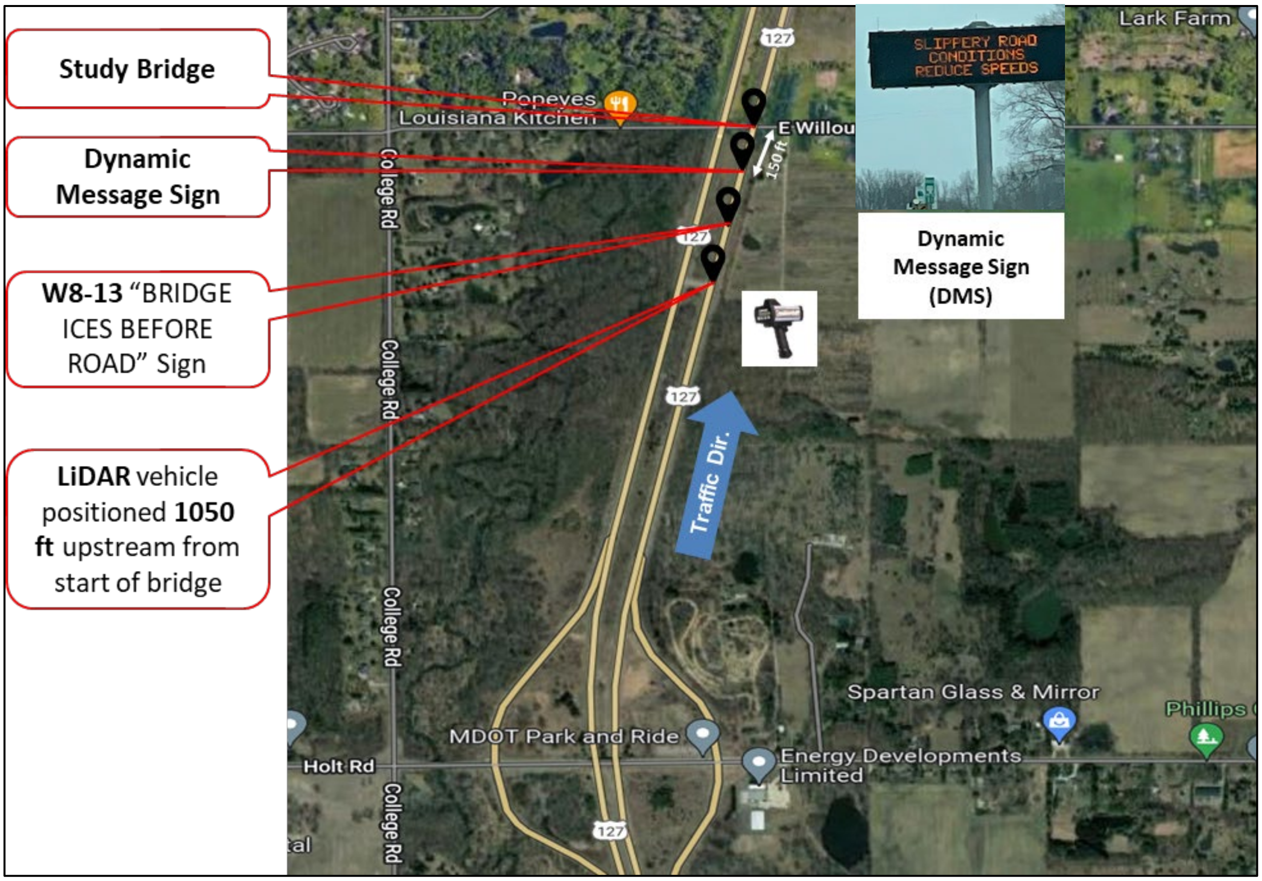


Figure 18. Field Evaluation Layout and for DMS Evaluation at NB US-127 Lansing Site

Four different DMS messages were selected and tested, including three related to winter weather warning along with the standard travel time message, which served as the baseline messaging condition. The four test messages along with the selection rationale for each message are displayed in **Table 5**, with field photos of each message shown in **Figure 19.** The DMS test messages were pre-programmed by MDOT TOC staff to be changed every 20 minutes during data collection, which afforded some control over the variation in weather conditions and general driver behavior throughout the day. This messaging cycle was repeated four times during the data collection period, providing four sets of data for each test message.

To better control for weather conditions, data were collected on a single weekday in early March, 2023 between 8 AM and 5 PM. The weather that day was heavily overcast in the low 30-degree Fahrenheit range, with light snow occurring regularly during data collection. Regular snow removal and de-icing of the pavement by MDOT created a wet pavement condition throughout the entire data collection period.

Figure 19. DMS Test Messages at NB US-127 Study Site

Table 5. DMS Test Messages and Selection Rationale at NB US-127 Study Site

Message Number	DMS Message Display	Rationale
Travel Time Message Test Message 1 (Base Condition)	TRAVEL TIME TO I-69 12 MI 11 MIN ST JOHNS 25 MI 22 MIN	This message represents the basedline DMS messaging utilzied by MDOT during normal conditions.
Weather Related Test Message 2	BRIDGES ICE BEFORE ROAD REDUCE SPEEDS	This message was selected at it reinforced the message displayed on the W8-13 sign (BRIDGE ICES BEFORE ROAD), while adding the desired action of "REDUCE SPEEDS".
Weather Related Test Message 3	SLIPPERY ROAD CONDITIONS REDUCE SPEEDS	This message was selected at it represented MDOT's standard DMS messaging during winter weather conditions.
Weather Related Test Message 4	SLIPPERY ROAD CONDITIONS REDUCE SPEEDS	This message is the same as above, but split into two frames, with each frame displayed for 4 seconds.

3.4 Data Collection Methods

The speeds of individual vehicles were tracked while traversing through each evaluation site. As a minimum, speed measurements were taken for each vehicle both at the bridge warning sign and at the start of the bridge. Two different methods were employed for the collection of speed data between the three evaluation locations. A series of elevated high-definition video cameras were installed at site 1 (NB US-131 Cadillac), while a LiDAR gun was used at site 2 (SB US-131 Cadillac) and site 3 (NB US-127 Lansing). The method of data collection was selected based on the suitability of the shoulder and roadside and the safety of the data collectors during adverse weather conditions.

The data were collected during each of the specified sign test conditions and across different weather conditions (i.e., sunny, cloudy, snow), pavement conditions (i.e., dry, wet), and times of day (i.e., dawn, morning, afternoon, dusk, evening, and night). All data was collected during weekdays only. The details of the data collection and data extraction process of these two methods were explained in the following subsections.

3.4.1 *High Definition Video Cameras*

At the NB US-131 Cadillac site, vehicle speed data were collected simultaneously at the control and study site using a series of four pole-mounted video cameras that recorded high-definition video at 60 frames per second. The cameras were elevated to a height of 15 feet and aimed towards a pre-determined location on the roadway. This camera setup allowed for spot speeds of individual vehicles to be tracked at the warning sign and bridge at both the control site and BDWS site, as shown in **Figure 12**. The general field views from the four camera setups are displayed in **Figure 20**. Data were collected periodically at the NB US-131 Cadillac site using this method between December 2021 and March 2022.

The video data collected at US-131 Cadillac were manually reviewed by a team of trained technicians using QuickTime software, which allowed for a frame-by-frame review for speed and headway estimation. Subject vehicles were initially identified at the furthest upstream video (e.g., at the control site sign camera) and subsequently tracked through each of the four cameras between the control and BDWS sites. Tracking individual vehicles in this manner controls for differences between drivers, weather, and pavement surface conditions, thereby allowing for the effects of the test sign condition to be isolated. The following data related to the vehicle and site conditions were collected for each subject vehicle at each camera location: vehicle type, headway, speed (estimated by the time to traverse successive lane lines), pavement surface conditions, weather conditions, and time of day. In order to isolate driver speed selection behavior, as opposed to forced speed selection during platooning, only free-flowing vehicles with a headway greater than 4 seconds were considered in this analysis. Vehicles were also excluded if they changed lanes while traversing through the site. The final dataset included speed measurements taken at each of the four camera locations for 3,017 vehicles, including 2,547 passenger cars and 470 heavy vehicles.

Control Sign **Control Bridge**

BDWS Sign **BDWS Bridge**

Figure 20. Example Fields of View from Speed Tracking Cameras, NB US-131, Cadillac

3.4.2 *LIDAR Guns*

At site 2 (SB US-131, Cadillac) and site 3 (NB US-127, Cadillac), vehicle speed measurements were made using handheld light detection and ranging (LiDAR) guns. In this method, free-flowing vehicles (minimum headway of 4 seconds) were continuously tracked from the location of the LiDAR vehicle to the start of the bridge. The LiDAR guns were ProLaser III manufactured by Kustom Signals, which detect vehicular speed and distance at a rate of three times per second with an accuracy of ±1 mph up to 6,000 ft. However, line-of-sight obstructions, such as geometry and encroachment of other vehicles, limit the practical operating range to approximately 1,500 ft. The LiDAR data collection vehicle was positioned on the edge of the shoulder upstream of the test sign as shown in **Figure 21**. The positioning of the data collection vehicle ensured that the vehicle was away from any critical speed assessment points (e.g., BDWS, bridge) to minimize the influence of the data collection vehicle on drivers. The LiDAR data were collected from the same location and using the same procedures across each of the data collection periods.

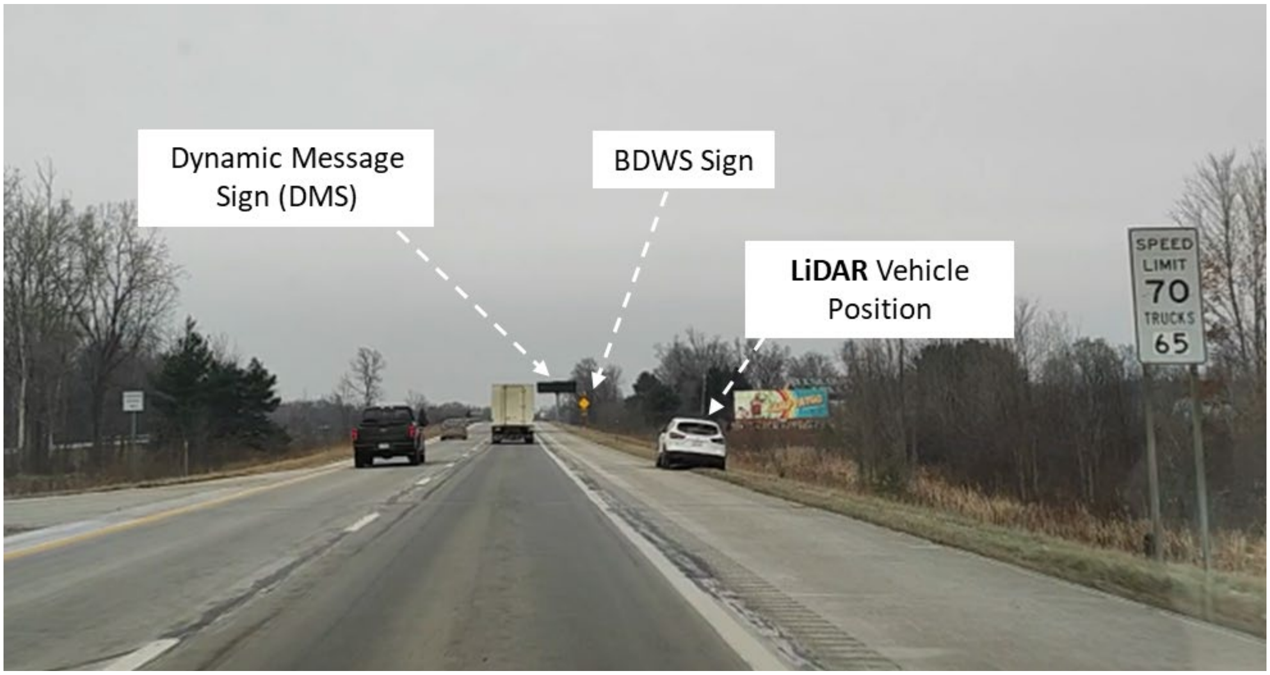
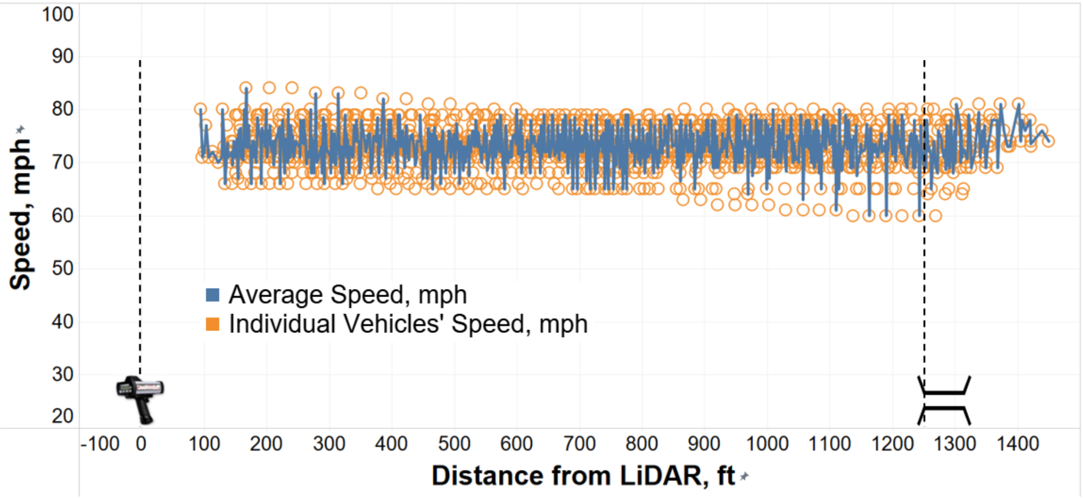


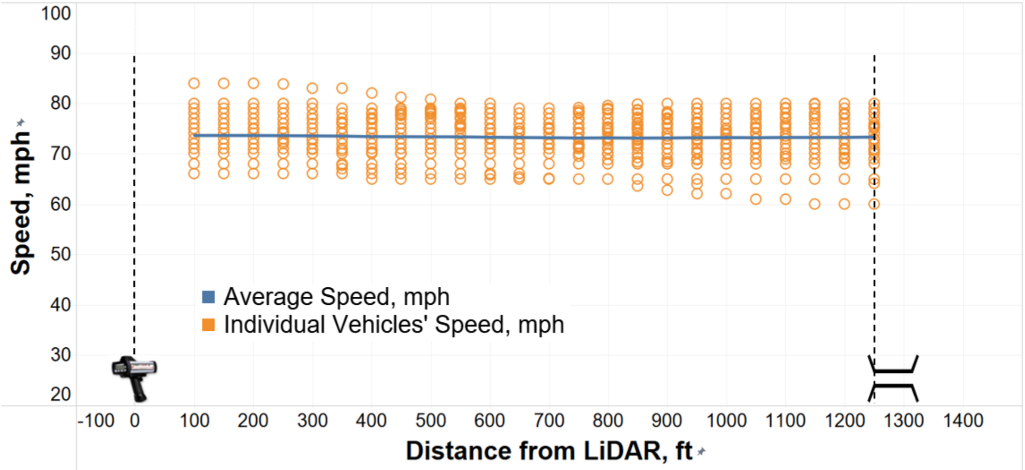
Figure 21. Position of LiDAR Vehicle at the NB US-127 Lansing Site

The LiDAR gun was connected to a laptop using a serial cable, which allowed for real-time recording of the time stamp, distance, and speed for each LiDAR measurement. The technician would begin the speed tracking process when the subject vehicle was at least 100 ft beyond the data collection vehicle and would continue to track each subject vehicle until it had reached the start of the bridge deck. After completion of the LiDAR tracking for each subject vehicle, data collectors added information regarding the vehicle type, weather, roadway surface condition, bridge surface condition, temperature, and time of day. The data was stored in a text file format, which was converted into an Excel file for further data processing. Vehicles that were tracked less than the point of start of the bridge were removed from the file along with any vehicles that changed lanes or made any other unusual behavior, as noted in the comments.

Using LiDAR for tracking vehicular speeds provides a significant advantage over cameras or pneumatic tubes, as it produces continuous speed measurements over the entire segment of interest, as opposed to spot speeds at fixed points. Because LiDAR speeds can't be measured at the same locations on the roadway for every vehicle, the speed data were converted to a series of spot speeds at 50 ft increments using linear interpolation in order to allow for speeds to be assessed at specific reference points of interest (e.g., at the BDWS, at the start of the bridge). An example of the raw and interpolated speed data is shown in **Figure 22**. As the relative distances between the LiDAR collectors and all of the points of interest (e.g., BDWS sign, the start of the bridge) were known, all distances were converted relative to the start of the bridge prior to further analysis. The final dataset for site 2 (SB US-131 Cadillac) contained 1,098 vehicles, including 852 passenger cars and 246 heavy vehicles. Further, site 3 (US-127 Lansing) contained complete speed trajectories for 1,800 passenger cars. Heavy vehicles (e.g., trucks and buses) were excluded due to low volumes at the site.



(a) Raw speed data



(b) Interpolated speed data binned at 50 feet intervals

Figure 22. Raw and Interpolated Speed Data for Vehicles Approaching the Bridge

3.5 Dataset Preparation

The vehicle speed data were compiled and analyzed separately for each site due to differences between the sign test conditions and data collection procedures between the sites. The datasets were structured such that each row in the file represented the record for a single vehicle traversing the site during the specified sign test condition. The sign test conditions that were evaluated as a part of this field study included the following:

- BDWS
    - Inactive BDWS / Standard W8-13 (Base sign condition)
    - BDWS type (flashing LED border vs. flashing beacon)
    - Addition of a DSFS beneath the BDWS
    - DSFS Message Type (“SLOW DOWN” vs. “ICY ROAD”)
    - DSFS Message Display Method (Non-Pulsing vs. Pulsing Message)
- DMS
    - Travel time message (Base sign condition)
    - BRIDGE ICES BEFORE ROAD
REDUCE SPEEDS
    - SLIPPERY ROAD CONDITIONS
REDUCE SPEEDS
    - Frame 1: SLIPPERY ROAD CONDITIONS (4-second display)
Frame 2: REDUCE SPEEDS (4-second display)

The sign test condition was coded as a series of binary variables, which allowed for the speed-related effects for each sign test condition to be analyzed against the base sign condition. The remaining categorical factors were also added as a series of binary variables, which, where applicable, included: vehicle type (passenger vehicle, heavy vehicle), weather condition (clear, cloudy, snow, rain), pavement condition (wet, dry), and time of day (morning, mid-day, afternoon, night). The speed of each subject vehicle at the furthest upstream measurement location was included as an independent variable in the analysis to control for the normal behavior of each driver prior to encountering the test sign. Again, note that data were collected for heavy vehicles, across various weather conditions, and at night only at US-131 in Cadillac. Data were only collected during wet daytime conditions at the NB US-127 Lansing site.

3.6 Measure of Effectiveness

The speed of vehicles measured at the start of the BDWS bridge deck was the primary measure of effectiveness (MOE) related to driver response to the sign test condition. This MOE allowed for assessment of the magnitude of the speed reduction associated with each sign test condition compared to the base condition (i.e., W8-13). The MOE was analyzed separately for heavy trucks and passenger vehicles at both Cadillac sites, where an adequate sample of trucks were available, while only passenger vehicles were analyzed at the Lansing site. The MOE was further analyzed based on driver type, which were categorized into slower, average, and faster drivers based on the speed measured at the furthest upstream location. Finally, the MOE was also assessed for a sample of nighttime data collected at the SB US-131 Cadillac site.

3.7 Analytical Method

The data were analyzed using linear regression. All analyses were performed using RStudio. The general form of the linear regression model is given by **Equation 1**:

$$\mathrm{Y_i} = \beta_0 + \beta_1 \mathrm{X_{i1}} + \beta_2 \mathrm{X_{i2}} + \cdots + \beta_k \mathrm{X_{ik}} + \varepsilon_i \qquad \textbf{(Eq. 1)}$$

where Y_i is the measured speed at the bridge for vehicle i, X_{i1} to X_{ik} are independent variables affecting the dependent variables, β_0 is an intercept, β_1 to β_k are estimated regression coefficients for each independent variable, and ε_i is a normally distributed error term with variance σ^2.

It should be noted that speed at the speed at the furthest upstream measurement location was included as an independent variable (covariate) in each model. Including upstream speed as a covariate controlled for the variation in the speed selection tendencies of drivers between the data collection periods, in thereby controlling for variations in road conditions, weather conditions, and general driver behavior in order to better isolate the effects of the sign treatment condition.

3.8 Summary of Field Evaluation Methodology

A summary of the sign test conditions, data collection methods, analytical conditions, and measure of effectiveness employed for each of the three study sites are summarized in **Table 6**.

Table 6. Summary of Field Evaluation Methodology for Each Site

Sign Test Conditions		Data Collection Method	Analysis Conditions	Measure of Effectiveness
Site 1: NB US-131 over E-50 Rd, Cadillac				
	Inactive sign (base condition)	Video cameras were used to track speeds of individual vehicles while approaching both the upstream control bridge and the BDWS bridge.	The data were analyzed across the various sign test conditions, with separate analyses for low, average, and high-speed drivers and heavy trucks.	Speed at the BDWS bridge
	Flashing LED border			
	Flashing LED border plus DSFS with pulsing "SLOW DOWN" message			
Site 2: SB US-131 over E-50 Rd, Cadillac				
	Inactive sign (base condition)	Handheld LiDAR guns were used to track speeds of individual vehicles while approaching the BDWS bridge.	The data were analyzed across the various sign test conditions, with separate analyses for low, average, and high-speed drivers, heavy trucks, and at night.	Speed at the BDWS bridge
	Flashing LED border			
	Flashing LED border plus DSFS with pulsing "SLOW DOWN" message			

Table 6. Summary of Field Evaluation Methodology for Each Site (Continued)

Sign Test Conditions		Data Collection Method	Analysis Conditions	Measures of Effectiveness
Site 3: NB US-127 over Willoughby Rd, Lansing				
	Inactive sign (base condition)	Handheld LiDAR guns were used to track speeds of individual vehicles while approaching the BDWS bridge.	The data were analyzed across the various sign test conditions for passenger vehicles only, with separate analyses for low, average, and high-speed drivers.	Speed at the BDWS bridge
	Flashing beacon			
	Flashing beacon plus DSFS with pulsing “SLOW DOWN” message			
	Flashing beacon plus DSFS with steady “SLOW DOWN” message			
	Flashing beacon plus DSFS with steady “ICY ROAD” message			
	Dynamic Message Sign			

3.9 Data Summary – Bridge Deck Warning System Evaluation

The descriptive statistics (minimum, maximum, mean, and standard deviation) of the dependent variables and independent variables for the BDWS field evaluation are presented separately by site in **Tables 7, 8, and 9**. The mean values for the categorical variables listed in the tables represent the proportion of the total data set represented by that variable. The descriptive statistics of the NB US-131 Cadillac (**Table 7**) and SB US-131 Cadillac (**Table 8**) are further divided based on vehicle type (passenger cars vs. heavy vehicles). As mentioned in the previous chapter, 2,547 passenger cars and 470 heavy vehicles were observed at the NB US-131 Cadillac site. Similarly, at the SB US-131 Cadillac site, 852 passenger cars and 246 heavy vehicles were recorded. At the US-127 Lansing site, 1,800 passenger cars were recorded; heavy vehicles were not recorded due to relatively low volumes. It should again be noted that data was only collected during wet pavement conditions at the US-127 Lansing site. The proportion of observations across the pavement conditions, weather conditions, times of day, and sign test conditions are also provided for each site in **Tables 7, 8, and 9**.

Table 7. Descriptive Statistics for BDWS Evaluation at Site 1 (NB US-131 Cadillac)

Passenger Cars (n = 2,547)				
Parameters	**Minimum**	**Maximum**	**Mean**	**Std. Dev.**
Speed at BDWS bridge (dependent variable), mph	41.497	96.332	74.925	5.740
Speed at upstream control site (covariate), mph	48.000	99.000	76.464	5.051
Sign Test Condition				
Inactive sign	0	1	0.236	0.424
Flashing LED Border	0	1	0.492	0.500
Flashing LED Border + DSFS with “SLOW DOWN” (Pulsing)	0	1	0.272	0.445
Pavement Condition				
Wet	0	1	0.349	0.477
Dry	0	1	0.651	0.477
Times of Day				
Morning	0	1	0.278	0.448
Mid-day	0	1	0.397	0.489
Evening	0	1	0.325	0.468
Weather Condition				
Clear	0	1	0.268	0.443
Cloudy	0	1	0.684	0.465
Snowy	0	1	0.048	0.214
Heavy Vehicles (n = 470)				
Parameters	**Minimum**	**Maximum**	**Mean**	**Std. Dev.**
Speed at BDWS bridge (dependent variable), mph	40.059	82.570	61.352	6.184
Speed at upstream control site (covariate), mph	54.000	82.000	65.266	3.556
Sign Test Condition				
Inactive sign	0	1	0.209	0.407
Flashing LED Border	0	1	0.487	0.500
Flashing LED Border + DSFS with “SLOW DOWN” (Pulsing)	0	1	0.304	0.461
Pavement Condition				
Wet	0	1	0.394	0.489
Dry	0	1	0.606	0.489
Time of Day				
Morning	0	1	0.372	0.484
Mid-day	0	1	0.366	0.482
Evening	0	1	0.262	0.440
Weather Condition				
Clear	0	1	0.287	0.453
Cloudy	0	1	0.653	0.476
Snowy	0	1	0.060	0.237

Note: 0=no, 1=yes for binary variables

Table 8. Descriptive Statistics for BDWS Evaluation at Site 2 (SB US-131 Cadillac)

Passenger Cars (n = 852)				
Parameters	**Minimum**	**Maximum**	**Mean**	**Std. Dev.**
Speed at BDWS bridge (dependent variable), mph	53.000	91.000	74.874	5.306
Speed upstream of the BDWS (covariate), mph	55.000	92.000	75.600	5.072
Sign Test Condition				
Inactive sign	0	1	0.306	0.461
Flashing LED Border	0	1	0.264	0.441
Flashing LED Border + DSFS with “SLOW DOWN” (Pulsing)	0	1	0.430	0.495
Pavement Condition				
Wet	0	1	0.540	0.499
Dry	0	1	0.460	0.499
Times of Day				
Morning	0	1	0.336	0.473
Evening	0	1	0.501	0.500
Night	0	1	0.163	0.370
Weather Condition				
Clear	0	1	0.062	0.242
Cloudy	0	1	0.803	0.398
Snowy	0	1	0.135	0.342
Heavy Vehicles (n = 246)				
Parameters	**Minimum**	**Maximum**	**Mean**	**Std. Dev.**
Speed at BDWS bridge (dependent variable), mph	54.000	81.000	66.552	4.040
Speed upstream of the BDWS (covariate), mph	56.000	81.000	67.018	3.702
Sign Test Condition				
Inactive sign	0	1	0.350	0.478
Flashing LED Border	0	1	0.248	0.433
Flashing LED Border + DSFS with “SLOW DOWN” (Pulsing)	0	1	0.402	0.491
Pavement Condition				
Wet	0	1	0.390	0.489
Dry	0	1	0.610	0.489
Time of Day				
Morning	0	1	0.407	0.492
Evening	0	1	0.354	0.479
Night	0	1	0.240	0.428
Weather Condition				
Clear	0	1	0.110	0.313
Cloudy	0	1	0.801	0.400
Snowy	0	1	0.089	0.286

Note: 0=no, 1=yes for binary variables

Table 9. Descriptive Statistics for BDWS Evaluation at Site 3 (NB US-127, Lansing)

Passenger Cars (n = 1,800)				
Parameters	**Minimum**	**Maximum**	**Mean**	**Std. Dev.**
Speed at BDWS bridge (dependent variable), mph	44.000	91.000	69.868	5.607
Speed upstream of the BDWS (covariate), mph	50.000	90.000	70.425	4.986
Sign Test Condition				
Inactive Sign	0	1	0.350	0.477
Flashing Beacon	0	1	0.248	0.432
Flashing Beacon + DSFS with "ICY ROAD" (Steady)	0	1	0.106	0.308
Flashing Beacon + DSFS with "SLOW DOWN" (Steady)	0	1	0.092	0.290
Flashing Beacon + DSFS with "SLOW DOWN" (Pulsing)	0	1	0.202	0.401
Time of Day				
Morning	0	1	0.356	0.479
Mid-day	0	1	0.487	0.499
Evening	0	1	0.155	0.362
Weather Condition				
Clear	0	1	0.198	0.398
Cloudy	0	1	0.310	0.463
Snowy	0	1	0.369	0.483
Rainy	0	1	0.123	0.328

Note: 0=no, 1=yes for binary variables. Data were only collected for passenger cars and wet pavement conditions.

Graphical representation of the average vehicle speed trajectories for each sign test condition are displayed by vehicle type in **Figure 23** (NB US-131 Cadillac), **Figure 25** (SB US-131 Cadillac), and **Figure 27** (NB US-127 Lansing). The speed trajectory data for passenger vehicles were further subdivided into groups representing slower, average, and faster drivers across each of the sign test conditions, based on the speed for each driver at the furthest upstream measurement point. After rank-ordering these data, the lowest 1/3 were characterized as slower drivers, the middle 1/3 were characterized as average drivers, and the highest 1/3 were characterized as faster drivers. Graphical representation of the average vehicle speed trajectories separated by driver type for each sign test condition are displayed in **Figure 24** (NB US-131 Cadillac), **Figure 26** (SB US-131 Cadillac), and **Figure 28** (NB US-127 Lansing).

In general, these figures show that with the BDWS sign active, speeds at the BDWS bridge were lower compared to when the BDWS was inactive, and the addition of a DSFS beneath the active BDWS further reduced speeds. The active BDWS (with or without the DSFS) had a greater speed reduction effect on heavy vehicles compared to passenger cars. Furthermore, although some differences in the speed reductions associated with the sign test conditions were observed across the driver behavior groups (e.g., slower, average, and faster), these differences were not consistent between the three sites. Further discussion on the BDWS effects will be provided in **Chapter 4**.

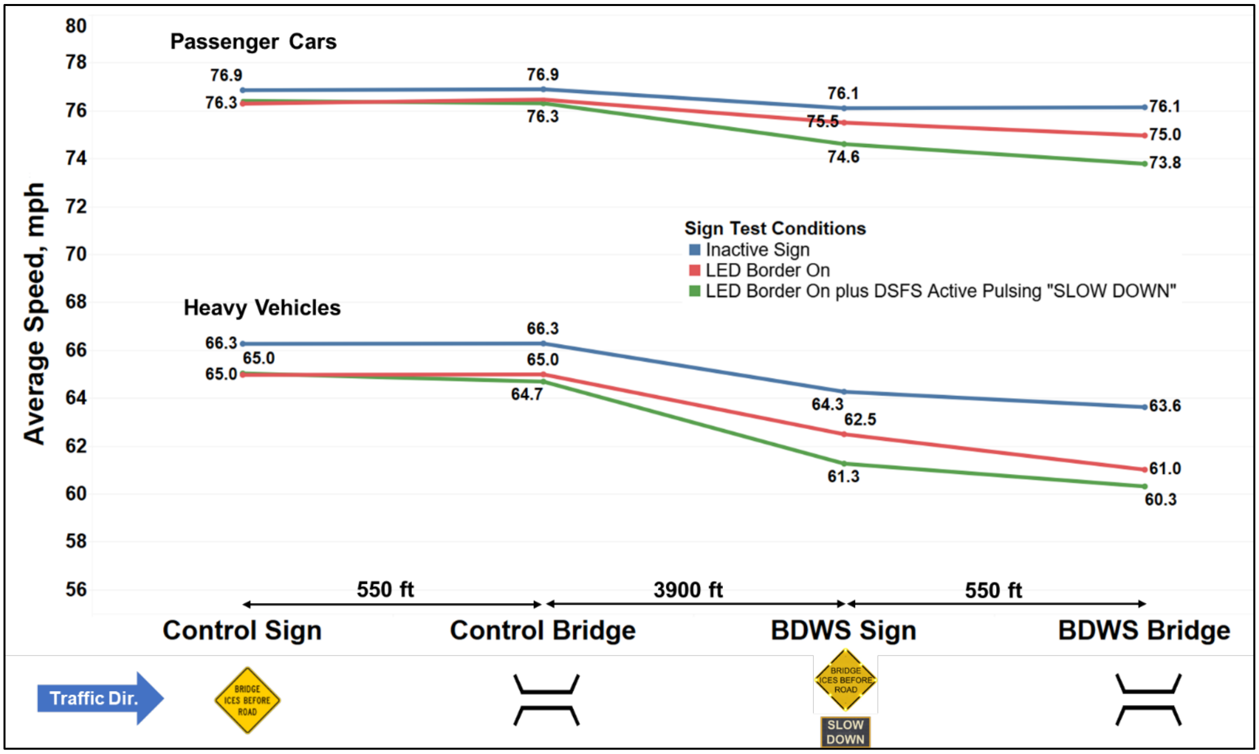


Figure 23. Average Speed Trajectories by Vehicle Type and Sign Test Condition, NB US-131 Cadillac

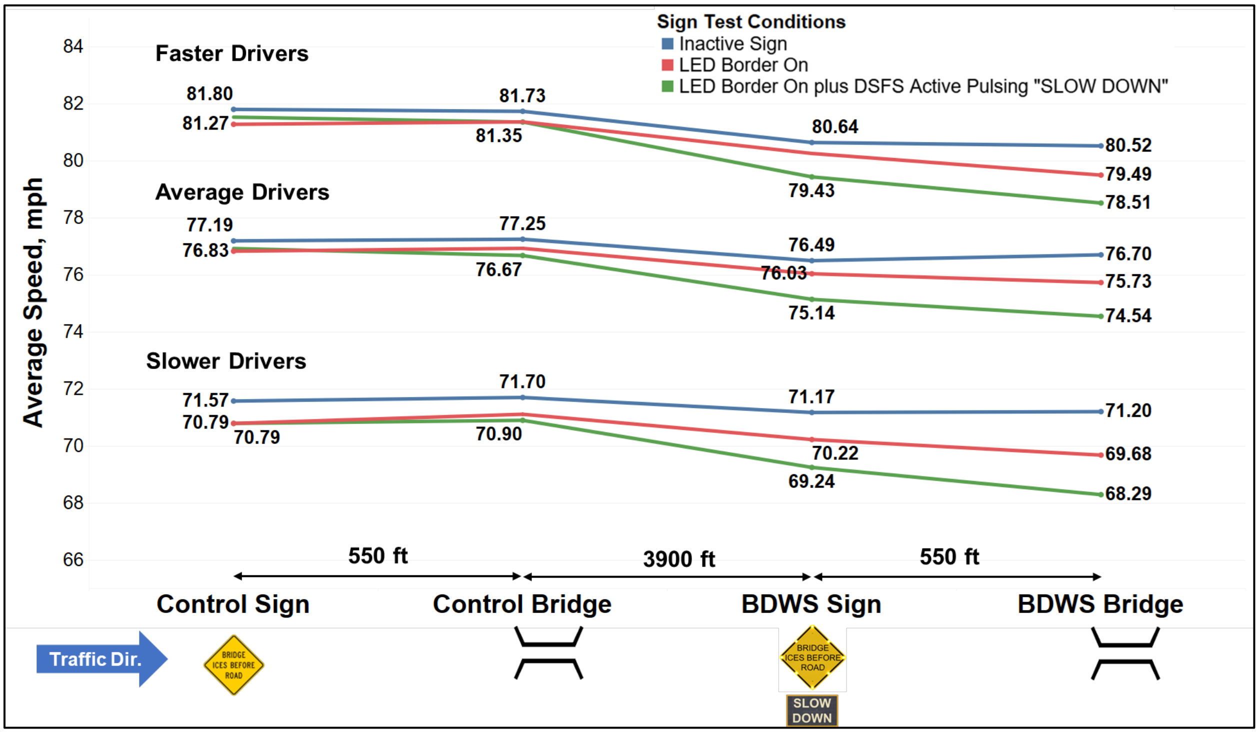


Figure 24. Average Speed Trajectories by Driver Type and Sign Test Condition, NB US-131 Cadillac

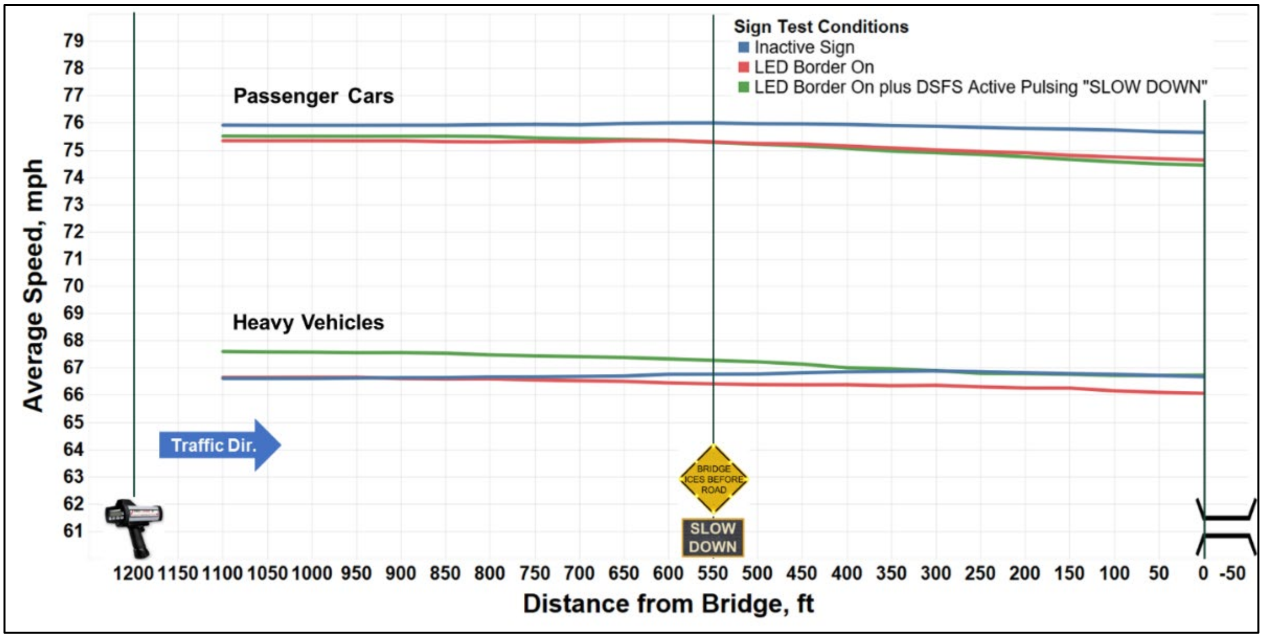


Figure 25. Average Speed Trajectories by Vehicle Type and Sign Test Condition, SB US-131 Cadillac

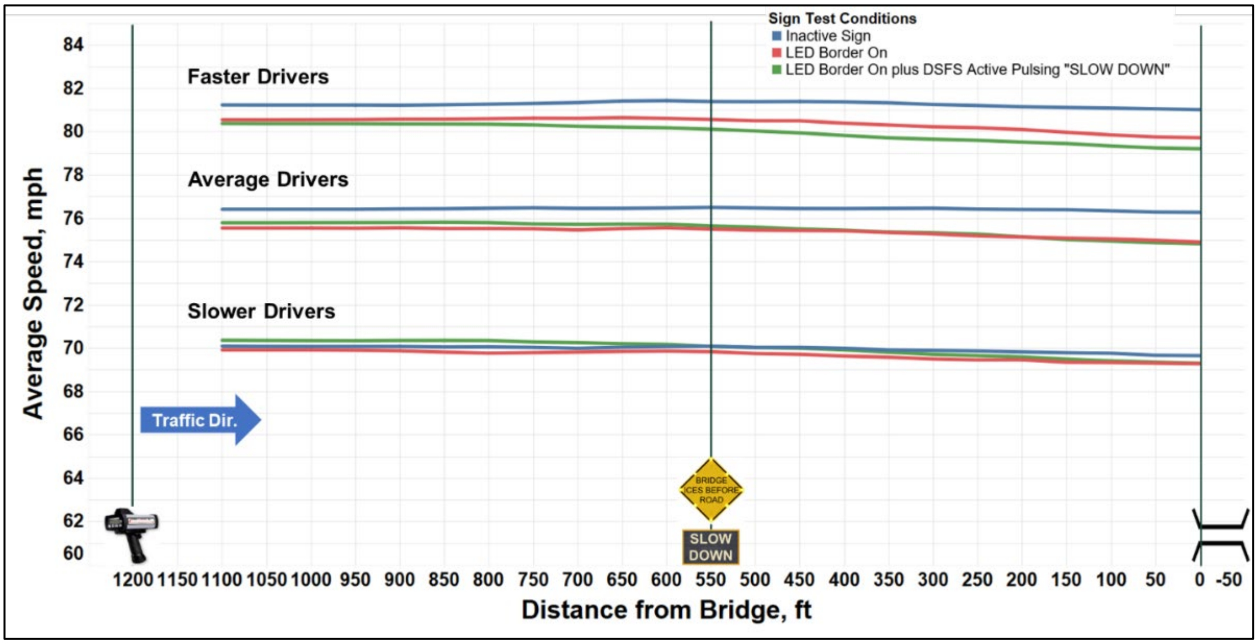


Figure 26. Average Speed Trajectories by Driver Type and Sign Test Condition, SB US-131 Cadillac

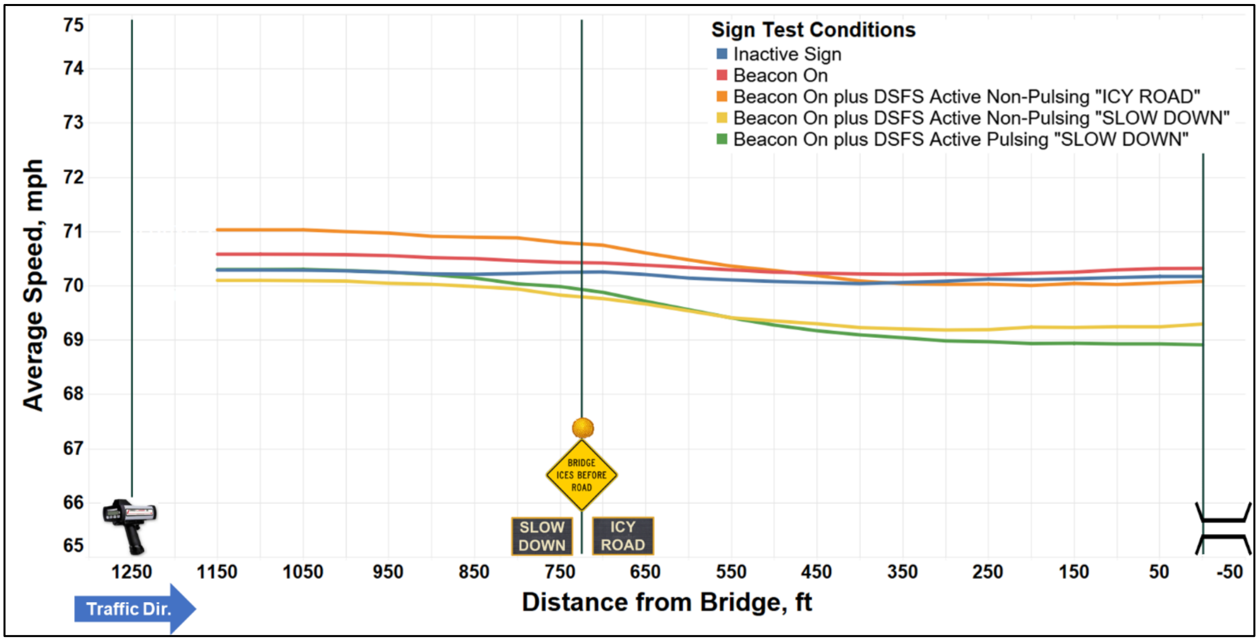


Figure 27. Average Speed Trajectories by Sign Test Condition, NB US-127 Lansing

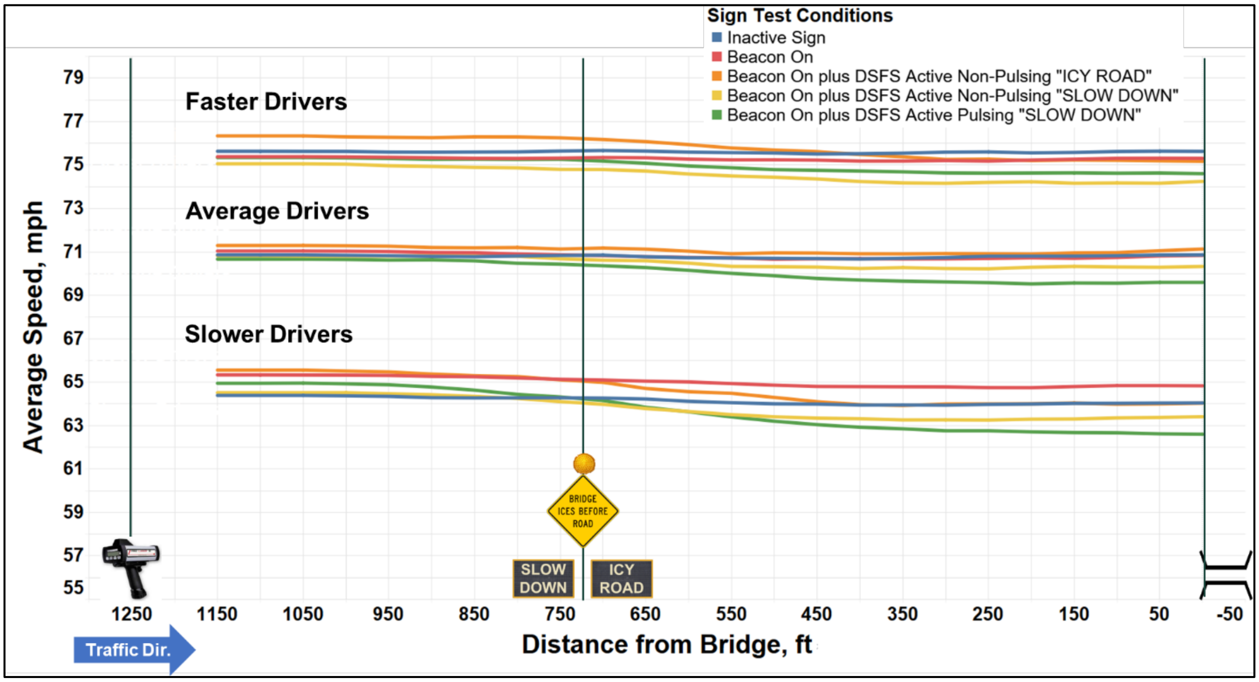


Figure 28. Average Speed Trajectories by Driver Type and Sign Test Condition, NB US-127 Lansing

Data were also collected during periods of darkness at SB-131 Cadillac (Site 2) for passenger cars only. **Figure 29** shows the comparison of the vehicle speed trajectories across between daytime and nighttime periods across the sign test conditions at SB US-131 Cadillac. It should be noted that nighttime data collection was limited to the inactive and LED border active sign conditions.

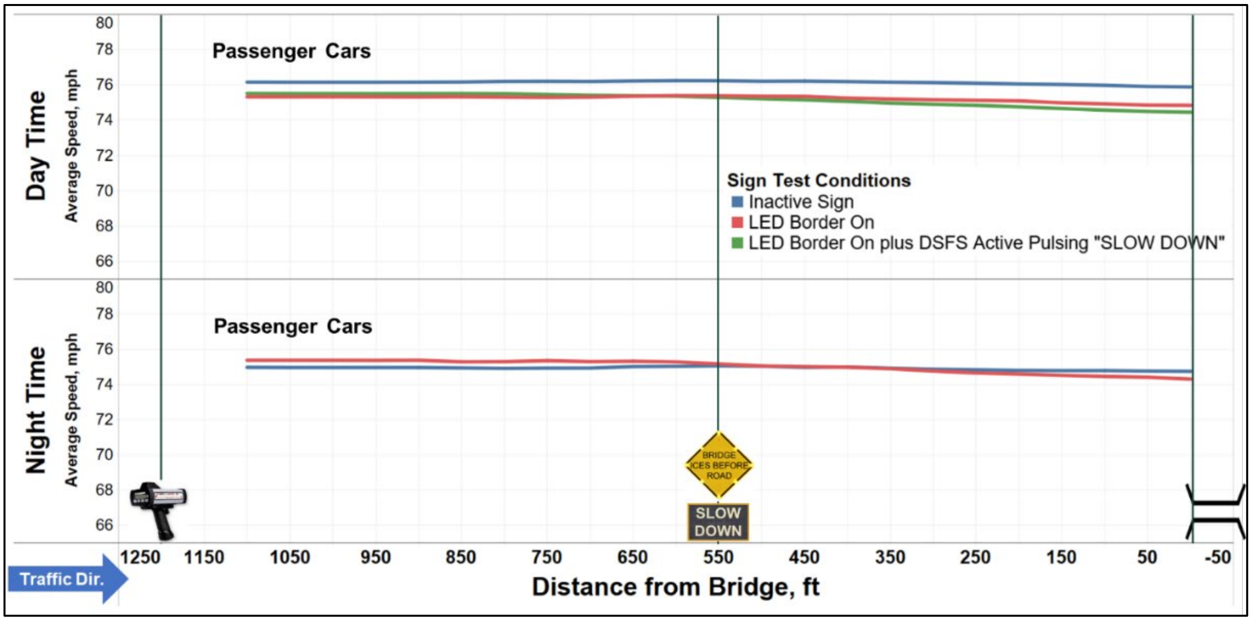


Figure 29. Average Speed Trajectories by Light Condition and Sign Test Condition, SB US-131 Cadillac

Figure 29 shows that inactive signs had minimal effects on speeds during both daytime and nighttime. However, when the LED border was active, a somewhat stronger reduction in mean speed as vehicles approached the BDWS bridge was observed during nighttime. This observation suggests that the BDWS sign was more effective during nighttime conditions when compared to daytime light conditions.

3.10 Data Summary – DMS Winter Weather Messaging Evaluation

The descriptive statistics of the dependent variables and independent variables are presented in **Table 10**. The mean values for the categorical variables listed in the table represent the proportion of the total data set represented by that variable. A total of 602 passenger cars were recorded during the DMS study performed at NB US-127. Heavy vehicles were not included due to low volumes. It should again be noted that the data were only collected during snowy weather and wet pavement conditions. Thus, variables related to the weather and pavement conditions are not included in **Table 10**. Further, because the messages were frequently rotated throughout the data collection period every 20 minutes, it was not necessary to include time-of-day as a factor in the model.

Graphical representation of the average vehicle speed trajectories for each DMS test message are displayed in **Figure 30.** The speed trajectory data for passenger vehicles were further subdivided into groups representing slower, average, and faster drivers across each of the sign test conditions, based on the speed for each driver at the furthest upstream measurement point (i.e., the lowest 1/3 were characterized as slower drivers, the middle 1/3 were characterized as average drivers, and the highest 1/3 were characterized as faster drivers). Graphical representation of the average vehicle speed trajectories separated by driver type for each sign test condition are displayed in **Figure 31.**

Table 10. Descriptive Statistics for DMS Weather Messaging Evaluation at US-127 Lansing

Passenger Cars (n = 602)				
Parameters	**Minimum**	**Maximum**	**Mean**	**Std. Dev.**
Speed at BDWS bridge (dependent variable), mph	49.000	85.000	69.244	5.324
Speed upstream of the BDWS (covariate), mph	50.000	86.000	69.724	5.174
DMS Message				
TRAVEL TIME	0	1	0.286	0.417
BRIDGES ICE BEFORE ROAD / REDUCE SPEEDS	0	1	0.256	0.437
SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS	0	1	0.224	0.417
SLIPPERY ROAD CONDITIONS and REDUCE SPEEDS	0	1	0.234	0.424

Note: 0=no, 1=yes for binary variables. Data were only collected for passenger cars during snowy weather and wet pavement conditions.

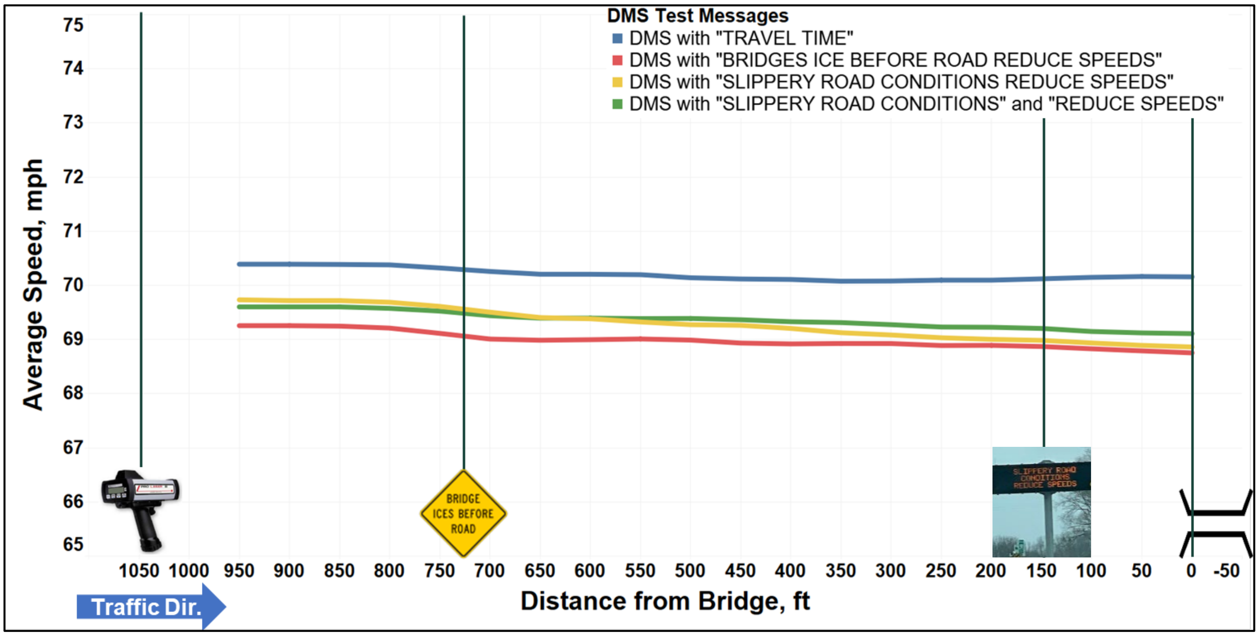


Figure 30. Average Speed Trajectories by DMS Test Message, NB US-127, Lansing

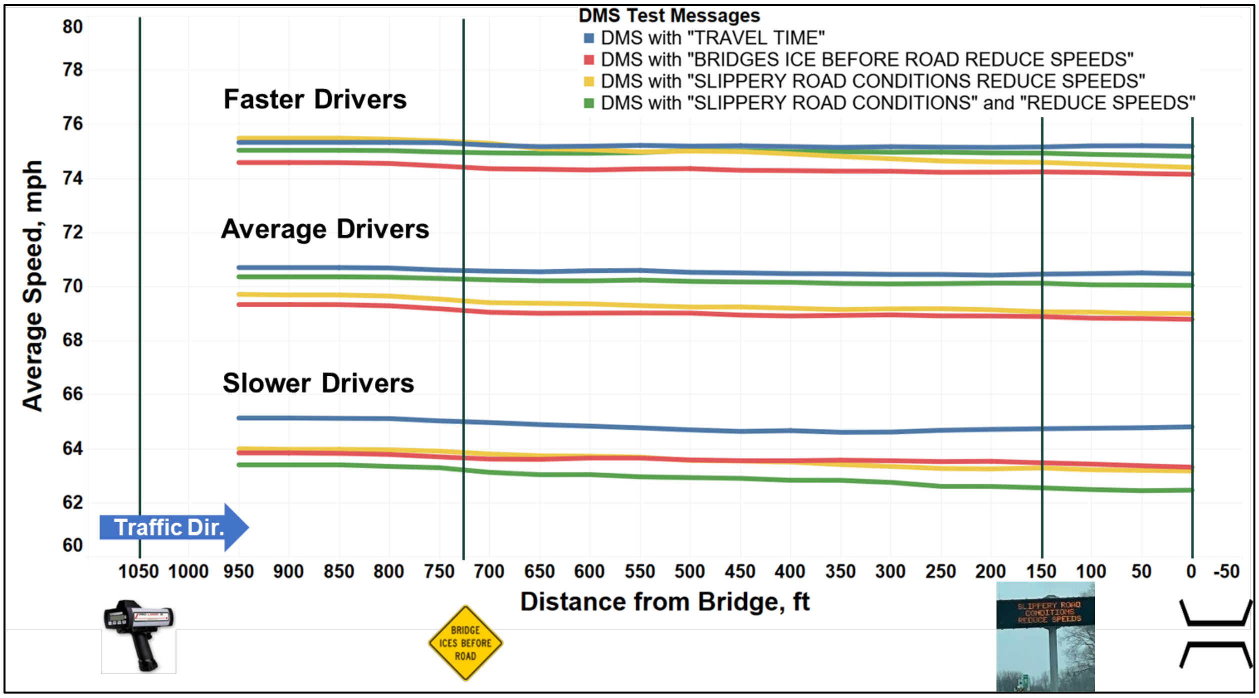


Figure 31. Average Speed Trajectories by DMS Test Message and Driver Type, NB US-127, Lansing

In general, these figures demonstrate that speeds at the bridge were somewhat lower with the DMS winter weather related messages, particularly the "SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS" message, compared to the travel time messages (base condition). Furthermore, although some differences in the speed reductions associated with the sign test conditions were observed across the driver behavior groups (e.g., slower, average, and faster), these differences were not consistent across the DMS messaging conditions. Further discussion on the DMS winter weather messaging effects on motorist speeds at the bridge will be provided in **Chapter 4**.

4. FIELD EVALUATION RESULTS

This chapter provides the statistical analysis results and corresponding discussion related to the effects of BDWS and DMS weather warning messages on driver speed selection behavior during winter weather conditions at the three evaluation sites: NB US-131 Cadillac (BDWS), SB US-131 Cadillac (BDWS), and NB US-127 Lansing (BDWS and DMS). **Section 4.1** covers the results of the BDWS evaluation, while **Section 4.2** covers the result of the DMS messaging evaluation.

4.1 Speed Reduction Effects of Bridge Deck Warning Systems

The speed at the BDWS bridge was analyzed across the sign test conditions, which included:

- Inactive BDWS (Base W8-13 sign condition),
- BDWS type (flashing LED border vs. flashing beacon),
- Addition of a DSFS beneath the BDWS,
- DSFS Message Type ("SLOW DOWN" vs. "ICY ROAD"), and
- DSFS Message Display Method (Non-Pulsing vs. Pulsing Message).

The data were analyzed to determine the magnitude of the speed reduction associated with each BDWS test condition compared to the base sign condition (e.g., inactive sign). Several preliminary versions of the models were developed and assessed for each site. Separate models were developed for passenger cars and heavy vehicles for the US-131 Cadillac sites, while only passenger cars were included in the model for US-127 Lansing due to an inadequate sample of trucks. Unfortunately, the US-131 Cadillac sites did not yield adequate sample sizes for each of the sign conditions across all weather conditions, surface conditions, and times of day, which created confounds in the analysis, and resulted in the removal of these variables from the final regression models. Exclusion of these variables was mitigated by including each subject vehicle's speed at the furthest upstream measurement location as a covariate in the models, thereby controlling for the effects of weather condition, surface condition, and time of day on driver behavior. Weather was included as an independent variable in the final US-127 Lansing model. In addition to the overall regression models for passenger cars, the data were also analyzed separately for slower, average, and faster drivers based on the speed measured at the furthest upstream location. A separate nighttime model was also generated for speed data collected at SB US-131 Cadillac.

The final linear regression model results for speed at the BDWS bridge for site 1, site 2, and site 3 are displayed in **Tables 11, 12, and 13,** respectively. Again, it should be noted that the speed at the furthest upstream measurement location was included as an independent variable (covariate) in the model. Including upstream speed as a covariate controlled for the variation in the speed selection tendencies of drivers between the data collection periods, which did occur during the evaluation as evidenced by comparison of the upstream portion of the speed trajectories displayed in **Figures 23-29**. This analytical strategy allowed for the magnitude of speed reduction during each sign test condition to be directly interpreted from the corresponding parameter estimates while controlling for variations in road conditions, weather conditions, and drivers (Gates et al., 2020; Mahmud et al., 2021, 2022, 2023, 2023).

As mentioned previously, the data were also subsequently grouped into slower, average, and faster drivers for each test sign condition based on the speed of each vehicle measured at the furthest upstream location, with separate regression models developed for each driver type category at each site. These results are also included in **Tables 11, 12, and 13**. It is important to note that these subsequent linear regression models for driver types were only developed for passenger cars due to the limited sample size of heavy vehicles.

Figures 32-37 display the speed change trajectories, which were developed by setting the speed measured at the furthest upstream point to zero. Displaying the speed data in this manner allows for visual comparison of the speed reduction effects associated with each of the sign test conditions, while adjusting for the travel speeds observed upstream of the BDWS. Thus, these graphics are generally reflective of the regression model results displayed in **Tables 11, 12, and 13** for speeds at the BDWS bridge across each of the sign test conditions. The results of the regression analyses are described in detail in the subsections that follow.

Table 11. Linear Regression Model for Speed at the BDWS Bridge, NB US-131 Cadillac

Model 1: All Drivers, Passenger Cars (n = 2,547)			
Parameters	**Estimates (mph)**	**Std. Err**	**p-value**
Intercept	6.038	1.013	<0.001
Upstream Speed	0.912	0.013	<0.001
Test Condition			
Inactive Sign	*Base Condition*		
Flashing LED Border	-0.667	0.165	<0.001
Flashing LED Border + DSFS with “SLOW DOWN” (Pulsing)	-1.955	0.186	<0.001
Model 2: Slower Drivers (n = 847)			
Parameters	**Estimates (mph)**	**Std. Err**	**p-value**
Intercept	6.571	2.306	0.004
Upstream Speed	0.903	0.032	<0.001
Test Condition			
Inactive Sign	*Base Condition*		
Flashing LED Border	-0.816	0.297	0.006
Flashing LED Border + DSFS with “SLOW DOWN” (Pulsing)	-2.202	0.333	<0.001
Model 3: Average Drivers (n = 850)			
Parameters	**Estimates (mph)**	**Std. Err**	**p-value**
Intercept	11.894	6.696	0.076
Upstream Speed	0.840	0.087	<0.001
Test Condition			
Inactive Sign	*Base Condition*		
Flashing LED Border	-0.669	0.257	0.010
Flashing LED Border + DSFS with “SLOW DOWN” (Pulsing)	-1.932	0.288	<0.001
Model 4: Faster Drivers (n = 850)			
Parameters	**Estimates (mph)**	**Std. Err**	**p-value**
Intercept	22.697	3.999	<0.001
Upstream Speed	0.707	0.049	<0.001
Test Condition			
Inactive Sign	*Base Condition*		
Flashing LED Border	-0.655	0.302	0.030
Flashing LED Border + DSFS with “SLOW DOWN” (Pulsing)	-1.810	0.337	<0.001
Model 5: Heavy Vehicles (n = 470)			
Parameters	**Estimates (mph)**	**Std. Err**	**p-value**
Intercept	-14.712	3.879	<0.001
Upstream Speed	1.182	0.058	<0.001
Test Condition			
Inactive Sign	*Base Condition*		
Flashing LED Border	-1.079	0.540	0.046
Flashing LED Border + DSFS with “SLOW DOWN” (Pulsing)	-1.847	0.585	0.002

Dependent variable = Speed at the BDWS bridge

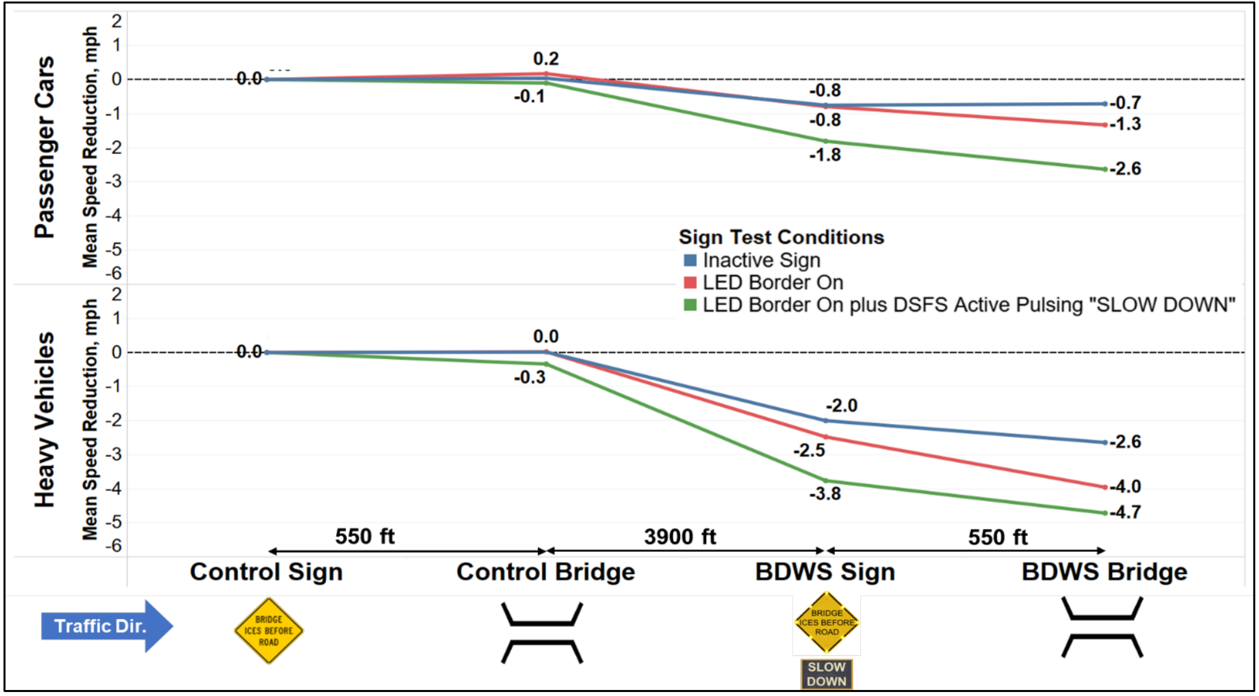


Figure 32. Average Speed Change Trajectories by Sign Test Condition and Vehicle Type, NB US-131, Cadillac

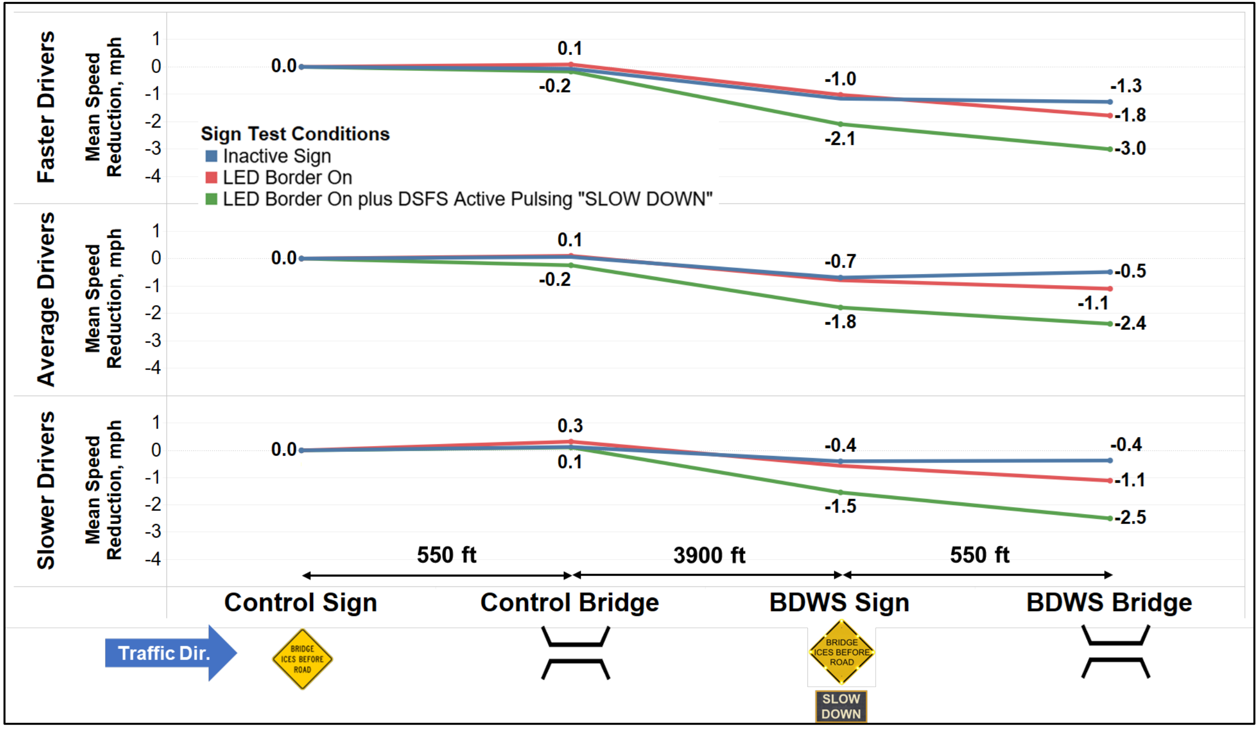


Figure 33. Average Speed Change Trajectories by Sign Test Condition and Driver Type, NB US-131 Cadillac

Table 12. Linear Regression Model for Speed at the BDWS Bridge, SB US-131 Cadillac

Model 1: All Drivers, Passenger Cars (n = 852)			
Parameters	**Estimates (mph)**	**Std. Err**	**p-value**
Intercept	0.022	0.801	0.978
Upstream Speed	0.996	0.010	<0.001
Test Condition			
Inactive Sign	*Base Condition*		
Flashing LED Border	-0.445	0.141	0.002
Flashing LED Border + DSFS with "SLOW DOWN" (Pulsing)	-0.802	0.126	<0.001
Model 2: Slower Drivers (n = 284)			
Parameters	**Estimates (mph)**	**Std. Err**	**p-value**
Intercept	-1.106	1.896	0.560
Upstream Speed	1.010	0.027	<0.001
Test Condition			
Inactive Sign	*Base Condition*		
Flashing LED Border	-0.202	0.271	0.456
Flashing LED Border + DSFS with "SLOW DOWN" (Pulsing)	-0.629	0.242	0.010
Model 3: Average Drivers (n = 284)			
Parameters	**Estimates (mph)**	**Std. Err**	**p-value**
Intercept	-2.441	5.843	0.676
Upstream Speed	1.030	0.076	<0.001
Test Condition			
Inactive Sign	*Base Condition*		
Flashing LED Border	-0.485	0.233	0.038
Flashing LED Border + DSFS with "SLOW DOWN" (Pulsing)	-0.810	0.204	0.000
Model 4: Faster Drivers (n=284)			
Parameters	**Estimates (mph)**	**Std. Err**	**p-value**
Intercept	5.478	3.020	0.071
Upstream Speed	0.930	0.037	<0.001
Test Condition			
Inactive Sign	*Base Condition*		
Flashing LED Border	-0.661	0.238	0.006
Flashing LED Border + DSFS with "SLOW DOWN" (Pulsing)	-1.007	0.213	<0.001
Model 5: All Drivers, Heavy Vehicles (n = 246)			
Parameters	**Estimates (mph)**	**Std. Err**	**p-value**
Intercept	2.948	2.317	0.204
Upstream Speed	0.957	0.035	<0.001
Test Condition			
Inactive Sign	*Base Condition*		
Flashing LED Border	-0.647	0.333	0.053
Flashing LED Border + DSFS with "SLOW DOWN" (Pulsing)	-0.892	0.295	0.003

Dependent variable = Speed at the BDWS bridge

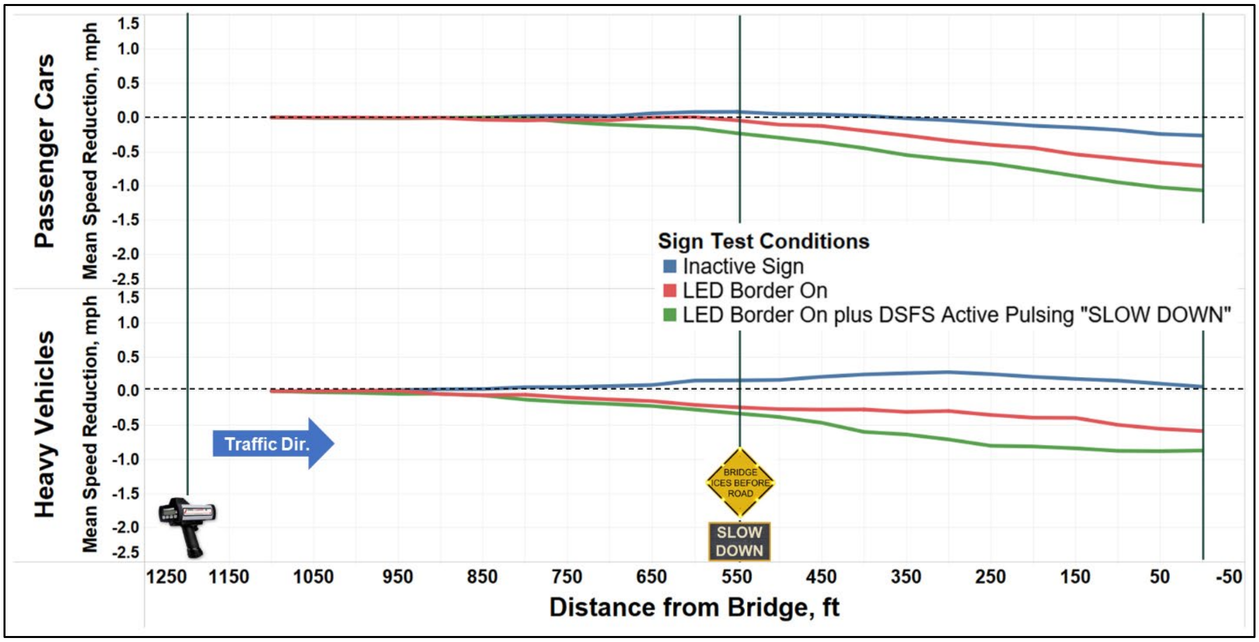


Figure 34. Average Speed Change Trajectories by Sign Test Condition and Vehicle Type, SB US-131 Cadillac

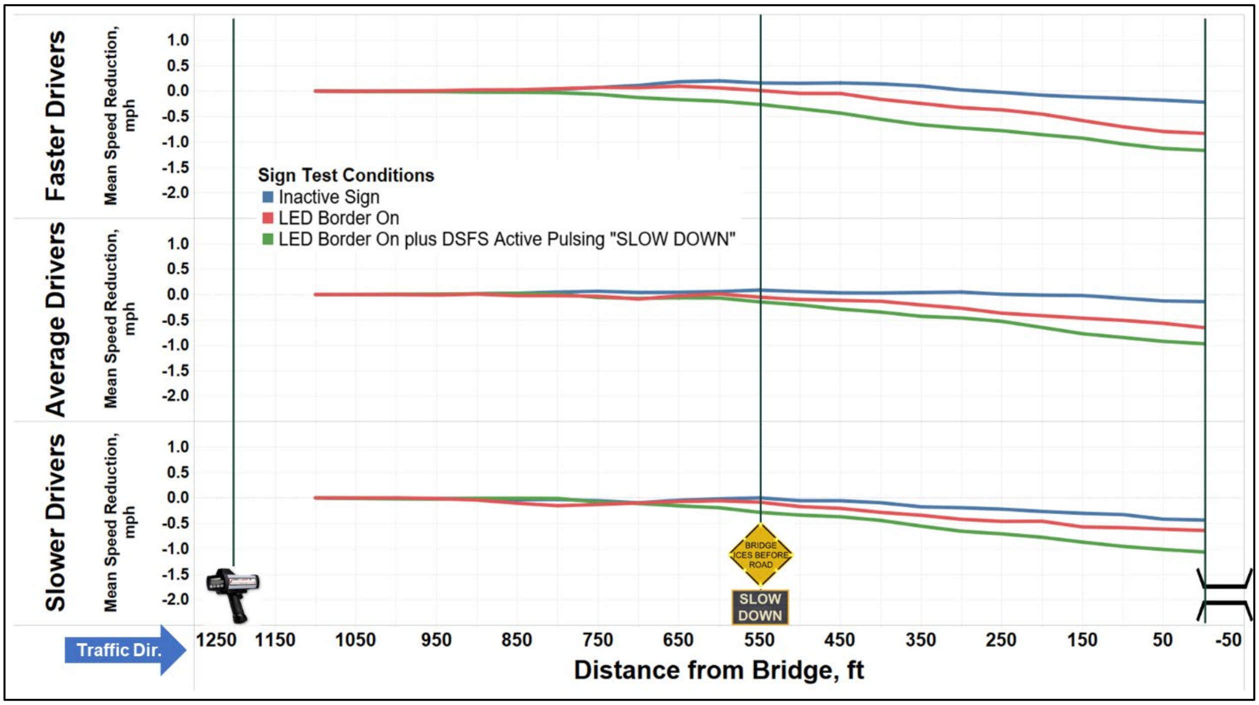


Figure 35. Average Speed Change Trajectories by Sign Test Condition and Driver Type, SB US-131 Cadillac

Table 13. Linear Regression Model for Speed at the BDWS Bridge, NB US-127 Lansing

Model 1: All Drivers, Passenger Cars (n = 1,800)

Parameters	Estimates (mph)	Std. Err	p-value
Intercept	-2.893	0.706	<0.001
Upstream Speed	1.042	0.010	<0.001
Test Condition			
Inactive Sign		*Base Condition*	
Flashing Beacon	-0.163	0.122	0.181
Flashing Beacon + DSFS with “ICY ROAD” (Steady)	-0.881	0.164	<0.001
Flashing Beacon + DSFS with “SLOW DOWN” (Steady)	-0.779	0.176	<0.001
Flashing Beacon + DSFS with “SLOW DOWN” (Pulsing)	-1.235	0.137	<0.001
Weather Condition			
Clear		*Base Condition*	
Cloudy	-0.064	0.140	0.648
Snowy	-0.406	0.138	0.003
Rainy	-0.228	0.181	0.207

Model 2: Slower Drivers (n = 602)

Parameters	Estimates (mph)	Std. Err	p-value
Intercept	-0.287	1.885	0.879
Upstream Speed	1.008	0.028	<0.001
Test Condition			
Inactive Sign		*Base Condition*	
Flashing Beacon	-0.066	0.243	0.788
Flashing Beacon + DSFS with “ICY ROAD” (Steady)	-1.175	0.322	<0.001
Flashing Beacon + DSFS with “SLOW DOWN” (Steady)	-0.834	0.338	0.014
Flashing Beacon + DSFS with “SLOW DOWN” (Pulsing)	-1.932	0.269	<0.001
Weather Condition			
Clear		*Base Condition*	
Cloudy	-0.579	0.340	0.090
Snowy	-0.694	0.312	0.026
Rainy	-0.770	0.363	0.034

Model 3: Average Drivers (n = 599)

Parameters	Estimates (mph)	Std. Err	p-value
Intercept	-5.637	4.619	0.223
Upstream Speed	1.081	0.065	<0.001
Test Condition			
Inactive Sign		*Base Condition*	
Flashing Beacon	-0.222	0.195	0.256
Flashing Beacon + DSFS with “ICY ROAD” (Steady)	-0.223	0.264	0.399
Flashing Beacon + DSFS with “SLOW DOWN” (Steady)	-0.574	0.284	0.044
Flashing Beacon + DSFS with “SLOW DOWN” (Pulsing)	-1.082	0.219	<0.001
Weather Condition			
Clear			
Cloudy	0.041	0.221	0.853
Snowy	-0.229	0.218	0.294
Rainy	-0.196	0.292	0.503

Model 4: Faster Drivers (n = 599)

Parameters	Estimates (mph)	Std. Err	p-value
Intercept	0.429	2.400	0.858
Upstream Speed	0.996	0.032	<0.001
Test Condition			
Inactive Sign		*Base Condition*	
Flashing Beacon	-0.113	0.193	0.556
Flashing Beacon + DSFS with “ICY ROAD” (Steady)	-1.239	0.261	<0.001
Flashing Beacon + DSFS with “SLOW DOWN” (Steady)	-0.907	0.282	0.001
Flashing Beacon + DSFS with “SLOW DOWN” (Pulsing)	-0.617	0.216	0.004
Weather Condition			
Clear			
Cloudy	0.080	0.200	0.688
Snowy	-0.562	0.213	0.008
Rainy	0.106	0.310	0.732

Dependent variable = Speed at the BDWS bridge

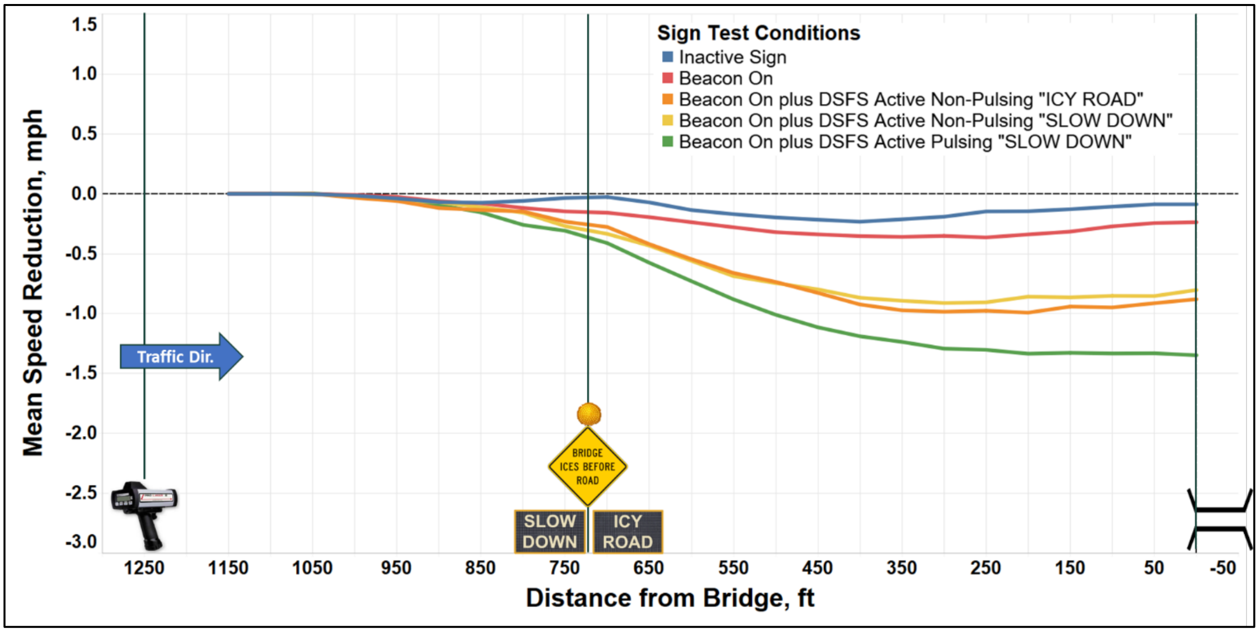


Figure 36. Average Speed Change Trajectories by Sign Test Condition, NB US-127 Lansing

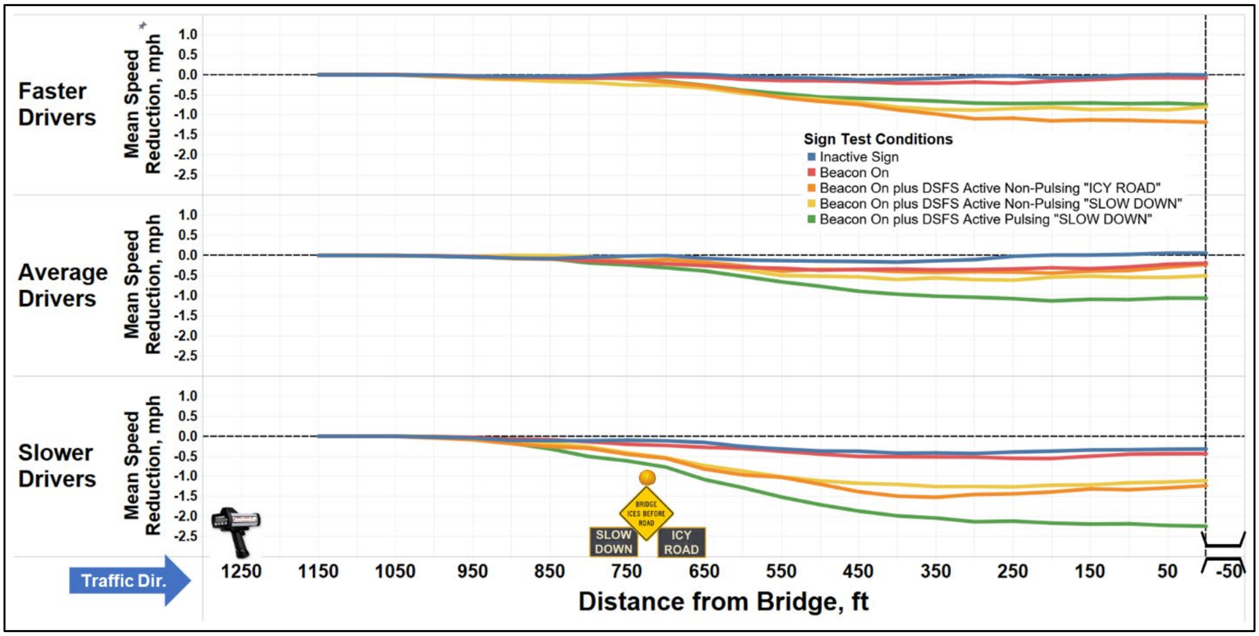


Figure 37. Average Speed Change Trajectories by Sign Test Condition and Driver Type, NB US-127 Lansing

4.1.1 *Effect of BDWS Type (Flashing LED Border vs. Flashing Beacon)*

The linear regression results presented in **Tables 11, 12, and 13** suggest that the BDWS used by itself had a statistically significant effect on the speed of vehicles at the BDWS bridge. When the flashing LED border was active at the NB US-131 Cadillac site, the speeds at the BDWS bridge were 0.7 mph lower for passenger cars and 1.1 mph lower for heavy vehicles compared to when the sign was inactive (base condition), and both these speed reductions were statistically significant (model 1). The effect was diminished slightly at the SB US-131 Cadillac site, as when the flashing LED border was active, the speeds at the BDWS bridge were 0.4 mph lower for passenger cars and 0.7 mph lower for heavy vehicles. However, the flashing overhead beacon at the US-127 Lansing location did not produce a statistically significant change in speed at the bridge.

The results presented in **Tables 11, 12, and 13** also show somewhat inconsistent effects for the BDWS signs across the different driver type categories. From **Table 11** it can be observed that slower drivers showed greater speed reductions when the LED border was flashing at NB US-131 Cadillac compared to faster drivers. However, **Table 12** shows that faster drivers showed greater speed reductions at SB US-131 Cadillac when the LED border was flashing compared to slower drivers. As shown in **Table 13**, no significant speed reduction effects were observed for any of the driver types at the NB US-127 Lansing site when the overhead beacon was flashing.

It should be noted that the magnitude of the BDWS speed reductions observed here was considerably lower than the reductions noted in prior research, which ranged from 5 to 10 mph (Veneziano et al., 2014). The greater speed reductions observed in prior research efforts were likely amplified due to the more extreme weather conditions present while the beacons were flashing. The lack of a control site or inclusion of speed measurements taken upstream of the BDWS location made it impossible to determine whether speed reductions were due to the flashing warning sign or the extreme weather conditions.

4.1.2 *Effect of Adding a DSFS to the BDWS*

In addition to assessing the speed reduction effect associated with the active BDWS by itself, the study also evaluated the effects of the active BDWS paired with a DSFS installed beneath the sign. In order to compare results across the three sites, only the results for the pulsing "SLOW DOWN" message will be discussed in this section. The results presented in **Tables 11, 12, and 13** indicate that the combined use of BDWS and DSFS produced speed reduction effects that exceeded what was achieved when only the BDWS was active.

Table 11 shows that when the flashing LED border was combined with the DSFS "SLOW DOWN" message at the NB US-131 Cadillac site, vehicles were traveling approximately 2.0 mph slower, on average, at the BDWS bridge compared to when the sign was inactive. From **Table 12** it can be observed that the "SLOW DOWN" message was less effective at the SB US-131 Cadillac when compared to the NB direction, although still provided greater speed reductions than the flashing LED border alone. These effects were consistent between passenger vehicles and heavy vehicles. Further, the results obtained from US-127 Lansing (**Table 13**) shows that when both the overhead flashing beacon and DSFS pulsing "SLOW DOWN" message were active, the speeds at the bridge were 1.2 mph lower compared to the baseline condition, which was a considerable improvement over the flashing beacon alone. These results provide substantial evidence to suggest that the addition of DSFS to the existing BDWS deployment elicits a stronger driver speed reduction response when approaching a bridge during winter conditions.

The results presented in **Tables 11, 12, and 13** again show somewhat inconsistent effects associated with the addition of a pulsing "SLOW DOWN" message to the flashing BDWS across the different driver type categories. From **Tables 11 and 13** it can be observed that slower drivers showed greater speed reductions compared to faster drivers when the pulsing "SLOW DOWN" message was displayed at NB US-131 Cadillac and NB US-127 Lansing. However, **Table 12** shows that faster drivers showed greater speed reductions compared to slower drivers at SB US-131 Cadillac when the pulsing "SLOW DOWN" message was displayed.

4.1.3 *Effect of DSFS Message Type*

The field evaluation performed at the NB US-127 Lansing site allowed for the comparison of two different DSFS messages, "ICY ROAD" and "SLOW DOWN," when used in conjunction with the flashing overhead beacon. In order to isolate the effects of the message itself, only the results for the steady (non-pulsing) messages at the US-127 Lansing site will be discussed in this section. From **Table 13**, it can be observed that the speed reduction effects were similar between the "ICY ROAD" message and the "SLOW DOWN" message. When the DSFS was displaying the "ICY ROAD" message, speeds at the bridge were approximately 0.9 mph lower than when the signs were inactive. Similarly, speeds at the bridge were 0.8 mph lower with the "SLOW DOWN" message displayed on the DSFS compared to when the signs were inactive. Thus, the two messages show relatively similar effects on speeds. Furthermore, from **Table 13** it appears that the "ICY ROAD" message provided slightly greater speed reductions for both the faster *and* slower drivers.

4.1.4 *Effect of DSFS Message Display Method*

It was also possible to evaluate the effects of adding a pulse to the DSFS message when used in conjunction with the flashing overhead beacon at the NB US-127 Lansing site. In order to isolate the effects of the pulsing message, only the results pertaining to the "SLOW DOWN" messages at the NB US-127 Lansing site will be discussed in this section. The model results in **Table 13** indicate that when the DSFS displayed a pulsing "SLOW DOWN" message, speeds were 1.2 mph lower compared to speeds observed when the signs were inactive. However, the speeds were only 0.8 mph lower than the baseline sign condition when the steady (non-pulsing) "SLOW DOWN" message was utilized. These results suggest that adding a pulse to the DSFS message reduced speeds by an additional 0.4 mph, on average, compared to the steady DSFS message. Furthermore, from **Table 13** it appears that the message pulse provided greater speed reductions for both the slower and average driver groups.

4.1.5 *Effect of Weather Condition*

As mentioned earlier, each of the warning signs conditions were tested during various weather conditions at NB US-127 Lansing. The linear regression results shown in **Table 13** suggest that speeds were 0.4 mph lower during snowy conditions compared to clear conditions. No significant speed differences were observed between clear, cloudy, or rainy conditions. Again, note that data were only collected during wet pavement surface conditions at the NB US-127 Lansing site.

4.1.6 *Effect of BDWS During Darkness*

As previously discussed, data collection at the SB US-131 Cadillac site also extended to periods of darkness. It should be noted that during nighttime data collection, only two sign conditions, inactive sign and flashing LED border active conditions, were tested in the field. Separate passenger car models were developed to compare the effect of the BDWS during daylight vs. dark conditions, with the results presented in **Table 14** and reflected in **Figure 38**. From the model results, it was found that when the LED border was active during the daytime, speeds at the bridge were 0.2 mph lower compared to the baseline condition. However, during nighttime, speeds at the bridge were approximately 0.8 mph lower compared to the baseline condition, which represents a 0.6 mph greater speed reduction effect compared to daytime conditions. This demonstrates that drivers responded more to the flashing LED border during the periods of darkness compared to daylight, perhaps due to the increased visibility of the flashing LED border during dark conditions.

Table 14. Linear Regression Model for Speed at the BDWS Bridge by Light Condition, SB US-131 Cadillac

Daytime, Passenger Cars (n = 713)			
Parameters	**Estimates (mph)**	**Std. Err**	**p-value**
Intercept	-0.008	0.888	0.993
Upstream Speed	0.997	0.012	0.000
Test Condition			
Inactive Sign	*Base Condition*		
Flashing LED Border	-0.212	0.168	0.207
Nighttime, Passenger Cars (n = 139)			
Parameters	**Estimates (mph)**	**Std. Err**	**p-value**
Intercept	0.074	1.866	0.968
Upstream Speed	0.996	0.025	<0.001
Test Condition			
Inactive Sign	*Base Condition*		
Flashing LED Border	-0.842	0.286	0.004

Response variable = Speed at the BDWS bridge

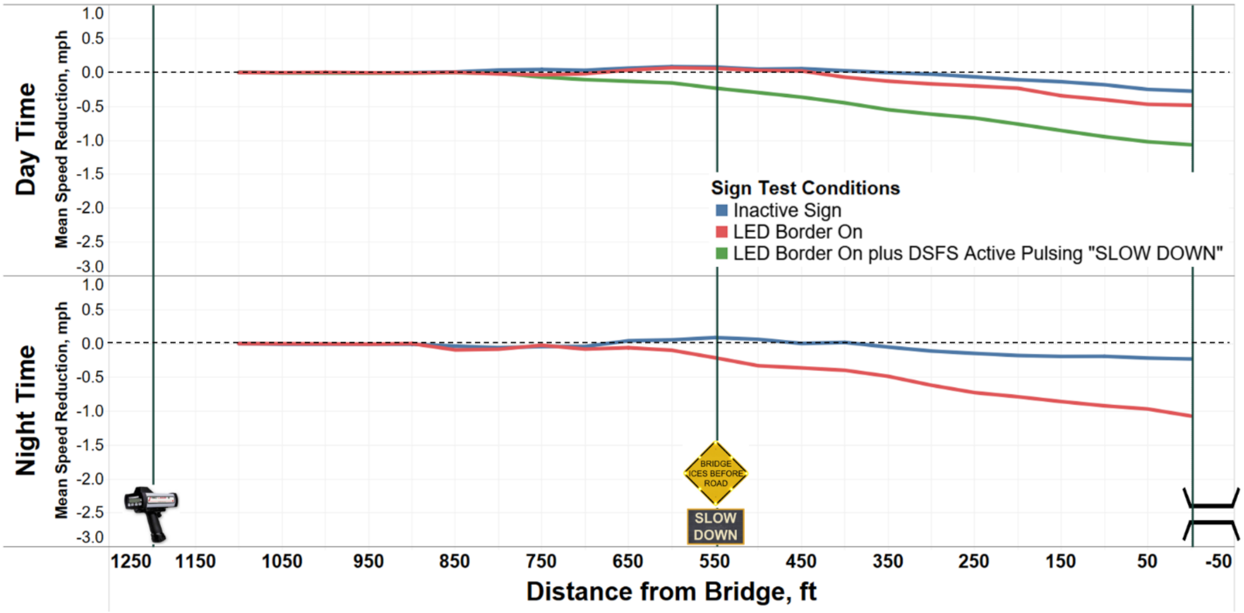


Figure 38. Average Speed Change Trajectories by Sign Test Condition and Light Condition, SB US-131, Cadillac

4.2 Speed Reduction Effects of DMS Winter Weather Messaging

The NB US-127 Lansing site was also utilized to evaluate the effectiveness of bridge related weather warning messages displayed on DMS located near the start of the bridge deck. As discussed in previous chapter, the speed at the bridge was analyzed across the DMS messaging conditions, which included:

- Travel time message (Base sign condition)
- BRIDGE ICES BEFORE ROAD
  REDUCE SPEEDS
- SLIPPERY ROAD CONDITIONS
  REDUCE SPEEDS
- Frame 1: SLIPPERY ROAD CONDITIONS (4-second display)
  Frame 2: REDUCE SPEEDS (4-second display)

The data were analyzed to determine the magnitude of the speed reduction associated with each DMS winter weather messaging strategy compared to the base DMS message (e.g., travel times). Heavy trucks were excluded from the models due to low volumes. It should again be noted that the data were only collected during snowy weather and wet pavement conditions. Thus, variables related to the weather and pavement conditions were not included in the model. Further, because the messages were rotated throughout the data collection period every 20 minutes, it was not necessary to include time-of-day as a factor. The data were also analyzed separately for slower, average, and faster drivers based on the speed measured at the furthest upstream location.

The final linear regression model results are presented in **Table 15**. Again, it should be noted that speed at the bridge was the dependent variable for the linear regression model, while the speed at the furthest upstream measurement location was included as an independent variable (covariate) in the model. Including upstream speed as a covariate controlled for the variation in the speed selection tendencies of drivers between the data collection periods, which did occur during the evaluation as evidenced by comparison of the upstream portion of the speed trajectories displayed in **Figures 30 and 31**. This analytical strategy allowed for the magnitude of speed reduction during each DMS message test condition to be directly interpreted from the corresponding parameter estimates while controlling for variations in road conditions, weather conditions, and drivers (Gates et al., 2020; Mahmud et al., 2021, 2022, 2023, 2023).

Figures 39 and 40 display the speed reduction profiles, which were developed by setting the speed measured at the furthest upstream point to zero. Displaying the speed data in this manner allows for visual comparison of the speed reduction effects associated with each of the DMS message test condition, while adjusting for the travel speeds observed upstream of the DMS. Thus, these graphics are generally reflective of the regression model results displayed in **Table 15** for speeds at the bridge across each of the DMS message test conditions. The results of the regression analyses are described in detail in the subsections that follow.

Table 15. Linear Regression Model Results for Speed at the Bridge, NB US-127 Lansing

Model 1: All Drivers, Passenger Cars (n = 602)			
Parameters	**Estimates (mph)**	**Std. Err**	**p-value**
Intercept	-0.147	0.695	0.833
Upstream Speed	0.999	0.010	<0.001
DMS Test Messages			
TRAVEL TIME		*Base Condition*	
BRIDGES ICE BEFORE ROAD / REDUCE SPEEDS	-0.231	0.138	0.093
SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS	-0.638	0.142	<0.001
SLIPPERY ROAD CONDITIONS and REDUCE SPEEDS	-0.190	0.141	0.177
Model 2: Slower Drivers (n=202)			
Parameters	**Estimates (mph)**	**Std. Err**	**p-value**
Intercept	1.599	1.833	0.384
Upstream Speed	0.970	0.028	<0.001
DMS Test Messages			
TRAVEL TIME		*Base Condition*	
BRIDGES ICE BEFORE ROAD / REDUCE SPEEDS	-0.127	0.251	0.613
SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS	-0.528	0.260	0.043
SLIPPERY ROAD CONDITIONS and REDUCE SPEEDS	-0.474	0.260	0.070
Model 3: Average Drivers (n = 200)			
Parameters	**Estimates (mph)**	**Std. Err**	**p-value**
Intercept	17.551	4.080	<0.001
Upstream Speed	0.748	0.058	<0.001
DMS Test Messages			
TRAVEL TIME		*Base Condition*	
BRIDGES ICE BEFORE ROAD / REDUCE SPEEDS	-0.658	0.231	0.005
SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS	-0.728	0.232	0.002
SLIPPERY ROAD CONDITIONS and REDUCE SPEEDS	-0.157	0.223	0.482
Model 4: Faster Drivers (n = 200)			
Parameters	**Estimates (mph)**	**Std. Err**	**p-value**
Intercept	-0.625	2.796	0.823
Upstream Speed	1.006	0.037	<0.001
DMS Test Messages			
TRAVEL TIME		*Base Condition*	
BRIDGES ICE BEFORE ROAD / REDUCE SPEEDS	-0.289	0.239	0.227
SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS	-0.941	0.245	<0.001
SLIPPERY ROAD CONDITIONS and REDUCE SPEEDS	-0.083	0.243	0.731

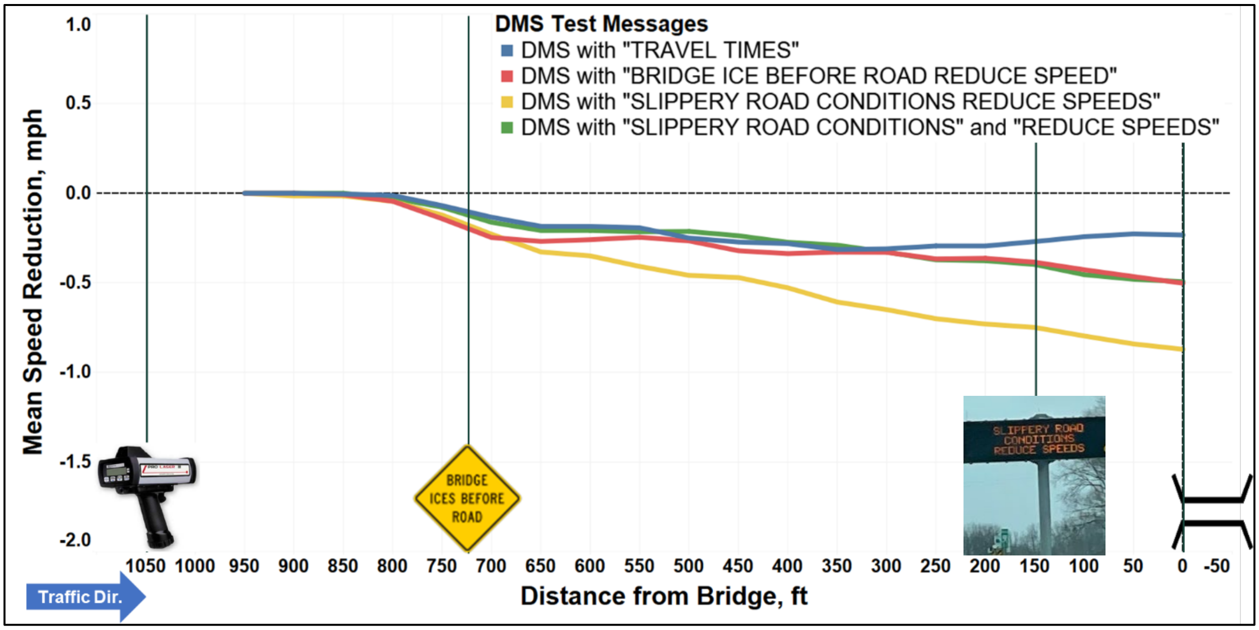


Figure 39. Average Speed Change Trajectories by DMS Test Message, NB US-127, Lansing

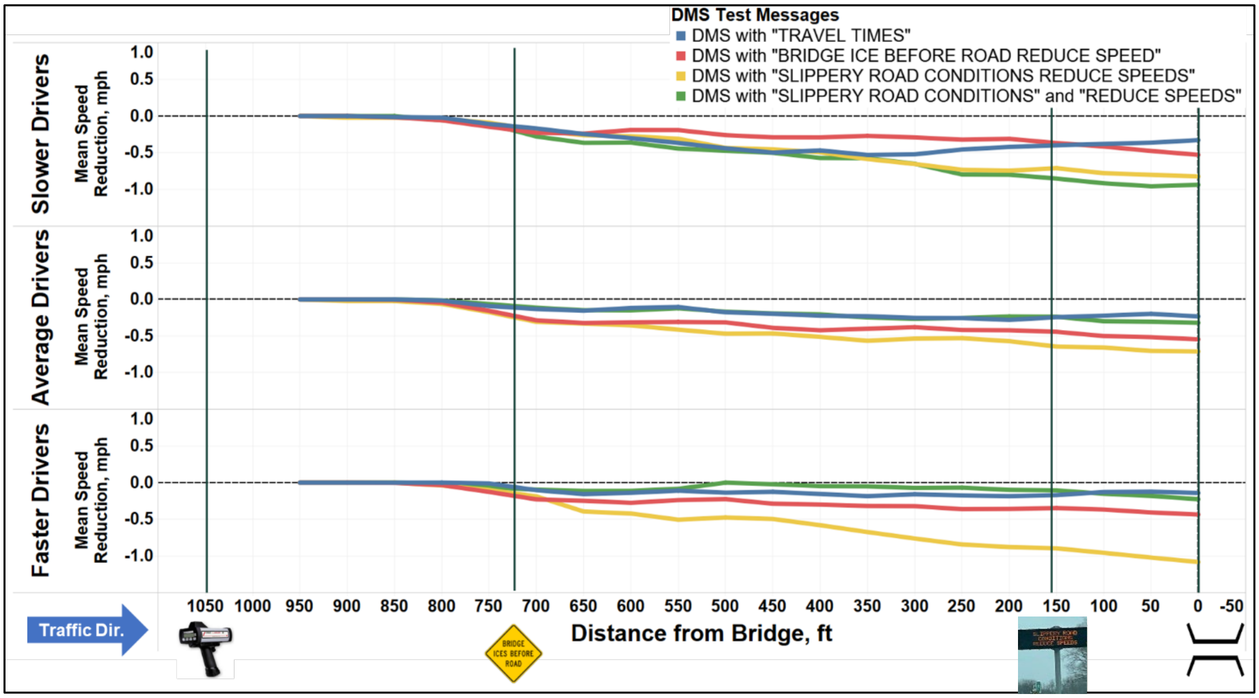


Figure 40. Average Speed Change Trajectories by DMS Test Message and Driver Type, NB US-127, Lansing

The linear regression results presented in **Table 15** suggest that the DMS winter weather messaging had variable effects on vehicular speeds at the bridge. The strongest speed reduction effects were observed when the "SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS" message was displayed continuously on a single frame. With this message displayed, the speeds at the bridge were 0.6 mph lower for passenger cars compared to when travel time messages were displayed on the DMS (base condition), and this speed reduction was statistically significant. However, the other winter related messages (BRIDGE ICES BEFORE ROAD / REDUCE SPEEDS and SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS in two frames) produced a smaller and non-significant 0.2 mph speed reduction effect compared to the base travel time messages.

The results presented in **Table 15** also shows consistent effects for the DMS messaging across the different driver type categories. Each of the driver type groups showed the greatest speed reductions when the "SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS" message was display on a single frame. The strongest effects associated with this message were observed among faster drivers, as speeds at the bridge were 0.9 mph lower for this group compared to when travel time messages were display on the DMS. Slower and average drivers were also most affected by the "SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS", with speed reductions of 0.5 mph and 0.7 mph, respectively. Neither of the other two winter weather messages showed consistent speed reductions across the driver groups compared to the travel time messages, especially for the critical faster driver group

The relatively strong speed reduction effects associated with the "SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS" message might be due to the elevated risk perceived by drivers from this message, as it indicates both the current condition and suggested action within the same frame. This was particularly evident by the magnitude of the speed reductions observed in the group of faster drivers, which supports the continued use of this DMS message by MDOT during winter weather conditions. In comparison, the diminished speed reduction effects associated with the "BRIDGES ICE BEFORE ROAD / REDUCE SPEEDS" message, might be due to drivers perceiving the message as less directly related to the current condition, thereby lowering the risk perception. Further, splitting the "SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS" message between alternating frames reduces the likelihood for drivers to read both messages, providing a potential explanation for the lower observed speed reductions.

4.3 Summary of Field Evaluation Results

A summary of the field evaluation results are provided **Table 16** for the BDWS evaluation and **Table 17** for the DMS winter weather messaging evaluation.

Table 16. Summary of Speed Effects for BDWS Sign Test Conditions

Sign Test Condition		Primary Findings
Flashing LED border		• On average, speeds at the bridge were 0.7 mph lower for passenger cars and 1.1 mph lower for heavy trucks compared to the inactive sign • The speed reduction effect was similar for slower and faster drivers • Average speed reductions were 0.6 mph greater at night than during the day
Flashing Beacon		• No significant speed reduction effect
Flashing LED Border plus DSFS with *pulsing* "SLOW DOWN" message		• On average, speeds at the bridge were 2.0 mph lower for passenger cars and 1.8 mph lower for heavy trucks compared to the inactive sign • On average, speeds at the bridge were 1.3 mph lower for passenger cars and 0.8 mph lower for heavy trucks compared to the flashing LED border alone • The speed reduction effect was greater for slower drivers than for faster drivers
Flashing Beacon plus DSFS with *pulsing* "SLOW DOWN" message		• On average, speeds of passenger cars at the bridge were 1.2 mph lower compared to the inactive sign and 1.1 mph lower compared to the flashing beacon alone • The speed reduction effect was greater for slower drivers than for faster drivers
Flashing Beacon plus DSFS with *steady* "ICY ROAD" message		• On average, speeds of passenger cars at the bridge were 0.9 mph lower compared to the inactive sign and 0.7 mph lower compared to the flashing beacon alone • The speed reduction effect was similar for slower and faster drivers
Flashing Beacon plus DSFS with *steady* "SLOW DOWN" message		• On average, speeds of passenger cars at the bridge were 0.8 mph lower compared to the inactive sign and 0.6 mph lower compared to the flashing beacon alone • The speed reduction effect was similar for slower and faster drivers

Table 17. Summary of Speed Effects for DMS Winter Weather Message Test Conditions

Sign Test Condition	Primary Findings
	- On average, speeds of passenger cars at the bridge were 0.2 mph lower compared to the base travel time message - The speed reduction effect was similar for slower and faster drivers
	- On average, speeds of passenger cars at the bridge were 0.7 mph lower compared to the base travel time message - The speed reduction effect was greater for faster drivers than for slower drivers
Frame 1:  Frame 2: 	- On average, speeds of passenger cars at the bridge were 0.2 mph lower compared to the base travel time message - The speed reduction effect was greater for slower drivers than for faster drivers

5. TRAFFIC CRASH ANALYSIS AND NETWORK SCREENING FOR FUTURE BDWS DEPLOYMENTS

Given the potential safety benefits associated with BDWS demonstrated by the speed reductions presented in **Chapter 4**, a comprehensive analysis of historical traffic crash data related to snowy or icy bridge decks in Michigan was conducted to provide MDOT with a series of data-driven tools to support future applications of BDWS. Initially, a series of engineering data were collected specific to bridges along Michigan's trunkline highway network (**Section 5.1**). This included bridge characteristics, historical traffic crash and volume data, roadway characteristics, and weather data. This dataset was used to benchmark current snowy or icy bridge deck safety performance in Michigan as well as to conduct a network screening to identify candidate bridge decks that may benefit from future BDWS treatments (**Section 5.2**). A series of analytical tools were developed for both MDOT and local agencies (for non-freeways) to evaluate candidate bridge decks for BDWS treatments and a list of sites for further assessment were included. Finally, a preliminary before-and-after assessment was conducted for the eleven existing MDOT BDWS deployments for which least one winter season of post-installation data were available (**Section 5.3**). While there is not yet sufficient post-installation data available in Michigan to develop statistically valid crash modification factors related to these deployments, this preliminary investigation does suggest BDWS may offer promising safety performance benefits.

It is important to note that the bridge deck safety analyses included within this evaluation are disaggregated into three distinct scenarios, including:

- Bridges along mainline limited access freeway facilities, excluding ramps or segments within complex system interchanges.
- Bridges along freeway ramp facilities or other freeway scenarios (such as mainline segments within a complex interchange) that were not considered as a mainline facility.
- Bridges along the trunkline non-freeway network included within the national highway system (NHS), excluding facilities where adjacent traffic control (such as a signal, all-way stop, or roundabout) is present.

Examples of BDWS in Michigan that have been installed along each of the three bridge scenarios are shown in **Figure 41**.

Figure 41. Examples of Freeway, Freeway Ramp, and Non-Freeway Trunkline BDWS

5.1 Data Collection

Initially, inventory information was obtained for all of the 4,518 bridges maintained by MDOT along Michigan's trunkline highway network, or structures carrying traffic with a span of at least 20 feet. These bridge inventory data were disaggregated into the three distinct scenarios shown in **Figure 41** and a series of additional engineering data were merged with each bridge in order to conduct the safety performance analysis. While these details are summarized in subsequent subsections, it should be noted that a number of bridges were removed from the database to ensure only homogenous bridge decks were included in the statistical analysis (all trunkline NHS bridges were ultimately considered in the network screening). This included scenarios where:

- Bridges where the potential traffic crash influence area overlapped (or bridges that are located in immediate proximity along the same direction of travel).
- Bridges where significant realignment within the study period (2013-2022) was detected.
- Bridges along the non-freeway trunkline NHS network where traffic control (including signals, all-way stops, or roundabouts) was present within the crash influence area.
- Other scenarios where the geometric conditions (such as a bridge located at the end of a route) or complex geometry that could not be appropriately modeled with systemwide data.

Figure 42 provides a map of all 4,518 bridges maintained by MDOT and the 1,691 bridges included in this evaluation. Given that each direction of travel was evaluated as a single site, bridges along divided highways where one structure carries both directions of travel (and is represented by one point in the bridge inventory data) were converted to two sites.

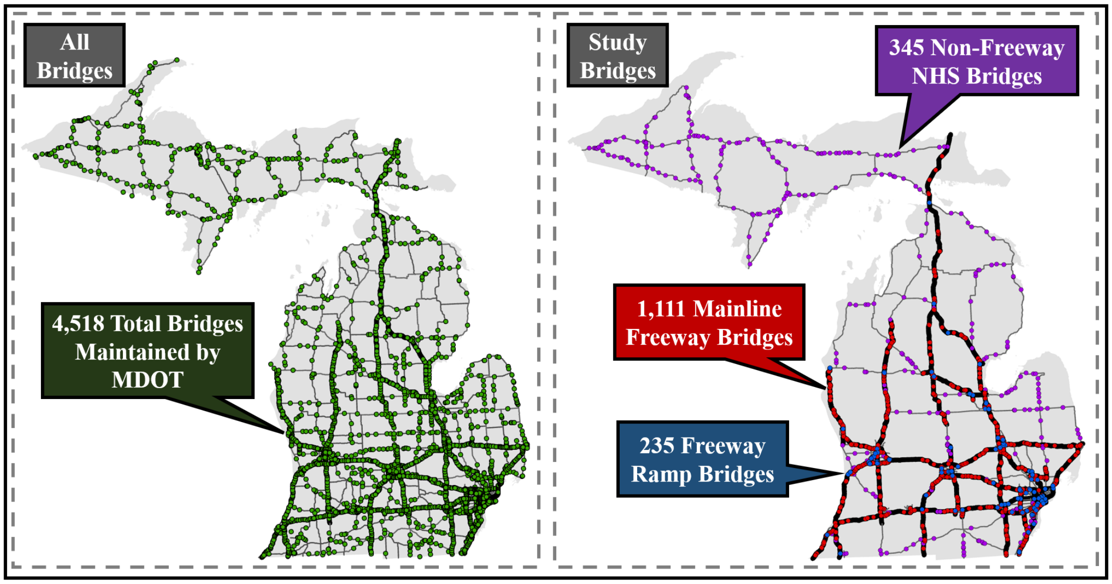


Figure 42. Map of All MDOT Bridges (N=4,518) and Study Bridges in Evaluation (N=1,691)

5.1.1 *Bridge Inventory Data*

A number of key characteristics were obtained from Michigan's bridge inventory data as well as the National Bridge Inventory (NBI) dataset maintained at the federal level. This included the total structure length, the number of through lanes, and the intersecting feature. A summary of these data by scenario is provided in **Table 18**.

Table 18. Bridge Characteristics Obtained from Bridge Inventory Data

Bridge Characteristic	Mainline Freeways (N = 1,111)			Freeway Ramps (N = 235)			Non-Freeways (N = 345)		
	Min	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
Structure Length (*Feet*)	20.0	170.4	999.9	27.9	276.7	1,534.1	20.0	97.2	870.1
Lanes (*Through Lanes*)*	2.0	2.3	4.0	1.0	1.5	4.0	2.0	2.3	5.0
Intersects Roadway (*Binary*)	0.00	0.58	1.00	0.00	0.82	1.00	0.00	0.09	1.00

**Per direction for mainline freeways, freeway ramps, and divided non-freeways, includes total of both directions and continuous two-way left-turn lanes if present for undivided non-freeways*

5.1.2 *Traffic Volume Data*

Traffic volume data in the form of annual average daily traffic (AADT) estimates for each bridge were obtained from the annual shapefiles maintained by MDOT as well as MDOT's *Transportation Data Management System*. This included a distinct count for each year of the study period, which was the ten-year period between 2013 and 2022. Years in which no AADT estimates were available were either interpolated between AADT estimates or extrapolated based on the last available year of data. The AADT estimate was specific to one direction of travel for mainline freeways, freeway ramps, and divided non-freeways. The AADT estimate includes both directions of travel for undivided non-freeways. The distribution of the mean AADT estimates by scenario is shown in **Figure 43**.

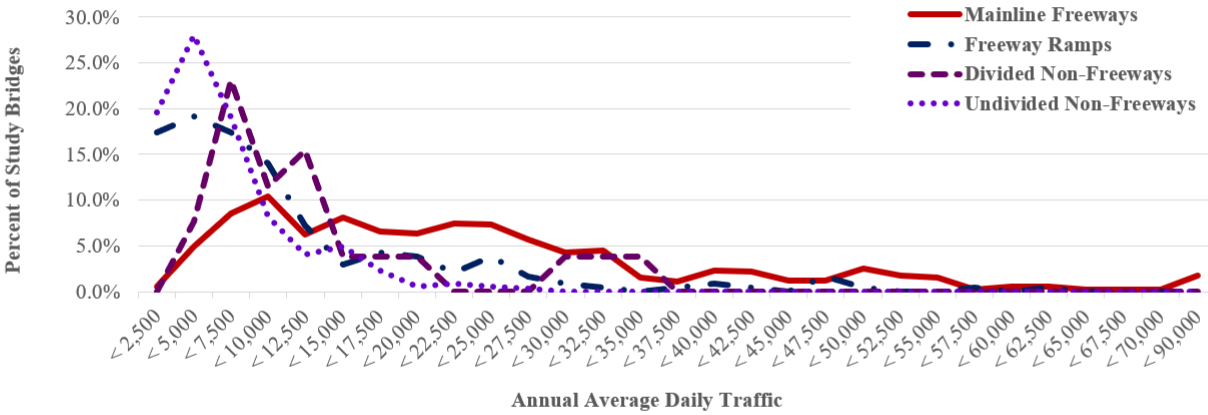


Figure 43. Distribution of Mean AADT Estimates by Scenario (2013-2022)

5.1.3 *Traffic Crash Data*

Traffic crash data for each of the 1,691 study bridge decks was obtained from the annual databases maintained by the Michigan State Police (MSP). ArcGIS was used to conduct a spatial join to identify crashes occurring both within close proximity to the bridge deck as well as along the same route and travel direction (or excluding crashes along other roadway facilities within close proximity to the bridge deck). While this crash influence area approach varied across the three bridge scenarios (detailed in **Table 19**), a diagram of this process for the freeway bridge sites is shown in **Figure 44**. Crash data was collected for each year of the study period, which was the ten-year period between 2013 and 2022.

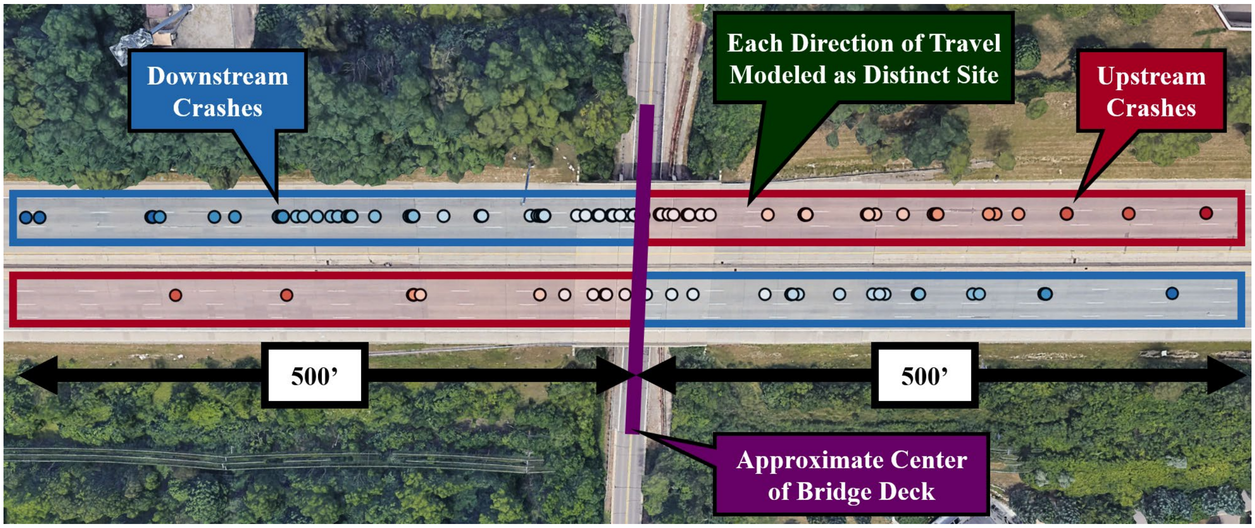


Figure 44. Traffic Crash Data Collection Process at Freeway Bridge Sites

Table 19. Bridge Crash Influence Areas by Scenario

Bridge Scenario	Crash Influence Area
Mainline Freeways	Traffic crashes that occurred within 500’ upstream or downstream of the approximate center of the bridge deck were collected for further analysis. Each direction of travel (e.g. northbound vs. southbound) was treated as a unique site and therefore the total influence area for each mainline freeway bridge was 1,000 feet.
Freeway Ramps and Interchanges	Traffic crashes that occurred within a window between 50’ upstream of the start of the bridge deck and 200’ downstream of the end of the bridge deck were collected for further analysis. Therefore, the total crash influence area for freeway ramp bridges is equal to the bridge deck structure length plus 250 feet.
Trunkline NHS Non-Freeways	Traffic crashes that occurred within 500’ upstream or downstream of the approximate center of the bridge deck were collected for further analysis. Each direction of travel (e.g. northbound vs. southbound) was treated as a unique site for divided roadways, and undivided roadways were treated as a single site (or both directions of travel were modeled together consistent with roadway inventory data). The total influence area for non-freeway bridge decks was 1,000 feet.

A total of 33,880 crashes were identified for the ten-year study period within the crash influence areas for the 1,691 study bridge decks. A subset of "target" crashes that may be related to slippery conditions along the bridge deck were then identified from all crashes that occurred within the influence area. This included crashes that were coded by the responding officer as having occurred with road conditions that were "icy", "snowy', or "slushy" as well as crashes in weather conditions that were coded as "snow", "sleet/hail", or "blowing snow". Animal-related crashes were removed from the analysis. A total of 9,688 target crashes were identified within the ten-year study period, representing 28.6 percent of all crashes that occurred within the crash influence areas. A summary of annual average crash counts for each of the three bridge deck scenarios is provided in **Table 20**.

Table 20. Annual Average Traffic Crash Frequency at Study Bridges (2013-2022)

Annual Average Traffic Crashes	Mainline Freeways (N = 1,111)			Freeway Ramps (N = 235)			Non-Freeways (N = 345)		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
All Crashes	0.00	2.54	39.30	0.00	1.03	8.70	0.00	0.93	12.80
Target Crashes	0.00	0.76	10.40	0.00	0.28	2.00	0.00	0.17	1.40

5.1.4 *Horizontal Curve Data*

The presence of horizontal curvature within the crash influence area was identified by employing a spatial algorithm developed by the MSU research team that estimates the length and radius of curves along the state's spatial roadway inventory data. An example of this process is shown in **Figure 45**. The radius estimated by the algorithm was used to categorize horizontal curves by the approximate maximum design speed based on an assumed six percent superelevation consistent with the AASHTO *Green Book*. Curve presence, which is summarized in **Table 21**, was indicated by a binary variable that is equal to 1 if the bridge contains a curve with design speed less than or equal to the noted design speed and 0 otherwise. For example, 16 percent (0.16) of mainline freeway bridges contain a curve with a design speed that is less than or equal to 85 mph.

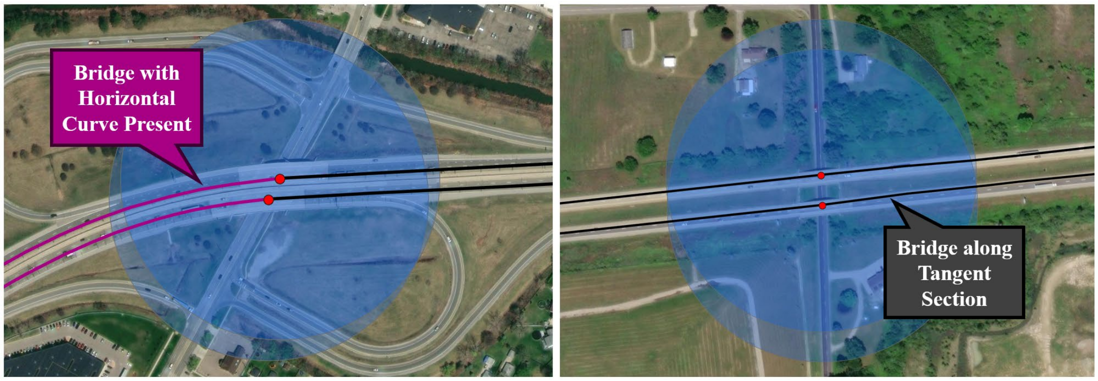


Figure 45. Example of Horizontal Curve Presence at Freeway Bridge

Table 21. Presence of Horizontal Curves on Study Bridges, by Design Speed

Maximum Curve Design Speed	Mainline Freeways (N = 1,098)			Freeway Ramps (N = 235)			Non-Freeways (N = 345)		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
85 MPH	0.00	0.16	1.00	0.00	0.83	1.00	0.00	0.13	1.00
70 MPH	0.00	0.03	1.00	0.00	0.73	1.00	0.00	0.04	1.00
45 MPH	0.00	0.00	1.00	0.00	0.30	1.00	0.00	0.00	1.00

5.1.5 *Weather Data*

In addition to the bridge, traffic, and roadway information that was collected for each study bridge deck, it was also important to consider how the frequency of winter-season precipitation impacts bridge deck safety performance. The annual number of winter-season days with precipitation at weather stations within or adjacent to Michigan were obtained from the National Oceanic and Atmospheric Administration's (NOAA) *2006-2020 U.S. Climate Normals* data (NCEI, 2023). A spatial join was used in ArcGIS to associate each bridge deck with the data from the nearest weather station. As shown in **Figure 46**, this information is critical to consider within Michigan as lake effect precipitation results in considerable regional variance across the state.

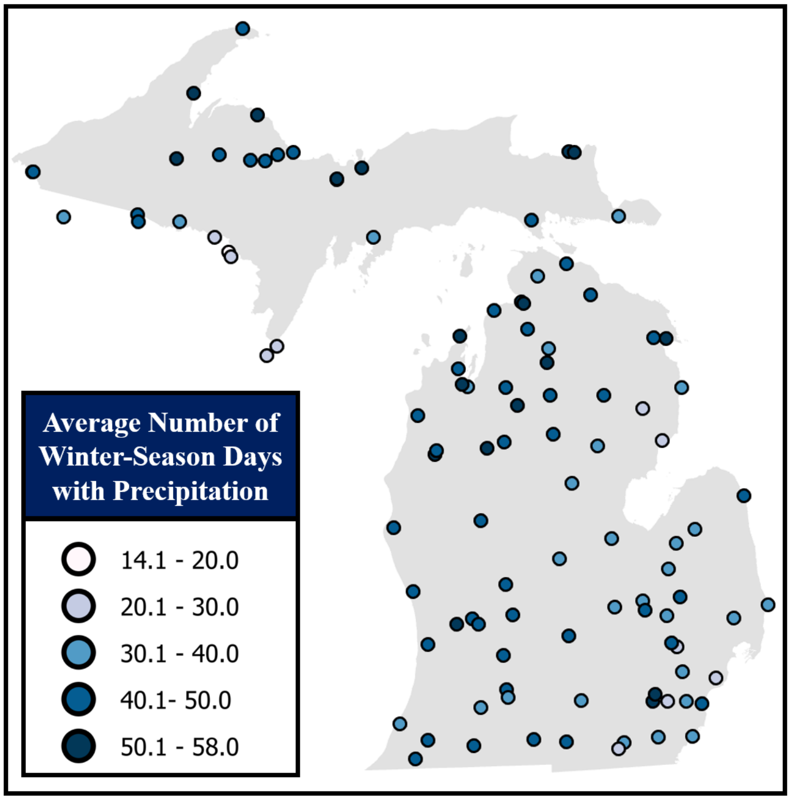


Figure 46. Weather Stations with NOAA Annual Climate Normals for Average Number of Winter-Season Days with Precipitation (NCEI, 2023)

5.2 Network Screening to Identify Candidate Bridges for Potential BDWS Treatments

Based on the data collection process outlined in **Section 5.1**, a comprehensive network screening was conducted to identify candidate bridge decks along Michigan's trunkline highway network to consider for future BDWS treatments. Consistent with MDOT's commitment to the *Safe System Approach*, this network screening included analytical approaches that were both proactive (or risk-based methods not tied to observed target crash data) and reactive (or methods that consider observed target crash data) towards identifying candidate bridge decks for further evaluation. The network screening is broadly divided into two main components:

- An Empirical Bayes (EB) method analytical approach that considers the 1,691 study bridges, where distinct analyses were conducted for mainline freeways, freeway ramps, and non-freeway trunkline bridge decks (**Sections 5.2.1 - 5.2.3**).
- A manual review of the remaining structures along the trunkline national highway system that could not be adequately modeled with systemwide data via a target crash concentration map (**Section 5.2.4**).

The EB method analytical approach was conducted consistent with the AASHTO *Highway Safety Manual* (HSM), shown in **Figure 47**. A series of safety performance functions (SPFs) were estimated for each bridge scenario, or models that relate target crash frequency to a series of explanatory variables (including traffic volume, road or bridge characteristics, and weather data).

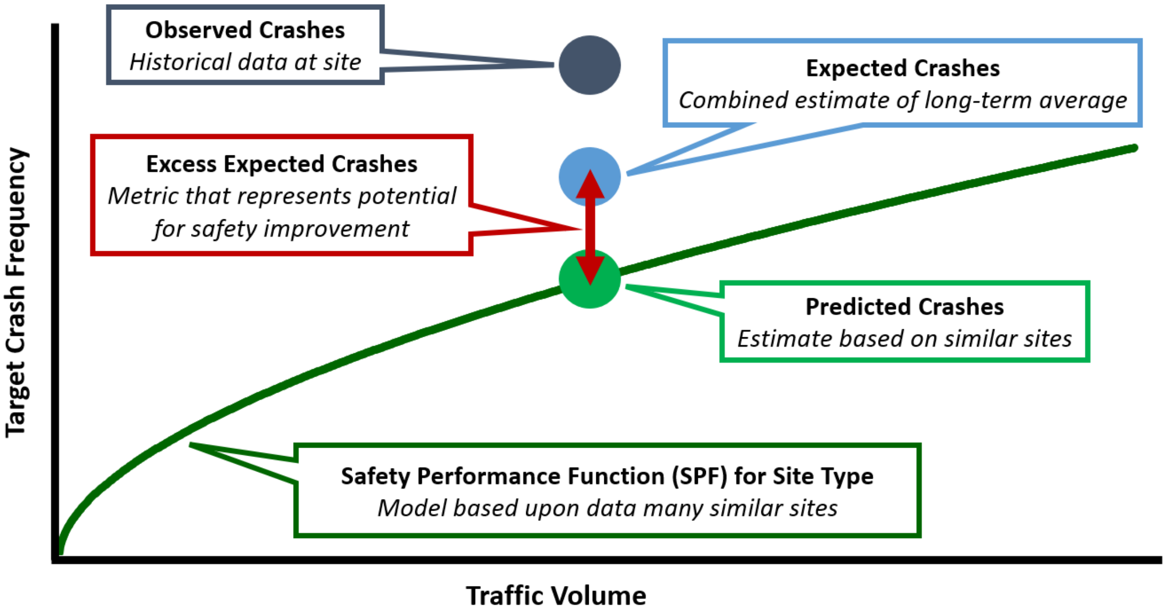


Figure 47. Empirical Bayes Methodology for Network Screening

Four metrics were used to assess each study bridge deck on both a proactive and reactive basis in terms of annual target crash frequency (**Table 22)**. The final list of candidates presented in **Section 5.2.5** was developed by considering safety performance across all four metrics.

Table 22. Bridge Deck Target Crash Metrics Used in Network Screening

Target Crash Metric	Description
Observed (*Reactive*)	The annual average observed target crashes that occurred within the bridge deck's influence area over the ten-year study period (2013-2022). It should be noted that for the bridge decks that were excluded from the modeling approach, observed target crash frequency is the only metric available for analysis (**Section 5.2.4**).
Expected (*Reactive and Proactive*)	The expected annual target crash frequency uses the EB method process to combine the observed traffic crash data at the site with a predicted value estimated via an SPF developed from similar sites. The expected annual target crash frequency represents an estimate of the long-term average annual target crash frequency at each bridge deck.
Predicted (*Proactive*)	The predicted annual target crash frequency is estimated for each site based on an SPF developed from similar sites that considers traffic volumes, roadway and bridge characteristics, and weather data. The annual predicted crash frequency is estimated independent of observed crash data and represents a proactive risk-based approach to identifying candidates.
Excess Expected (*Reactive and Proactive*)	The excess expected annual target crash frequency is determined by subtracting the annual expected crash frequency from the predicted crash frequency, or the number of annual expected target crashes greater than the average predicted value from similar sites. The excess expected annual target crash frequency is often used as a metric to identify sites with the potential for safety improvement compared to average peers. Within the context of this network screening, this excess expected value is best used in conjunction with the other three metrics to ensure that bridge decks with relatively large target crash counts (either observed or predicted) are identified as candidates, not simply sites with greater than the average frequency alone.

Negative binomial regression models were estimated to develop a series of SPFs that relate the annual number of target crashes at a given bridge deck to a series of traffic, bridge, and roadway characteristics, or the predicted value in **Figure 47**. The negative binomial was employed, or a generalized form of the Poisson model. In the Poisson regression model, the probability of bridge deck i experiencing yi target crashes during a specific period (one year in this study) is given by:

$$P(y_i) = \frac{EXP(-\lambda_i)\lambda_i^{y_i}}{y_i!} \qquad \textbf{(Eq. 2)}$$

where P(yi) is probability of bridge deck i experiencing yi crashes during the period and λi is equal to the bridge deck's expected number of target crashes, E[yi]. Poisson regression models are estimated by specifying this Poisson parameter λi as a function of several explanatory variables. The most common functional form of this equation is λi = EXP(βXi), where Xi is a vector of explanatory variables (or traffic volume, structure length, horizontal curve presence, etc.) and β is a vector of estimable parameters. The negative binomial model is derived by rewriting the Poisson parameter for each bridge deck i as λi = EXP(βXi + εi), where EXP(εi) is a gamma-distributed error term with mean 1 and variance α. The addition of this term allows the variance to differ from the mean as VAR[yi] = E[yi] + αE[yi]2. The α term is also known as the overdispersion parameter, which is reflective of the additional variation in target crash counts beyond the Poisson model (where α is assumed to equal zero or the mean and variance are assumed to be equal).

5.2.1 *Freeway Bridges*

A total of 1,111 mainline freeway bridges were included in the SPF development process and screened for potential BDWS treatments via the EB method process (**Figure 48**). Note that the remaining mainline freeway bridges that could not be appropriately modeled with systemwide data were manually screened as outlined in **Section 5.2.5**. A summary of the traffic crash and volume data specific to these facilities is provided in **Table 23**.

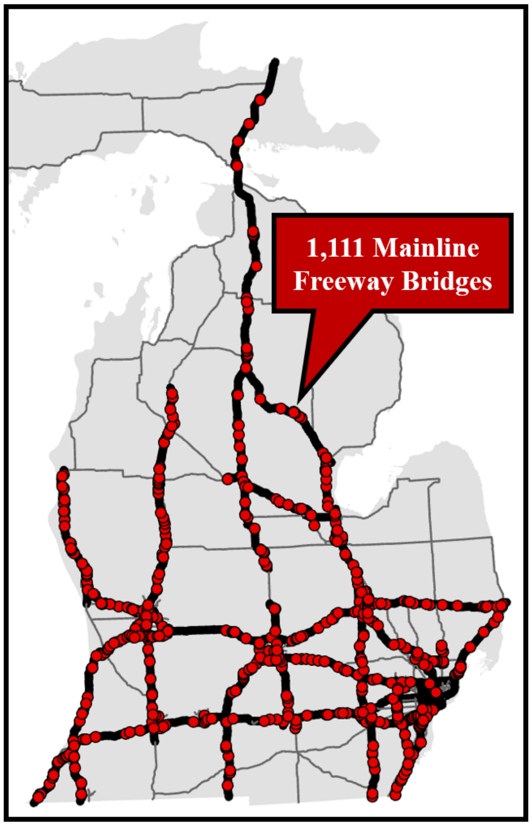


Figure 48. Map of Study Mainline Freeway Bridge Decks

Table 23. Mainline Freeway Bridge Deck Traffic Crash and Volume Summary (2013-2022)

Freeway Bridge Information		Average AADT	Traffic Crash Frequency (Ten-Year Total)		Traffic Crash Rate per 100M VMT	
Intersects	Count		All	Target	All	Target
Roadway	641	23,847	22,041	6,594	208.6	62.4
River	164	17,057	1565	497	80.9	25.7
Rail	136	23,342	2207	711	100.6	32.4
Creek	128	21,047	1636	487	87.8	26.2
Drain	24	22,216	334	74	90.6	20.1
Trail	10	16,362	90	21	79.6	18.6
Other	8	30,530	389	62	230.4	36.7
All Bridges	**1,111**	**22,406**	**28,262**	**8,446**	**164.2**	**49.1**

While the sample of mainline freeway bridge decks evaluated in this study supported traffic above a variety of intersecting features, the majority of these bridges intersected another roadway (or 57.7 percent). Traffic volumes along the sample of freeway bridge decks ranged from 1,980 vehicles per day up to 87,320 vehicles per day with an average of 22,406 vehicles per day. A total of 8,446 target crashes occurred within the mainline freeway bridge deck influence areas during the ten-year study period, representing approximately 30 percent of all traffic crashes. Average traffic crash rates per 100M vehicle miles traveled within the influence area of the bridge deck were highest along facilities that intersect another roadway (62.4) and lowest along facilities that intersect drains (20.1) or trails (18.6). **Table 24** provides a summary of the mainline freeway bridge deck crash data by worst injury in the crash and crash type.

Table 24. Mainline Freeway Bridge Deck Crashes by Worst Injury in Crash and Crash Type (2013-2022)

Worst Injury In Crash	Total Crashes		Target Crashes	
	Frequency	Share	Frequency	Share
Fatality (K)	75	0.3%	15	0.2%
Serious Injury (A)	384	1.4%	91	1.1%
Minor Injury (B)	1,291	4.6%	363	4.3%
Possible Injury (C)	3,446	12.2%	1,084	12.8%
Property Damage Only	23,066	81.6%	6,893	81.6%
Total	**28,262**	**100.0%**	**8,446**	**100.0%**
Crash Type	**Total Crashes**		**Target Crashes**	
	Frequency	**Share**	**Frequency**	**Share**
Single Vehicle	14,258	50.4%	5,696	67.4%
Head On	73	0.3%	36	0.4%
Head On Left-Turn	9	0.0%	1	0.0%
Angle	258	0.9%	116	1.4%
Rear End	7,411	26.2%	963	11.4%
Sideswipe Same	4,701	16.6%	1,094	13.0%
Sideswipe Opposite	41	0.1%	16	0.2%
Other	1,511	5.3%	524	6.2%
Total	**28,262**	**100.0%**	**8,446**	**100.0%**

A total of 106 persons were either killed or seriously injured in target crashes occurring within the study mainline freeway bridge deck influence areas over the ten-year study period, representing approximately 23 percent of all fatalities and serious injuries occurring at these locations. This demonstrates the potential impact BDWS or other countermeasures intended to reduce such snowy or icy bridge deck crashes can have towards achieving the state's *Towards Zero Death* vision.

Intuitively, approximately two-thirds of target crashes involved a single vehicle, compared to approximately one-half of all crashes occur within the study bridge influence areas.

A negative binomial regression model was estimated for the 1,111 study mainline freeway bridge decks, summarized in **Table 25**. Note that the post-installation years were removed for the freeway bridge decks that have been treated with BDWS. The observed annual target crashes at these bridge decks versus AADT is shown in **Figure 49**, in addition to this safety performance function where all other factors aside from traffic volume have been set to average values.

Table 25. Negative Binomial Model Results for Mainline Freeway Bridge Decks (N = 1,111)

Parameter	Estimate	Std. Error	P-Value
Intercept	-10.275	0.451	< 0.001
Annual Average Daily Traffic (*ln Vehicles per Day*)	0.708	0.025	< 0.001
Structure Length (*ln Structure Length in Feet*)	0.278	0.028	< 0.001
Days of Winter-Season Precipitation (*ln Number of Days*)	0.224	0.100	0.025
Horizontal Curve Present with 85 MPH Design Speed (*Binary*)	0.146	0.045	< 0.001
Horizontal Curve Present with 70 MPH Design Speed (*Binary*)	0.637	0.073	< 0.001
Intersects Roadway (*Binary*)	0.799	0.035	< 0.001
Northern Region [Superior, North, Bay, Grand] (*Binary*)	0.257	0.0367	< 0.001
Overdispersion Parameter	1.003	-	-

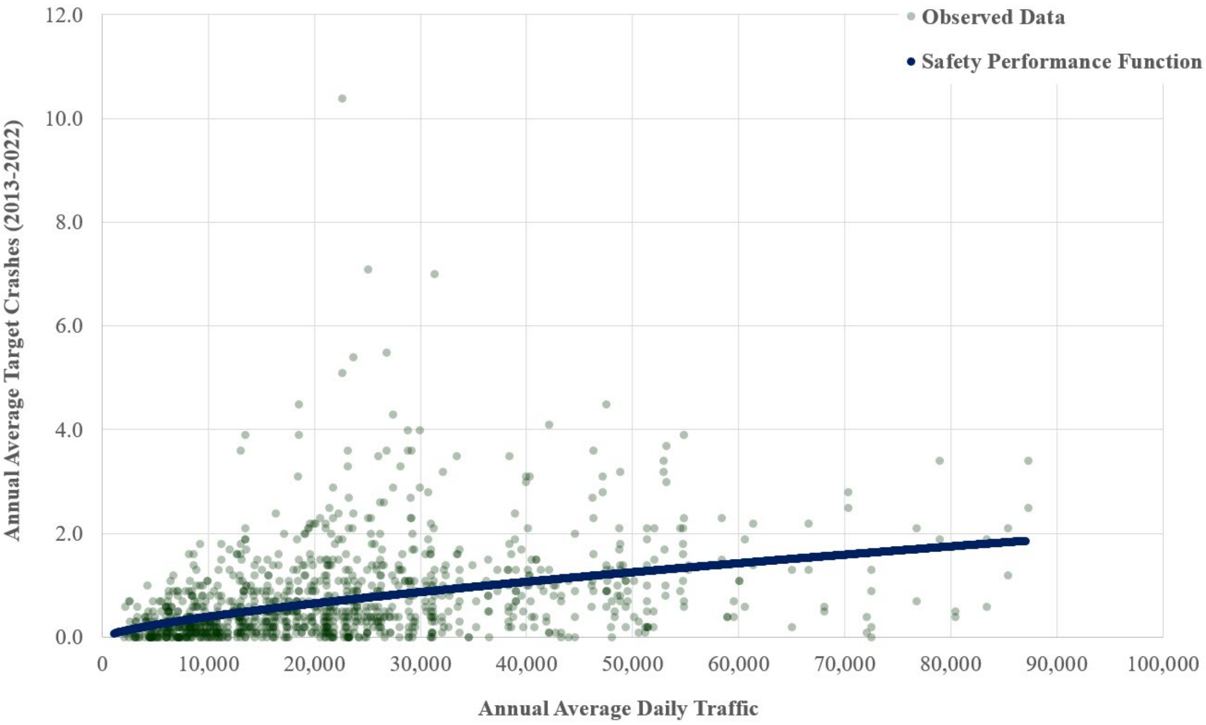


Figure 49. Target Crash Frequency vs. AADT – Mainline Freeways (N = 1,111)

Table 25 displays that several factors beyond traffic volume influence target crash frequency along mainline freeway bridges. For example, target crash frequencies were larger at bridge decks that had longer structure lengths or intersected other roadway facilities. Freeway bridges where a horizontal curve was present with an 85 MPH maximum design speed (or relatively gentle curves that generally do not require any specific curve warning signs) experienced larger target crash frequencies compared to bridges along tangent roadway segments. This effect was magnified where horizontal curves were present with a maximum design speed of 70 MPH (or tighter curves that may require specific curve warning signs). Freeway bridges that experience a greater number of winter-season days with precipitation tended to experience more target crashes. Additionally, freeway bridges that are located in the northern MDOT regions (including Bay, Grand, North, and Superior) where temperatures are generally lower also tended experience more target collisions.

Each of the four target crash metrics summarized in **Table 22** were employed to identify 65 candidate bridge decks from the 1,111 study mainline freeway bridges. While the list of these bridge decks can be found in **Section 5.2.5**, the distribution of study bridge decks by annual excess expected target crashes is shown in **Figure 50**. Locations with annual excess expected target crash counts greater than zero suggest that there may be potential for improvement with respect to snowy or icy bridge deck crashes.

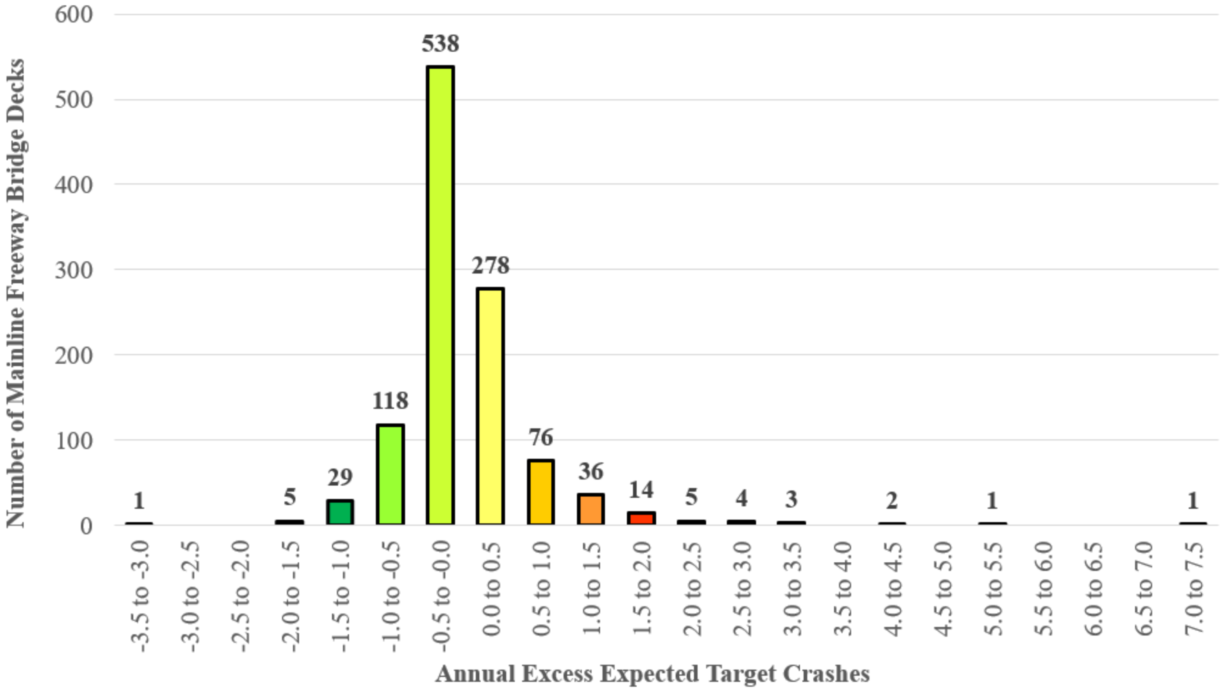


Figure 50. Study Mainline Freeway Bridges by Annual Excess Expected Target Crashes

5.2.2 *Freeway Ramp and Interchange Bridges*

A total of 235 freeway ramp bridges were included in the SPF development process and screened for potential BDWS treatments via the EB method process (**Figure 51**). Note that the remaining freeway ramp bridges that could not be appropriately modeled with systemwide data were manually screened as outlined in **Section 5.2.5**. A summary of the traffic crash and volume data specific to these facilities is provided in **Table 26**.

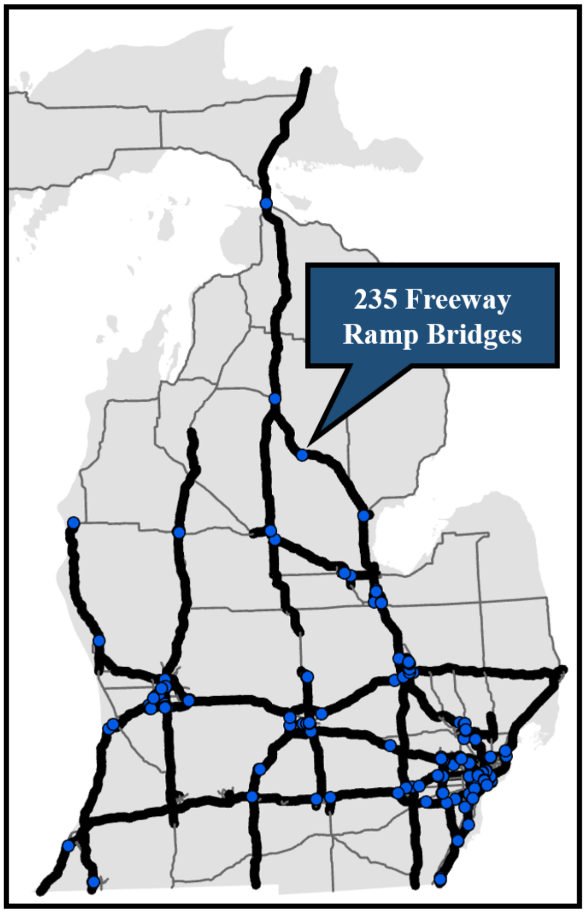


Figure 51. Map of Study Freeway Ramp Bridge Decks

Table 26. Freeway Ramp Bridge Deck Traffic Crash and Volume Summary (2013-2022)

Bridge Information		Average AADT	Traffic Crash Frequency (Ten-Year Total)		Traffic Crash Rate per 100M VMT	
Type	Count		All	Target	All	Target
Mainline at Interchange	23	23,351	501	106	297.3	62.9
Collector-Distributor	13	11,146	70	14	148.1	29.6
Flyover Ramp	155	9,889	1688	496	276.9	81.4
Entrance Ramp	21	3,906	89	32	358.4	128.9
Exit Ramp	23	4,177	73	15	245.1	50.4
All Ramp Bridges	**235**	**10,182**	**2,421**	**663**	**275.1**	**75.3**

Approximately two-thirds of ramp bridge decks included in this evaluation were flyover ramps connecting interchanges. The remaining bridge decks represented mainline segments within complex system interchanges, collector-distributor facilities, as well as conventional exit or entrance ramps. Traffic volumes along the sample of freeway ramp bridge decks ranged from 150 vehicles per day up to 60,550 vehicles per day with an average of 10,182 vehicles per day. A total of 663 target crashes occurred within the mainline freeway bridge deck influence areas during the ten-year study period, representing 27.4 percent of all traffic crashes. The average traffic crash rates per 100M vehicle miles traveled within the influence area of the bridge deck were larger for freeway ramps (75.3) than the mainline freeway bridges (49.1). **Table 27** provides a summary of the freeway ramp bridge deck crash data by worst injury in the crash and crash type.

Table 27. Freeway Ramp Bridge Deck Crashes by Worst Injury in Crash and Crash Type (2013-2022)

Severity	Total Crashes		Target Crashes	
	Frequency	Share	Frequency	Share
Fatality (K)	8	0.3%	0	0.0%
Serious Injury (A)	34	1.4%	4	0.6%
Minor Injury (B)	119	4.9%	23	3.5%
Possible Injury (C)	341	14.1%	93	14.0%
Property Damage Only	1,919	79.3%	543	81.9%
Total	**2,421**	**100.0%**	**663**	**100.0%**
Type	**Total Crashes**		**Target Crashes**	
	Frequency	**Share**	**Frequency**	**Share**
Single Vehicle	1,218	50.3%	457	68.9%
Head On	8	0.3%	3	0.5%
Head On Left-Turn	1	0.0%	0	0.0%
Angle	34	1.4%	9	1.4%
Rear End	674	27.8%	88	13.3%
Sideswipe Same	396	16.4%	75	11.3%
Sideswipe Opposite	0	0.0%	0	0.0%
Other	90	3.7%	31	4.7%
Total	**2,421**	**100.0%**	**663**	**100.0%**

While no fatalities occurred at the freeway ramp bridges during the ten-year study period, four persons were seriously injured in target crashes occurring within the bridge deck influence areas. Similar to the findings for mainline freeway bridge decks, approximately two-thirds of target crashes involved a single vehicle, compared to approximately one-half of all crashes occurring within the study bridge influence areas.

A negative binomial regression model was estimated for the 235 study freeway ramp bridge decks, summarized in **Table 28**. The observed annual target crashes (normalized to 500' of influence area length) at these bridge decks versus annual average daily traffic is shown in **Figure 52**, in addition to this safety performance function where all other factors aside from traffic volume have been set to average values.

Table 28. Negative Binomial Model Results for Freeway Ramp Bridge Decks (N = 235)

Parameter	Estimate	Std. Error	Significance
Intercept	-13.861	1.076	< 0.001
Annual Average Daily Traffic (*ln Vehicles per Day*)	0.411	0.050	< 0.001
Days of Winter-Season Precipitation (*ln Number of Days*)	0.627	0.256	0.014
Horizontal Curve Present with 85 MPH Maximum Design Speed (*Binary*)	0.400	0.152	0.009
Overdispersion Parameter	1.639	-	-

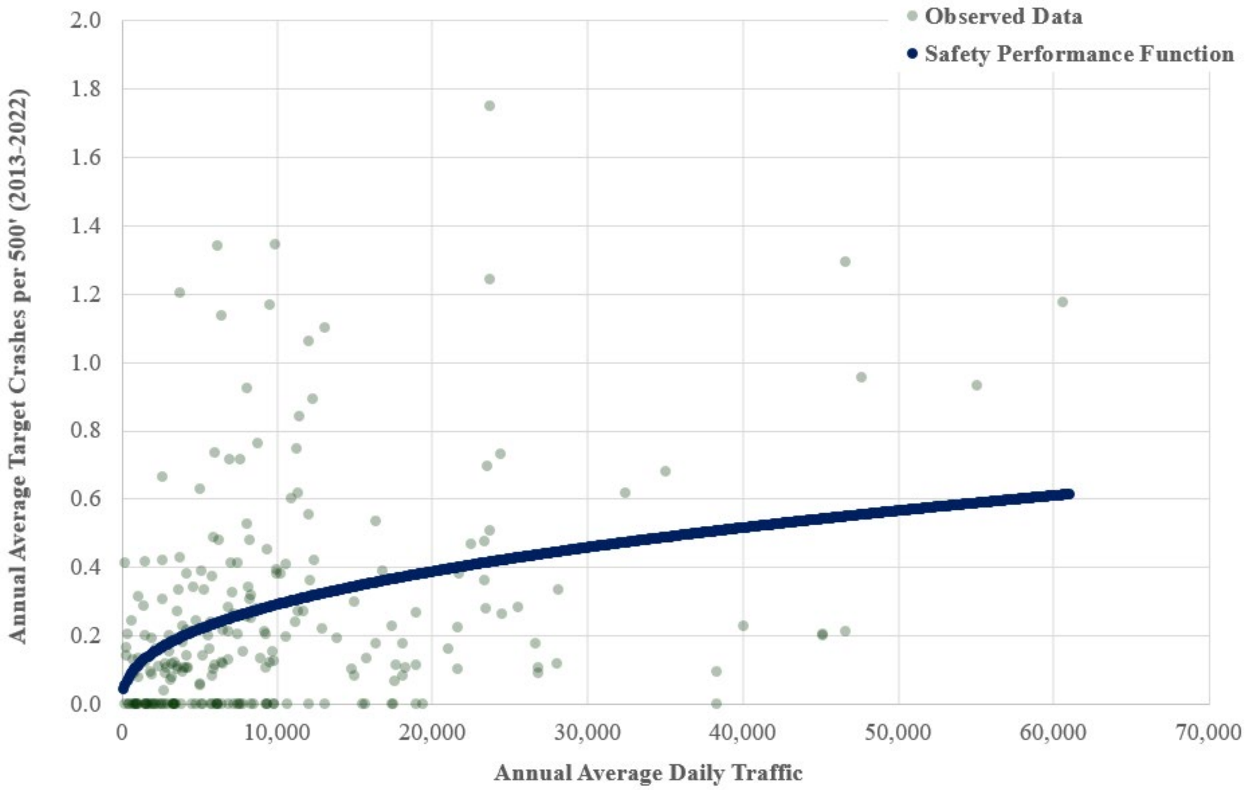


Figure 52. Target Crash Frequency per 500' vs. AADT – Freeway Ramps (N = 235)

Similar to the mainline freeway model, ramp bridges that experience a greater number of winter-season days with precipitation tended to experience more target crashes. Additionally, ramp bridges where a horizontal curve was present with an 85 MPH maximum design speed experienced larger target crash frequencies compared to bridges along tangent roadway segments.

Each of the four target crash metrics summarized in **Table 22** were used to identify 23 candidate bridge decks from the 235 study ramp bridges. While the list of these bridge decks can be found in **Section 5.2.5**, the distribution of study bridge decks by annual excess expected target crashes is shown in **Figure 53**. Locations with annual excess expected target crash counts greater than zero suggest that there may be potential for improvement with respect to snowy or icy bridge crashes.

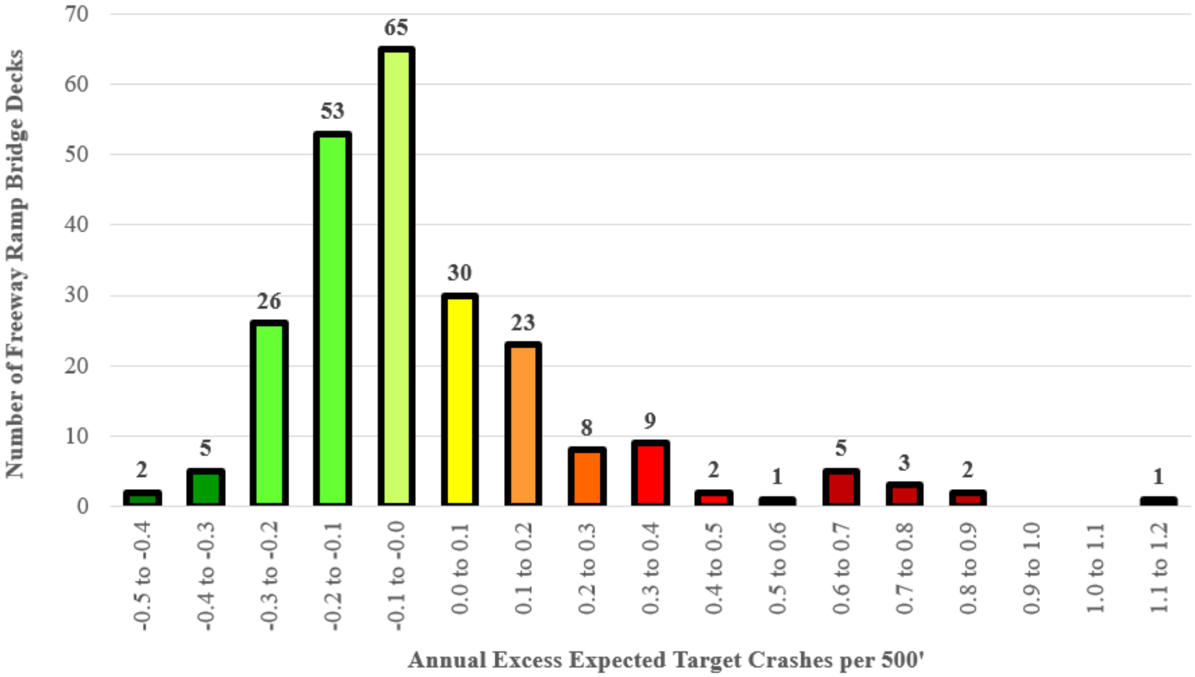


Figure 53. Study Freeway Ramp Bridges by Annual Excess Expected Target Crashes

5.2.3 *Non-Freeway Bridges*

A total of 345 trunkline NHS non-freeway bridges were included in the SPF development process and screened for potential BDWS treatments via the EB method process (**Figure 54**). It should be noted that this included only bridge decks along highways with a speed limit of 50 miles per hour or higher. Additionally, the remaining trunkline NHS non-freeway bridges that could not be appropriately modeled with systemwide data were manually screened as outlined in **Section 5.2.5**. A summary of the traffic crash and volume data specific to these facilities is provided in **Table 29**.

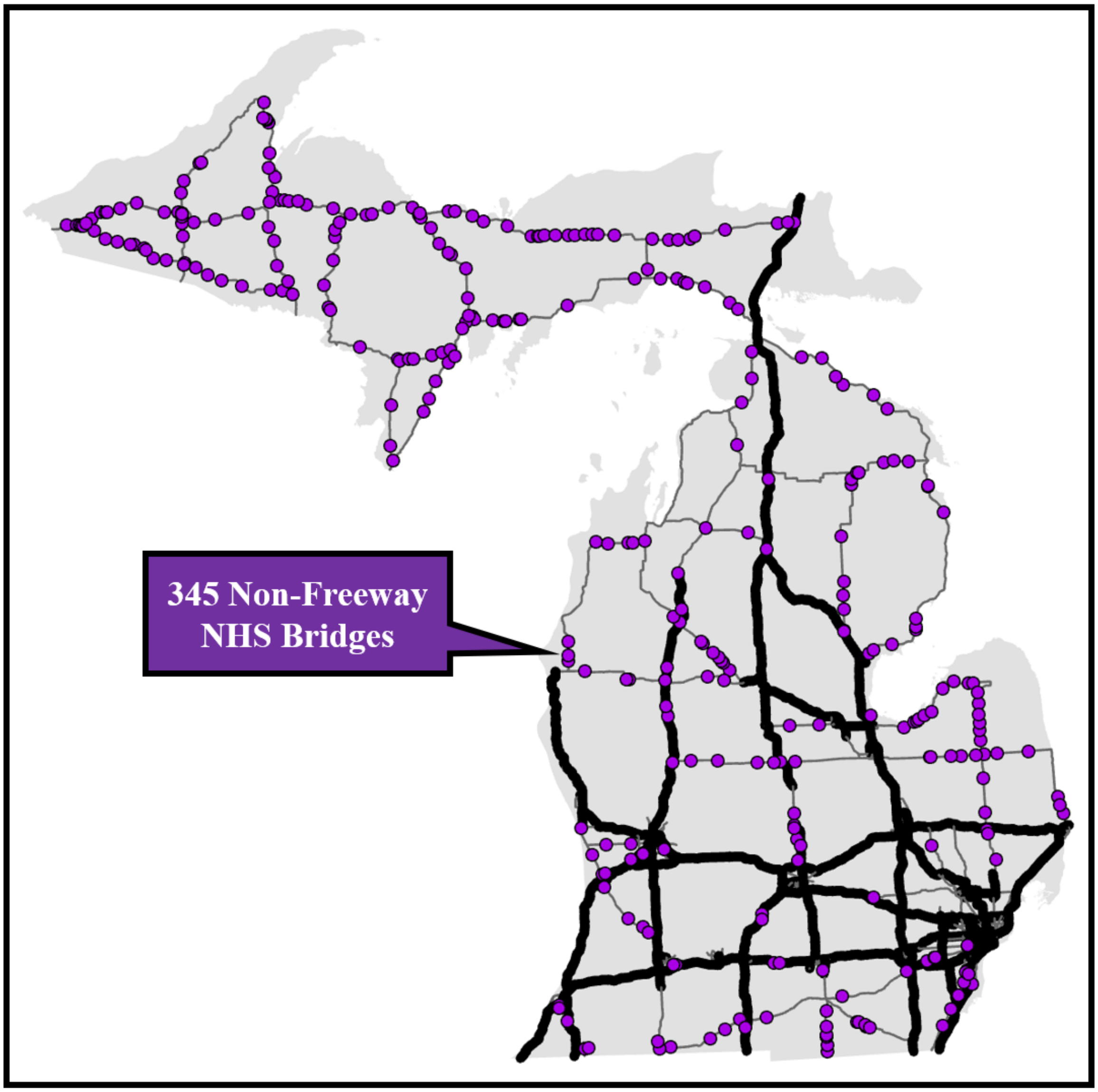


Figure 54. Map of Study Trunkline NHS Non-Freeway Bridge Decks

Table 29. Non-Freeway Trunkline NHS Bridge Deck Traffic Crash and Volume Summary (2013-2022)

Non-Freeway Bridge Information		Average AADT	Traffic Crash Frequency (Ten-Year Total)		Traffic Crash Rate per 100M VMT	
Intersects	**Count**		**Target**	**All**	**Target**	**Target**
Roadway	26	10,010	414	95	230.1	52.8
River	157	6,252	1,422	249	209.6	36.7
Rail	14	9,919	114	32	118.8	33.3
Creek	116	5,712	943	140	205.9	30.6
Drain	18	7,905	207	36	210.5	36.6
Other	14	7,998	97	27	125.3	34.9
Total	**345**	**6,660**	**3,197**	**579**	**201.3**	**36.5**

In contrast to the mainline freeway bridge ramps, more than three-quarters of the study non-freeway bridges intersected a river or a creek. Traffic volumes along the sample of non-freeway bridge decks ranged from 780 vehicles per day up to 34,380 vehicles per day with an average of 6,660 vehicles per day. A total of 579 target crashes occurred within the mainline freeway bridge deck influence areas during the ten-year study period, representing approximately 18 percent of all traffic crashes. Average traffic crash rates per 100M vehicle miles traveled within the influence area of the bridge deck were highest along facilities that intersect another roadway (52.8). **Table 30** provides a summary of the trunkline non-freeway bridge deck crash data by worst injury in the crash and crash type.

Table 30. Non-Freeway Bridge Deck Crashes by Worst Injury in Crash and Crash Type (2013-2022)

Severity	Total Crashes		Target Crashes	
	Frequency	Share	Frequency	Share
Fatality (K)	20	0.6%	3	0.5%
Serious Injury (A)	64	2.0%	11	1.9%
Minor Injury (B)	137	4.3%	24	4.1%
Possible Injury (C)	285	8.9%	62	10.7%
Property Damage Only	2,691	84.2%	479	82.7%
Total	**3,197**	**100.0%**	**579**	**100.0%**
Type	**Total Crashes**		**Target Crashes**	
	Frequency	**Share**	**Frequency**	**Share**
Single Vehicle	1,985	62.1%	365	63.0%
Head On	47	1.5%	26	4.5%
Head On Left-Turn	53	1.7%	2	0.3%
Angle	209	6.5%	30	5.2%
Rear End	551	17.2%	72	12.4%
Sideswipe Same	193	6.0%	32	5.5%
Sideswipe Opposite	52	1.6%	18	3.1%
Other	107	3.3%	34	5.9%
Total	**3,197**	**100.0%**	**579**	**100.0%**

A total of 14 persons were either killed or seriously injured in target crashes occurring within the study non-freeway bridge deck influence areas over the ten-year study period, representing approximately 17 percent of all fatalities and serious injuries occurring at these locations. Unlike the mainline freeway and ramp bridges, single vehicle crashes represented a similar proportion of both total and target crashes.

Distinct negative binomial regression models were estimated for the 303 bridge decks along undivided roadway facilities (**Table 31)** and the 42 bridge decks along divided roadway facilities

(**Table 32**). The observed annual target crashes at these bridge decks versus annual average daily traffic is shown in **Figures 55 and 56**, in addition to this safety performance function where all other factors aside from traffic volume have been set to average values.

Table 31. Negative Binomial Model Results for Undivided Non-Freeway Bridge Decks (N = 303)

Parameter	Estimate	Std. Error	Significance
Intercept	-9.782	0.662	< 0.001
Annual Average Daily Traffic (*ln Vehicles per Day*)	0.778	0.072	< 0.001
Structure Length (*ln Structure Length in Feet*)	0.277	0.056	< 0.001
Horizontal Curve Present with 85 MPH Design Speed (*Binary*)	0.358	0.139	0.010
Overdispersion Parameter	1.373	-	-

Table 32. Negative Binomial Model Results for Divided Non-Freeway Bridge Decks (N = 42)

Parameter	Estimate	Std. Error	Significance
Intercept	-9.528	1.618	< 0.001
Annual Average Daily Traffic (*ln Vehicles per Day*)	0.575	0.196	0.003
Structure Length (*ln Structure Length in Feet*)	0.571	0.185	0.002
Overdispersion Parameter	0.784	-	-

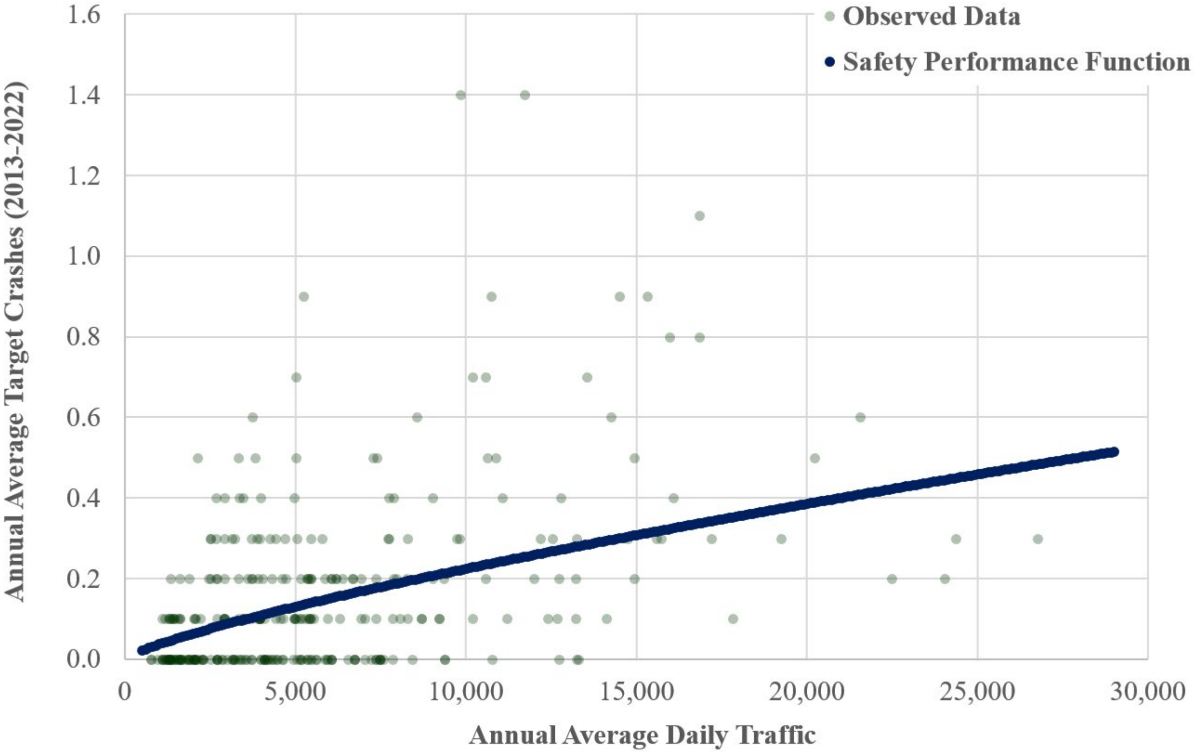


Figure 55. Target Crash Frequency vs. AADT – Undivided Non-Freeway Bridges (N = 303)

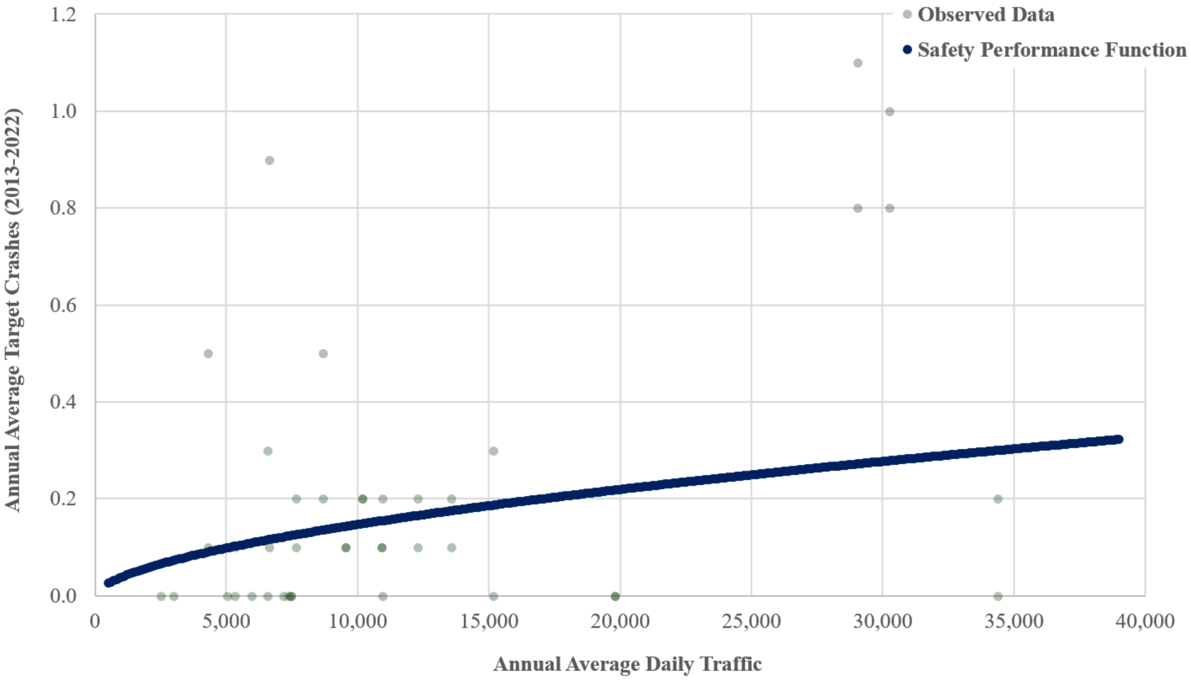


Figure 56. Target Crash Frequency vs. AADT – Divided Non-Freeway Bridges (N = 42)

Similar to the mainline freeway bridges, non-freeway bridges with larger structure lengths tended to experience larger frequencies of target crashes. This effect was present for both the undivided and divided non-freeway bridges. Additionally, bridge decks along undivided facilities where a horizontal curve was present with an 85 MPH maximum design speed (or relatively gentle curves that generally do not require any specific curve warning signs) experienced larger target crash frequencies compared to bridges along tangent undivided roadway segments. While this horizontal curvature effect was not present for the 42 divided non-freeway bridge decks evaluated in this study, it is likely that the relatively small sample of bridges limited the ability to detect a statistically significant impact on target crash frequency.

Each of the four target crash metrics summarized in **Table 22** were employed to identify 12 candidate bridge decks from the 345 study non-freeway bridges. While the list of these bridge decks can be found in **Section 5.2.5**, the distribution of study bridge decks by annual excess expected target crashes is shown in **Figure 57**. Locations with annual excess expected target crash counts greater than zero suggest that there may be potential for improvement with respect to snowy or icy bridge deck crashes.

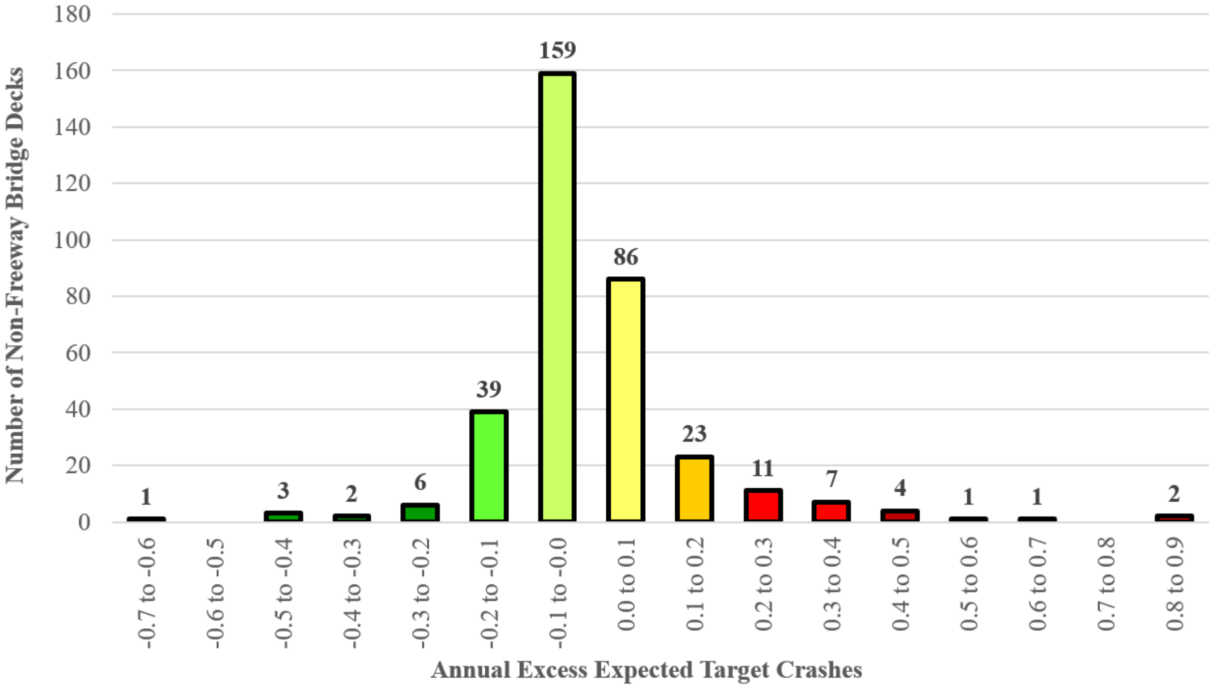


Figure 57. Study Trunkline NHS Non-Freeway Bridges by Annual Excess Expected Target Crashes

5.2.4 *Manual Review of Bridges Not Included in Model*

Due to the fact that a number of bridge decks along the trunkline NHS network in Michigan could not be modeled with systemwide data, it was necessary to conduct a manual review of target crashes occurring along the network. This was conducted by developing a crash concentration map (shown in **Figure 58**), which could be used to manually screen for areas along the network that are relative "hot spots" for target crashes. Bridge decks located along the trunkline highway network (including mainline freeways, freeway ramps, and NHS non-freeways) but not included in the evaluation presented in **Sections 5.2.1 to 5.2.3** were reviewed by examining the target crash concentration map. This allowed for the identification of 13 additional bridges that may benefit from the installation of a BDWS, presented in **Section 5.2.5**.

Figure 58. Example of Target Crash Concentration Map used in Manual Review

5.2.5 *Candidate Bridges for Potential BDWS Treatments*

Given the network screening process summarized in **Sections 5.2.1-5.2.4**, a total of 100 candidate bridge deck locations were identified that may benefit from BDWS treatments (**Figure 59**). This included 65 mainline freeway locations, 23 freeway ramp locations, and 12 non-freeway trunkline locations. It is critical to note that only a preliminary investigation of these locations was conducted (beyond the network screening process) by the research team via a review of satellite and street view imagery to ensure that there were not obvious site characteristics that would limit the use of BDWS. Additionally, the appearance of a specific location on the candidate list does not imply that a BDWS should be installed. Instead, these 100 candidate locations represent a menu of potential options for the department to consider as a part of expanding the BDWS program in Michigan. This should include a more detailed engineering study to determine feasibility at these locations, including the review of the Michigan UD-10 crash forms for crashes occurring near the bridge deck to determine if the target crashes identified within the network screening process indeed represent collisions related to road conditions along the bridge deck.

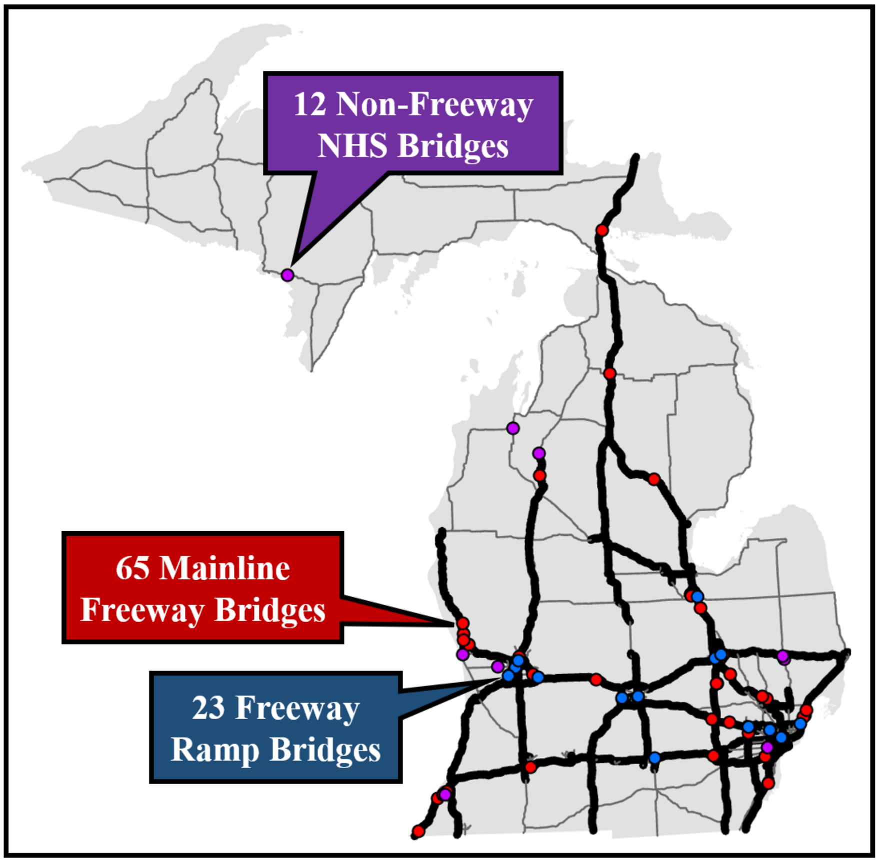


Figure 59. Map of 100 Candidate MDOT Bridges for Potential Future BDWS Implementation (N = 100)

Tables 33-35 provide a summary of the 100 candidate locations identified by the network screening process. While bridges were identified based on the four metrics outlined in **Table 22**, it should be noted that preference was given to locations that included nearby existing ESS installations that may allow for cost savings if selected for a BDWS treatment. The approximate distance to the nearest ESS along the route (if applicable) is shown in **Tables 33-35**. Note that statewide ESS location data was obtained by reviewing a number of MDOT resources and does not include the specific features included with each ESS (or there may not be any potential cost savings related to these existing systems). Candidates were also selected such that a number of locations were identified that may be candidates for BDWS treatments across all seven MDOT regions. A total of 13 bridge decks that were not included within the modeling process were manually identified by reviewing the crash concentration maps as noted in **Section 5.2.4**.

The candidate bridge decks presented in **Tables 33-35** are not presented in the order of any specific rank (i.e. any of the 100 locations represent suitable candidates to consider for implementation). Candidate bridge decks where only one direction of travel was identified as a possessing potentially increased risk for target crashes to occur are listed as a single site (for example, eastbound I-94 at Harper Avenue). Locations where both directions of travel (such as I-475 at Grand Traverse Street) were identified as potential candidates as listed as two distinct sites. Complete details for each of the 100 candidate locations are provided in **Appendix B**. A series of comments that provide more guidance specific to several of the identified candidate bridge decks is provided in **Table 36**.

Shapefiles of all 1,691 study bridge decks evaluated as a part of this study are included within the final deliverables for review by the department. There may be additional opportunities to install multiple BDWS at consecutive bridge decks adjacent to the candidate locations identified in **Tables 33-35** by reviewing these data while conducting a more detailed engineering study for each location. The department can also review these shapefiles for bridge decks beyond the 100 candidate locations that met the criteria to be included in **Tables 33-35** for potential consideration. Finally, both MDOT and local roadway agencies can identify additional locations beyond the network evaluated within this study (or the trunkline NHS system) for potential BDWS treatments using the tools included in **Sections 5.2.1-5.2.4**. This would include bridge decks along the high-speed trunkline non-NHS network as well as high-speed non-trunkline highways.

Table 33. Candidate Freeway (Mainline) Bridges for Potential BDWS Treatments (N = 65)

Freeway Bridge Information				Mean AADT	Annual Target Crash Metric				Distance to ESS (*Miles*)
Site Name	County	Intersects	Structure Length (*Feet*)		Observed	Expected	Predicted	Excess Expected	
I-475 NB @ Grand Traverse/Rail	Genesee	Other	357.0	22,565	10.40	10.12	2.67	7.45	1.0
I-475 SB @ Grand Traverse/Rail	Genesee	Other	357.0	22,565	5.10	4.90	1.63	3.27	1.0
I-496 EB/US-127 SB @ Trowbridge/Rail	Ingham	Other	305.1	31,261	7.00	6.83	2.50	4.33	0.5
I-94 EB @ Harper	Macomb	Road	173.6	47,496	4.50	4.43	2.66	1.77	0.5
I-94 EB @ 14 Mile	Macomb	Road	191.9	48,758	3.20	3.19	2.79	0.40	1.0
I-94 EB @ Clinton River	Macomb	River	357.9	52,863	3.20	3.13	1.86	1.27	2.5
I-94 WB @ Clinton River	Macomb	River	357.9	52,863	3.40	3.32	1.86	1.46	2.5
I-94 EB @ Jackson	Washtenaw	Road	190.9	26,738	3.60	3.53	2.05	1.48	na
I-94 WB @ Jackson	Washtenaw	Road	190.9	26,738	5.50	5.34	2.05	3.29	na
US-131 NB @ River Dr./Rail	Kent	Other	474.1	29,919	2.90	2.87	2.23	0.64	na
US-131 SB @ River Dr./Rail	Kent	Other	474.1	29,919	4.00	3.92	2.23	1.70	na
US-23 NB @ Silver Lake Rd./Rail	Genesee	Other	333.0	25,052	2.30	2.25	1.49	0.76	0.5
US-23 SB @ Silver Lake Rd./Rail	Genesee	Other	333.0	25,052	7.10	6.81	1.72	5.08	0.5
I-196 EB @ Market Ave/Grand River	Kent	Other	999.9	23,095	3.30	3.26	2.35	0.91	na
I-196 WB @ Market Ave/Grand River	Kent	Other	976.0	23,095	3.60	3.55	2.33	1.22	na
I-75 NB @ Lapeer Road	Oakland	Road	193.9	54,825	2.30	2.28	1.84	0.43	na
I-75 SB @ Lapeer Road	Oakland	Road	193.9	54,825	3.90	3.79	1.84	1.95	na
I-96 EB @ Milford	Oakland	Road	171.3	53,129	3.70	3.59	1.72	1.87	na
I-96 WB @ Milford	Oakland	Road	171.3	53,129	3.00	2.93	1.72	1.21	na
I-275 SB @ Eight Mile	Oakland	Road	166.0	87,317	3.40	3.35	2.23	1.12	1.0
US-31 NB @ Laketon	Muskegon	Road	226.0	28,718	3.60	3.47	1.53	1.94	2.0
US-31 SB @ Laketon	Muskegon	Road	226.0	28,718	4.00	3.85	1.53	2.32	2.0
I-96 EB @ Grand River	Livingston	Road	173.9	42,084	4.10	3.93	1.47	2.47	2.5
I-69 WB @ M-54	Genesee	Road	135.2	38,303	3.50	3.38	1.57	1.82	1.5
I-196 EB @ M-11	Kent	Road	156.5	32,025	3.20	3.12	1.77	1.36	na
I-196 WB @ Lane	Kent	Road	126.3	33,346	3.50	3.37	1.44	1.93	na
I-75 NB @ Dixie	Saginaw	Road	203.1	29,130	3.60	3.45	1.39	2.06	na
I-75 SB @ Dixie	Saginaw	Road	203.1	29,130	2.30	2.24	1.39	0.85	na
I-75 NB @ Bristol	Genesee	Road	153.9	47,165	2.80	2.75	1.88	0.87	na
I-75 SB @ Bristol	Genesee	Road	153.9	47,165	3.10	3.06	2.18	0.88	na
I-94 WB @ Telegraph	Wayne	Road	246.1	70,287	2.80	2.77	2.18	0.60	na

Freeway Bridge Information				Mean AADT	Annual Target Crash Metric				Distance to ESS (*Miles*)
Site Name	**County**	**Intersects**	**Structure Length (*Feet*)**		**Observed**	**Expected**	**Predicted**	**Excess Expected**	
I-94 EB @ Telegraph	Wayne	Road	246.1	70,287	2.50	2.49	2.18	0.31	na
I-94 EB @ Westnedge	Kalamazoo	Road	257.5	39,862	3.00	2.90	1.42	1.47	na
I-94 WB @ Westnedge	Kalamazoo	Road	257.5	39,862	3.10	2.99	1.42	1.57	na
US-31 NB @ M-120	Muskegon	Road	195.9	18,489	4.50	4.21	1.08	3.13	3.0
US-31 SB @ M-120	Muskegon	Road	195.9	17,175	3.90	3.66	1.08	2.58	3.0
I-94 EB @ Pipestone	Berrien	Road	223.8	27,364	4.30	4.03	1.09	2.94	5.0
I-94 WB @ Pipesone	Berrien	Road	223.8	27,364	2.90	2.75	1.09	1.66	5.0
I-96 WB @ 28th Street	Kent	Road	264.8	23,162	2.10	2.05	1.37	0.68	na
I-96 EB @ 28th Street	Kent	Road	264.8	23,162	2.70	2.61	1.37	1.24	na
I-75 NB @ Dixie Highway	Oakland	Road	299.9	25,959	3.50	3.30	1.12	2.19	na
I-75 SB @ M-32	Otsego	Road	133.9	6,371	1.10	0.98	0.44	0.54	1.5
US-131 NB @ Old US-131	Wexford	Road	190.9	4,182	1.00	0.87	0.38	0.49	6.0
I-96 WB @ Kent	Ionia	Road	147.0	18,375	3.10	2.94	1.13	1.81	na
I-94 EB @ Red Arrow	Berrien	Road	190.9	23,645	5.40	4.97	0.94	4.03	na
I-94 WB @ Red Arrow	Berrien	Road	191.9	23,645	2.40	2.26	0.94	1.32	na
I-675 NB @ Shattuck	Saginaw	Road	151.9	13,446	2.10	1.97	0.86	1.11	1.0
I-675 SB @ Shattuck	Saginaw	Road	151.9	13,446	3.90	3.58	0.86	2.73	1.0
I-675 NB @ Michigan	Saginaw	Road	196.9	13,446	1.90	1.88	1.51	0.37	0.5
I-675 SB @ Michigan	Saginaw	Road	196.9	13,446	1.90	1.88	1.51	0.37	0.5
I-96 WB @ Airline	Muskegon	Road	143.0	13,018	3.60	3.28	0.77	2.51	3.5
US-127 NB @ Kalamazoo	Ingham	Road	139.8	28,041	3.30	3.09	0.98	2.10	1.0
I-75 SB @ Mackinac Trail	Mackinac	Road	117.5	2,563	0.70	0.56	0.23	0.33	na
I-75 NB @ M-55	Ogemaw	Road	201.4	6,177	0.90	0.82	0.47	0.36	2.5
I-94 WB @ US-12	Berrien	Road	239.8	21,735	2.90	2.72	0.96	1.76	3.0
I-94 EB @ US-12	Berrien	Road	239.8	21,735	3.30	na	na	na	3.0
US-31 NB @ I-96	Muskegon	Road	220.0	23,856	2.50	na	na	na	0.5
US-31 SB @ I-96	Muskegon	Road	220.0	23,856	3.60	na	na	na	0.5
I-196 WB @ Butterworth	Kent	Road	211.9	21,353	6.30	na	na	na	na
I-94 WB @ Niles	Berrien	Road	320.9	25,975	3.80	na	na	na	na
I-94 EB @ Niles	Berrien	Road	320.9	25,975	3.40	na	na	na	na
I-75 NB @ Joslyn	Oakland	Road	213.9	40,925	2.90	na	na	na	na
I-75 SB @ Joslyn	Oakland	Road	213.9	40,925	4.10	na	na	na	na
I-75 NB @ Huron River	Wayne	Road	154.2	29,318	3.40	na	na	na	0.5
I-75 SB @ Huron River	Wayne	Road	154.2	29,318	3.10	na	na	na	0.5

Table 34. Candidate Freeway Ramps and Interchange Bridges for Potential BDWS Treatments (N = 23)

Ramp or Interchange Bridge Information				Mean AADT	Annual Target Crash Metric				Distance to ESS (*Miles*)
Site Name	County	Intersects	Structure Length (*Feet*)		Observed	Expected	Predicted	Excess Expected	
US-127 NB @ Red Cedar	Ingham	Other	263.8	23,673	1.75	1.60	0.46	1.14	0.5
US-127 SB @ Red Cedar	Ingham	Other	272.3	23,637	1.24	1.15	0.46	0.69	0.5
M-8 WB @ M-10	Wayne	Road	212.9	46,597	1.30	1.21	0.50	0.71	na
M-39 NB @ M-10	Oakland	Road	273.0	47,578	0.96	0.92	0.56	0.36	na
I-196 EB Ramp @ Buck Creek	Kent	Creek	134.8	9,496	1.17	1.06	0.37	0.68	na
I-496 EB Ramp to N US-127	Ingham	Road	202.8	13,074	1.10	1.00	0.36	0.63	0.5
M-45 Ramp to I-196 EB	Kent	Road	141.7	12,244	0.89	0.82	0.38	0.44	na
I-75 NB Ramp to I-69 EB	Genesee	Road	266.1	12,023	1.07	0.96	0.35	0.61	na
I-75 SB Ramp to I-69 EB	Genesee	Road	289.0	8,054	0.98	0.82	0.30	0.52	na
I-75 NB Ramp to I-69 WB	Genesee	Road	338.9	8,720	0.76	0.69	0.31	0.38	na
I-75 SB Ramp to I-69	Genesee	Creek	128.0	8,054	0.53	0.49	0.30	0.19	na
I-69 WB Ramp to I-496 EB	Eaton	Road	224.7	11,443	0.84	0.77	0.34	0.42	na
I-469 WB Ramp to I-69 WB	Eaton	Road	233.6	6,350	1.14	0.98	0.27	0.71	na
I-94 EB Ramp to I-696 WB	Macomb	Road	295.9	24,373	0.73	0.68	0.38	0.30	0.5
I-696 EB Ramp to I-94 EB	Macomb	Road	1,122.7	23,699	0.51	0.49	0.38	0.12	0.5
M-6 EB Ramp to I-96 EB	Kent	River	1,085.6	11,207	0.75	0.70	0.38	0.32	na
I-96 WB Ramp to M-6 WB	Kent	River	1,204.4	11,342	0.62	0.59	0.38	0.21	na
I-75 NB Ramp to I-675 NB	Saginaw	Road	270.0	9,865	1.35	1.16	0.29	0.87	na
I-696 WB Ramp to I-275 SB	Oakland	Road	628.9	35,027	0.68	0.66	0.49	0.17	na
I-94 WB Ramp to US-127 SB	Jackson	Road	165.4	3,737	1.20	0.96	0.19	0.77	na
US-127 NB to I-94 WB	Jackson	Road	165.4	10,880	0.60	0.55	0.30	0.25	na
I-475 SB Ramp to I-69 EB	Genesee	Road	581.0	878	0.48	0.45	0.30	0.15	0.5
I-96 EB Ramp to US-131 SB	Kent	Other	420.9	21,955	1.10	na	na	na	na

Table 35. Candidate Non-Freeway Bridges for Potential BDWS Treatments (N = 12)

Non-Freeway Bridge Information				Mean AADT	Annual Target Crash Metric				Distance to ESS (*Miles*)
Site Name	County	Intersects	Structure Length (Feet)		Observed	Expected	Predicted	Excess Expected	
US-2 @ Sturgeon River	Dickinson	River	240.2	5,243	0.90	0.71	0.20	0.51	na
M-37 @ Rail in Chums Corner	Grand Traverse	Rail	223.8	15,326	0.90	0.84	0.46	0.38	0.5
US-131 @ Manistee River	Wexford	River	335.0	10,748	0.90	0.82	0.39	0.43	2.0
M-153 EB @ Hines	Wayne	Road	169.9	29,033	1.10	0.98	0.50	0.48	na
M-153 WB @ Hines	Wayne	Road	167.7	29,033	0.80	0.74	0.50	0.24	na
US-31 NB @ Grand River	Ottawa	River	199.8	30,267	0.80	0.76	0.57	0.19	na
US-31 SB @ Grand River	Ottawa	River	199.8	30,267	1.00	0.92	0.57	0.36	na
M-53 @ Branch Belle River	Lapeer	River	21.7	16,850	1.10	0.91	0.26	0.66	na
M-53 @ Weston Drain	Lapeer	Drain	49.9	16,850	0.80	0.71	0.32	0.39	na
M-139 @ St. Joseph River	Berrien	River	405.8	10,185	0.70	0.68	0.56	0.12	na
M-45 WB @ Grand River	Ottawa	River	1,595.1	13,414	3.30	na	na	na	na
M-45 EB @ Grand River	Ottawa	River	1,595.1	13,414	1.80	na	na	na	na

Table 36. Additional Comments for Selected Candidate Bridge Deck Locations

Location	Comment
M-53 @ Branch Belle River and M-53 @ Weston Drain	These two bridge decks are located in close proximity along M-53 in Lapeer County and it may be possible to recognize cost-savings if systems are installed together.
I-75 and I-69 Interchange	There are four ramp locations identified at this interchange in Genesee County and it may be possible to recognize cost-savings if these systems are installed together.
I-69 and I-496 Interchange	There are two ramp bridge decks identified in close proximity at the I-69/I-496 interchange in Eaton County and it may be possible to recognize cost-savings if these systems are installed together.
I-94 and I-696 Interchange	There are two ramp bridge decks identified in close proximity at the I-94 and I-696 interchange in Macomb County (including an adjacent ESS) and it may be possible to recognize cost-savings if these systems are installed together.
I-69 and M-6 Interchange	There are two ramp bridge decks identified in close proximity at the I-69/M-6 interchange in Kent County and it may be possible to recognize cost-savings if these systems are installed together.
I-94 and US-127 Interchange	There are two ramp bridge decks identified in close proximity at the I-94/US-127 interchange in Jackson County and it may be possible to recognize cost-savings if these systems are installed together.
I-94 Corridor from 14 Mile Road to the Clinton River	There are a series of bridge decks (including the four candidate locations included in this evaluation) along the I-94 corridor in Macomb County (bounded by 14 Mile Road to the South and the Clinton River to the North) that represent potential candidates for BDWS and it may be possible to recognize cost-savings if these systems are installed together.

5.3 Preliminary Before-and-After Crash Data Assessment for Existing BDWS Sites

Given that MDOT has proactively installed at least twelve BDWS at bridge decks across the state (**Figure 60**), it was possible to perform a preliminary before-and-after assessment of the traffic crash data at these locations. It is critical to note that this assessment should be interpreted with caution as many of these systems are relatively new, greatly limiting the availability of post-installation data. Annual target crash counts along bridge decks are also relatively small and this therefore represents another concern due to the rare and random nature of traffic crash data. The development of statistically significant robust crash modification factors (CMFs) for BDWS would require a considerable number of additional systems and post-installation years to review. However, the findings presented in this section provides general guidance as to the preliminary experience at these locations in the interim period before such CMFs can be developed.

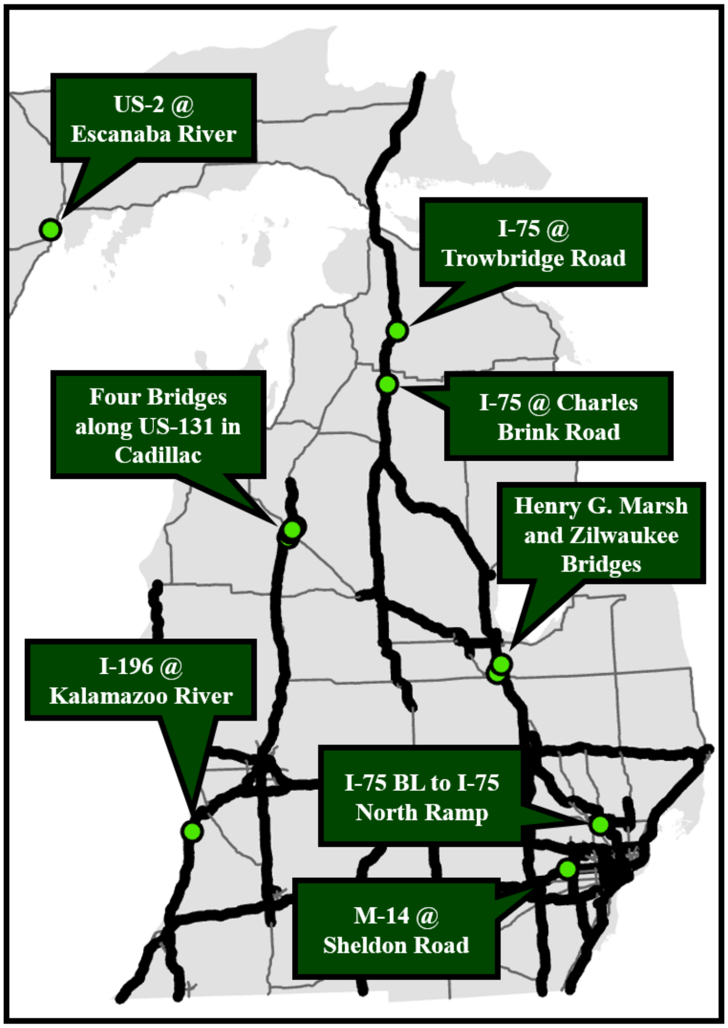


Figure 60. Location of Existing BDWS in Michigan as of 2023 (N = 12)

Traffic crash data were collected for the eleven systems where post-installation period data were available in a manner similar to the process outlined in **Section 5.1.3** with several key departures. A longer study period was used (2010 to 2023) to maximize the availability of pre- and post-installation period data. Additionally, crash counts were evaluated on a seasonal basis (October to April) as opposed to the annual crash counts employed within the network screening process. This allowed for the inclusion of data from 2023 that was obtained from the state's live Mi-CAT tool as opposed to the annual crash databases that are processed after the year is complete. The crash influence areas extended 250' in each direction beyond the ends of the bridge deck to maximize coverage of target crashes that were potentially related to the pavement condition along the bridge deck and minimize the inclusion of unrelated crashes. The influence area for the two unique "big bridge" locations (including the Zilwaukee and Henry G. Marsh bridges in Saginaw) included the entire bridge deck in addition to an area 50' upstream and 200' downstream of the bridge deck. Finally, any season that included either installation or testing of the BDWS was removed from the analysis.

Table 37 summarizes the pre- and post-installation crash data at each of the eleven locations included in the evaluation. It should be noted that consistent with the process outlined in **Section 5.1,** each direction of travel was evaluated as a separate site for the freeway bridge locations. Therefore, a total of 20 unique sites are available for assessment. **Table 38** provides an aggregated summary of these findings by scenario.

Table 37. Preliminary Before-and-After Traffic Crash Data at Existing BDWS Locations

BDWS Location	Travel Direction	Scenario	System Type	Structure Length (*feet*)	Seasons Before	Seasons After	Mean AADT	Annual Average Target Crash Frequency		
								Before	After	Percent Change
US-2 @ Escanaba River	WB/EB	Non-Freeway	LED	375.0	9	4	23,373	1.89	1.00	-47.1%
I-75 @ Charles Brink Road	NB	Freeway	Beacon	110.9	5	8	6,208	1.80	1.50	-16.7%
I-75 @ Charles Brink Road	SB	Freeway	Beacon	112.9	5	8	6,208	1.20	0.88	-27.1%
I-75 @ Trowbridge Road	NB	Freeway	LED	252.0	6	6	7,174	0.50	0.50	0.0%

BDWS Location	Travel Direction	Scenario	System Type	Structure Length (*feet*)	Seasons Before	Seasons After	Mean AADT	Annual Average Target Crash Frequency		
								Before	After	Percent Change
I-75 @ Trowbridge Road	SB	Freeway	LED	251.6	6	6	7,174	1.50	0.00	-100.0%
I-75 BL to I-75N Ramp	NB	Flyover Ramp	LED	469.2	8	5	26,765	1.88	1.00	-46.7%
US-131 @ E 50 Road	NB	Freeway	LED	117.8	10	2	6,483	0.70	1.00	42.9%
US-131 @ E 50 Road	SB	Freeway	LED	116.8	10	2	6,483	0.70	0.50	-28.6%
US-131 @ M-115	NB	Freeway	LED	138.8	10	2	6,483	0.40	0.00	-100.0%
US-131 @ M-115	SB	Freeway	LED	136.8	10	2	6,483	0.20	0.50	150.0%
US-131 @ Great Lakes Rail	NB	Freeway	LED	122.0	10	2	5,774	0.10	0.50	400.0%
US-131 @ Great Lakes Rail	SB	Freeway	LED	122.0	10	2	5,774	0.10	0.00	-100.0%
US-131 @ 43 Mile Road	NB	Freeway	LED	255.2	10	2	5,774	0.90	0.00	-100.0%
US-131 @ 43 Mile Road	SB	Freeway	LED	255.6	10	2	5,774	0.80	0.00	-100.0%
Henry G Marsh Bridge	SB	Big Bridge	Beacon	2,948.5	11	1	14,835	3.91	0.00	-100.0%
Henry G Marsh Bridge	NB	Big Bridge	Beacon	2,948.5	11	1	14,835	4.36	1.00	-77.1%
Zilwaukee Bridge	SB	Big Bridge	Beacon	8,061.0	11	1	25,789	7.00	6.00	-14.3%
Zilwaukee Bridge	NB	Big Bridge	Beacon	8,061.0	11	1	25,789	8.64	7.00	-18.9%
M-14 @ Sheldon Road	WB	Freeway	Beacon	252.0	9	2	39,973	1.89	1.50	-20.6%
M-14 @ Sheldon Road	EB	Freeway	Beacon	260.2	9	2	39,973	2.67	2.50	-6.2%

Table 38. Preliminary Before-and-After Traffic Crash Data by Scenario

Bridge Information		Winter Seasons		AADT		Target Crashes per Winter Season			Percent of Sites with Crash Reductions
Scenario	Count	Before	After	Before	After	Before	After	Percent Change	
Non-Freeway	1	9	4	23,216	23,728	1.89	1.00	-47.1%	100%
Flyover Ramp	1	8	5	28,186	24,490	1.88	1.00	-46.7%	100%
Big Bridge*	4	44	4	20,595	19,108	5.98	3.50	-41.4%	100%
Freeway	14	120	48	10,594	12,410	0.89	0.73	-18.2%	71.4%

**The "Big Bridge" category includes the Zilwaukee and Henry G. Marsh Bridges in Saginaw*

The findings presented in **Tables 37 and 38** suggest that safety performance may have improved with respect to target bridge deck crashes at the locations treated with BDWS. Average winter-season target crash counts were lower at 16 of the 20 sites, and it should be noted that the three sites that experienced increases had observed relatively low pre-installation target crash counts (one site had equal average crash frequencies before and after installation). It is also important to note that the BDWS installed along US-2 at the Escanaba River also included the replacement of a concrete median barrier with a two-way center left-turn lane, which could potentially influence the results. The I-75BL to I-75N BDWS in the Metro Region was installed during a project where the bridge deck was realigned, which may also influence the results at that location.

Ultimately, these findings suggest that BDWS remain a promising option to potentially address crashes related to icy bridge deck conditions but do not represent a statistically significant reduction factor that MDOT can use to evaluate economic feasibility. A long-term evaluation should be conducted subsequent to this research with a similar approach after sufficient post-installation period is available. This study should also incorporate the review of the diagram and narrative included within each Michigan UD-10 crash report form associated with crashes occurring near the bridge influence area to identify target crashes more precisely. The process to collect traffic crash data (via a spatial approach that relies on the accuracy of location and other information within the annual crash databases to identify target crashes) was sufficient for the network screening and this preliminary assessment. However, this more detailed approach would be a critical element of further work to develop CMFs as the data included in the annual crash databases may not be precise enough to associate traffic crashes with specific icy bridge decks.

6. RECOMMENDED BDWS EQUIPMENT SPECIFICATIONS

6.1 Bridge Deck Warning System – Technology Overview

A bridge deck warning system (BDWS) is a system which detects or measures real-time conditions and provides condition-specific warnings or advisories to motorists. Typically, a BDWS is desired to help mitigate crashes on bridges due to over-speed travel during inclement weather conditions. Standard components of a BDWS include non-invasive pavement sensors, static signs with a flashing beacon or LED border (see **Figure 61**), and a speed feedback sign (SFBS).

MDOT has deployed several BDWS at locations throughout the state. While each system is slightly different based on the geometrics of the road and the bridge structure itself, each tends to follow the same basic design. Most, if not all, of the BDWS throughout the state utilize a non-invasive pavement sensor installed on a structure placed just off the bridge deck (see **Figure 62**) but in a location where information about the bridge deck surface can be measured while there is airflow underneath. This sensor relays information regarding the bridge deck surface temperature and amounts of water, ice, and snow present on the roadway. Data collected is integrated into a remote processing unit (RPU) and/or roadside controller within a cabinet (see **Figure 63**) where the information is processed along with other weather data, and a message is deployed to motorists via static signing with an active component (flashing beacon or LED border), SFBS, or a dynamic message sign (DMS).

Figure 61. BDWS Signage on NB US-131 at E. 50 Road

Figure 62. BDWS Non-Invasive Sensor on NB US-131 at E. 50 Road

Figure 63. BDWS Non-Invasive Sensor on SB US-131 at E. 50 Road

6.1.1 ***Full BDWS – Environmental Sensor Suite***

An ESS site is a weather station that MDOT deploys at various locations throughout the state to assist the department in the assessment of real-time road conditions at frequently impacted locations and at locations that will aid in the collection of general, representative road weather observations. A BDWS is often a subsystem or component of a full ESS site. While the full ESS sensor suite is not necessary for effective BDWS operation, many of these additional sensors may be used by MDOT for other purposes. The BDWS uses the data from the ESS to determine when a bridge deck is slippery and uses active warning signs to provide to drivers advanced warnings of inclement weather conditions prior to crossing bridges. It is expected that warning messages will influence the drivers to lower their speeds in response to the potentially slippery bridge surface conditions, which will result in a corresponding reduction in crash occurrence and severity.

The base ESS sensor suite includes a wind sensor, precipitation sensor, air temperature sensor, humidity sensor, visibility sensor, surface pavement sensor, and sub-surface temperature probe. In addition, a field controller is required to connect the array of sensors to each ESS site. Furthermore, it is recommended to adopt the deployment of a tower mounted camera and an infrared (IR) illuminator to allow for remote confirmation that activations of the warning message are warranted based on visual observations of the bridge deck conditions. The camera may initially be deployed to capture still images of each site as the communication bandwidth may be limited. The IR illuminator will allow MDOT the capability of viewing night images via the camera. A camera positioned towards the BDWS signs would also be a useful component to allow for remote confirmation that the warning alert is activated, although doing so would require more cameras and may become financially burdensome. **Table 39** depicts the recommended components for a complete ESS site, including sensor quantities and general parameters. The following sections give a brief description of each device included in the base ESS sensor suite.

6.1.1.1 Field Controller (Remote Processing Unit)

The field controller device, also known as the remote processing unit (RPU), is physically and electronically connected to an MDOT-selected array of sensors at the ESS field site. The controller also provides the interface to the communications equipment that transfers the data from the field controller to the central server in a National Transportation Communications for Intelligent Transportation System Protocol (NTCIP) format.

6.1.1.2 Air Temperature/Relative Humidity Sensor:

The Air Temperature and Relative Humidity Sensor determines the air temperature and the level of humidity relative to the ambient temperature. The sensing elements are mounted inside a radiation shield that protects the sensors from solar radiation while allowing continual exchange of air. The sensor is typically mounted on an ESS tower at a height of 2 to 2.5 meters on the tower. Air temperature and moisture values are a typical measure reported by all ESS. While Relative Humidity measurements may seem like a secondary consideration, they're required to derive dew point temperature values. Dew point is a critical requirement for winter maintenance operations since it provides essential information for the determination of pavement condition status and guidance regarding the likelihood of frost when the dew point temperature is compared to the pavement temperature.

Table 39. ESS Base Suite Components

SENSOR	PARAMETER
Atmospheric Sensors	Humidity & Air Temperature with Dew Point Temperature Derivation Precipitation Type, Intensity & Rate Average Wind Speed, Wind Direction & Wind Gust Visibility
Pavement Sensors (Qty. 2)	Surface Temperature Road Condition Chemical Concentration Chemical Freeze Point
Sub-Surface Sensor	Temperature
Camera (w/ PTZ)	Images for verification of visibility & road weather condition
Infrared (IR) Illuminator	Nighttime viewability
Remote Processing Unit (RPU)	Processing Unit for ESS data

6.1.1.3 Wind Direction, Wind Speed, and Wind Gust

Wind sensors, typically known as anemometers, are ideal for determining wind speed, wind direction, and wind gusts. This sensor is typically mounted at a height of 10 meters (30 feet) on the tower for consistency with the World Meteorological Organization specifications. Wind direction, speed, and gusts are important considerations for both winter maintenance and weather support stakeholders. They are critical parameters in lake-affected snow areas and regions where blowing snow is a maintenance concern. The presence of large, forested areas strongly affects the surface winds by either reducing wind speeds in certain locations or inducing funneling effects in areas where the forests have been cleared for highways or farming.

6.1.1.4 Precipitation Sensor

Precipitation sensors are configured to delineate rain, snow, hail, freezing rain, and sleet. There are three critical entities measured by a precipitation sensor: precipitation type, precipitation rate, and precipitation accumulation. Precipitation accumulation per unit time may be measured directly or derived from an integration of sequential rate values. Precipitation intensity – used to better describe the precipitation type – can also be determined from the rate. Precipitation sensors are typically mounted on an ESS tower at a height of 5 to 6 meters and may be combined with a visibility sensor.

6.1.1.5 Visibility Sensor

Visibility sensors measure the visibility in a small volume of air at the instrument site. The visibility is equipped with an alerting feature, which can notify via the software when the visibility falls below a user-defined visual distance threshold (for example, fog, heavy rain, or white out conditions). Visibility sensors are typically mounted on an ESS tower at a height of 5 to 6 meters and may be combined with a precipitation sensor.

6.1.1.6 ESS Cameras

The effective use of multiple camera images provides a visual verification of remote site conditions at each ESS location. These views can also supplement the report of precipitation type and intensity provided by the precipitation sensor. Close-up views of the roadway can provide for a better understanding of the road conditions that are typically reported by the in-pavement and passive sensors. Thus, a camera is a very important part of the ESS instrument suite providing high quality information 24 hours a day. It is recommended that a camera be included in the sensor suite. Cameras are typically mounted near the top of 10-meter ESS towers to optimize full views of the roadway and an effective look angle for close-up views of road conditions. The ESS cameras can be analog or digital. These types of cameras include an embedded video server with an IP address capable of streaming live video and audio, thus eliminating the need of a digital video encoder (DVE). MDOT surveillance system special provisions require all cameras to communication using NTCIP. All communications between the central computer and the camera site must comply with the requirements detailed in the NTCIP 1205 standards.

6.1.1.7 CCTV Cameras

Closed circuit television (CCTV) cameras are extensively used in the transportation and security industry for video surveillance, recording and monitoring. There are various types of CCTVs such as analogue, digital or network (IP cameras). MDOT previously had analog cameras for traffic monitoring and surveillance, however almost all of them are now legacy equipment and have been replaced with the digital technology. The digital cameras provide higher resolution and allow for the live video stream to be saved directly to a PC or for display on a video wall. MDOT surveillance system special provisions require all cameras to communication using NTCIP. All communications between the central computer and the camera site must comply with the requirements detailed in the NTCIP 1205 standards.

6.1.1.8 Infrared (IR) Illumination Device

The IR illumination sensor is used to enhance the visibility at the site during the night hours. The MDOT surveillance system special provision currently calls for a day/night camera; however, due to limited street lighting and ambient light sources, the night mode may not provide a proper image for the end user. Several different models are available from various camera manufacturers and lighting companies. MDOT has decided to include an IR illuminator for nighttime maintenance and security at ESS sites. The benefit of being able to utilize the camera both during the day and night where ambient light is not available far outweighs the minimal cost of its procurement. The current Special Provision for IR Illuminators requires them to be able to provide illumination needed to produce a clear night vision image at a minimum of 500 feet from the mounting location.

6.1.1.9 Pavement Sensor

The current MDOT Special Provision for Pavement Sensor includes requirements for both invasive and non-invasive pavement sensors. There are two types of invasive pavement sensors (sensors that are installed directly in the pavement of the roadway) that are typically used in a ESS deployment – passive pavement sensors and active pavement sensors. Passive pavement sensors report pavement temperature and pavement conditions and report an indication of the salt/water/snow/ice mixture on the pavement. The passive sensor supports freeze-point calculations for one chemical mixture at a time. Active pavement sensors report pavement conditions for dry/wet pavements and provide freeze-point for multiple chemicals and mixtures; however, they cannot provide pavement temperature readings. The other primary pavement sensor type is a non-invasive sensor, which are units that are installed on a pole beyond the shoulder of the roadway or on structures above the roadway that point down towards the pavement and collect both temperature and condition information. A comparison between the sensor parameters and benefits/disadvantages are discussed below in **Table 40**. Based on manufacturer guidelines for installing the non-invasive sensor, the device is required to be mounted on a pole directly adjacent to the pavement. In addition, non-invasive sensors have a distance limitation which require the device to be mounted no more than 50 feet from sensor to pavement. The result is non-invasive sensors required a separate support structure and guardrail protection for that structure. In general, light standard shaft poles are used as the mounting structure.

6.1.1.10 Sub-surface Temperature Probe

The sub-surface temperature probe is a thermistor bead encased in resin that is placed at 40 cm (16 in) below the top of the pavement. This is typically near the depth of the interface between the sub-base and sub-grade. The temperatures at this depth provide a fair representation of the heat source or sink beneath the pavement and are an important factor in estimating the heat flux at the bottom of the pavement. A sub-surface temperature probe column can collect temperatures at various increments from 6 in – 72 in below the pavement.

6.1.1.11 BDWS Warning Alert Activation Algorithm

The BDWS software is a custom logic control software package that will process the data provided by the sensors and determine whether warning alerts or supplemental messages will be triggered. The software will gather sensor information and automatically activate the flashing beacons, LED border, or SFBS to reflect the conditions ahead. The software will be NTCIP compliant and include modular, scalable, and flexible architecture to allow for future modifications to the system or device expansions. The logic diagram shown in **Figure 64** shows the typical sequence of events taking place in the software logic processing. Please note that MDOT currently employs a simplified version of this algorithm for BDWS warning activation, based solely on bridge deck pavement surface temperature and surface friction.

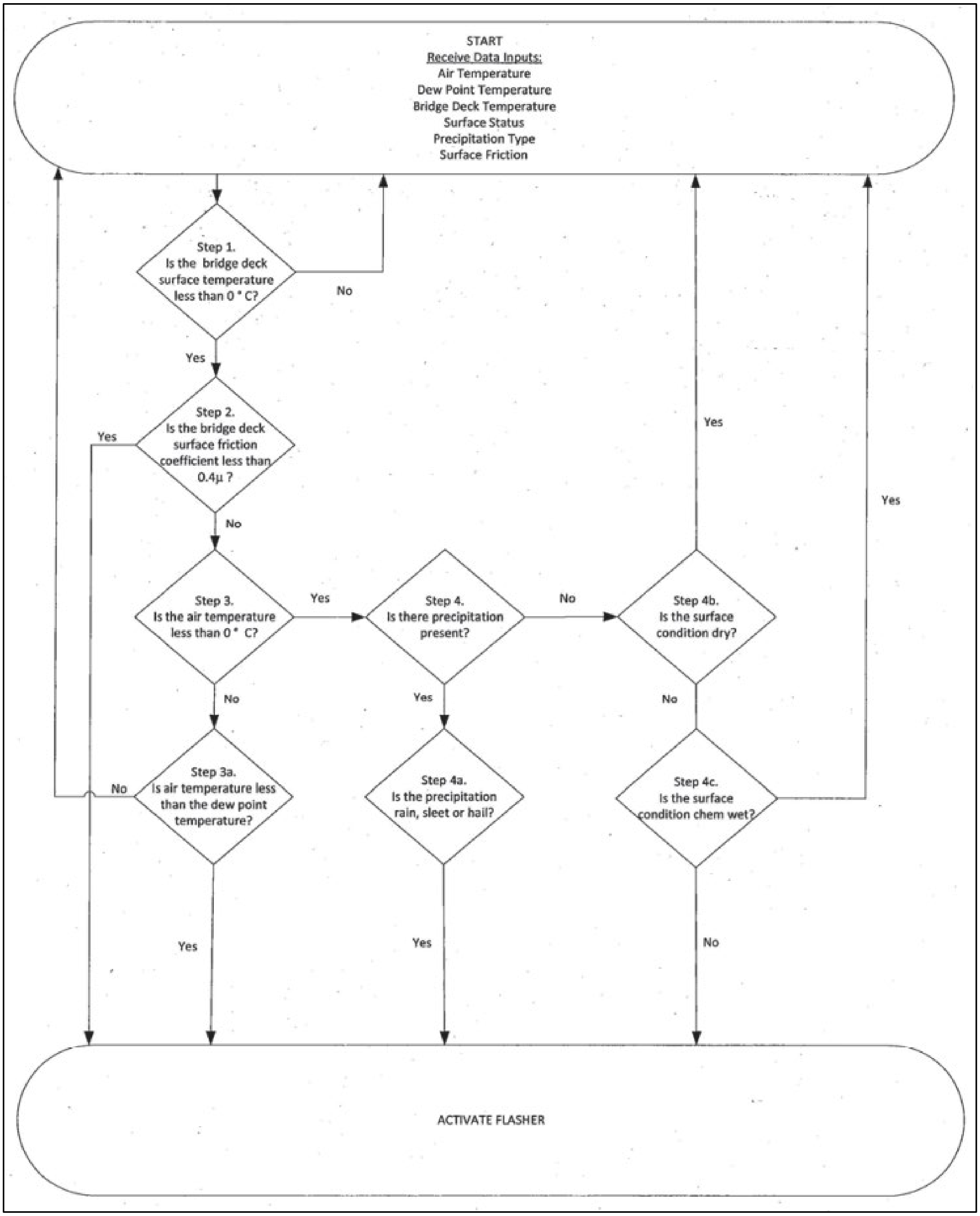


Figure 64. BDWS Framework Flowchart

Table 40. Invasive and Non-Invasive Sensors Comparison

	INVASIVE (PASSIVE) SENSOR	NON-INVASIVE SENSOR
Accuracy	+/- 0.36ºF for all parameters	+/- 1.44ºF (Temperature); 0.1 MM + 20% of measurement (layer thickness)
Surface Status	• Dry • Wet • Damp • Trace Moisture • Chemical Wet • Snow/Ice Watch • Snow/Ice Warming • Black Ice	• Dry • Wet • Ice • Slush • Snow or frost • Pavement Temperature
Chemical Factor	No	No
Ice Percent	Yes, but with limited success during thin film situations	Yes, but with less accuracy in deeper layers of snow, ice, and liquid
Freeze Point	Yes, if the chemical used by maintenance agency matches the preset chemical for that ESS	Yes, but with less accuracy in deeper layers of snow, ice, and liquid
Pros	• Rugged • Minimal maintenance • Accurate pavement temperature • Continuous output of readings • Chemical factor and measured concentration (if available) can be useful as a guide • Able to measure water film depth	• Minimal maintenance • Able to measure water film depth • Continuous output of readings • Accurate road conditions in thin film situations
Cons	• Warm bias in direct sun • Status inaccurate in thin film surface layers • Freeze-point and percent ice are often incorrect • Sensor must be replaced if sensor fails or is damaged by construction	• Status inaccurate in deeper surface layers • Misrepresentation of the chemical concentration when a layer of snow or ice (hard pack) exists on the pavement • Pavement temperature reading is not as accurate as an in-pavement sensor

6.1.2 *Partial BDWS – Non-Invasive Pavement Sensor*

There are some locations where a full ESS sensor suite is not required, but the ability to monitor a bridge deck for icy conditions is still desired. In these types of situations, a partial ESS site is deployed with the sole purpose of supporting a BDWS. The partial ESS sensor suite includes the best combination of equipment to meet the requirements at the most reasonable cost to MDOT. The partial ESS sensor suite typically includes an air temperature sensor, a surface pavement sensor, and a precipitation sensor. In addition, a field controller is required to connect the sensors to each ESS site. The same BDWS software and logic is utilized as a full BDWS (**Figure 65**), with the exception that only Steps 2 and 3 are followed to determine whether warning alerts or supplemental messages will be triggered. The software gathers information from the air temperature and pavement sensors to automatically activate the flashing beacons, LED border, or SFBS to reflect the conditions ahead.

Figure 65. BDWS on EB I-75 BL to NB I-75 in Bloomfield Hills

6.2 Power System Requirements and Strategies

Powering a BDWS can be done in one of two ways: utilizing grid power from a local utility company or by employing solar panels and batteries. Preference is usually given to grid power from a local utility company since BDWS serve in a safety capacity, and it is critical to ensure that when the system is required to be active that power is available.

6.2.1 *Power Requirements*

Power consumption in general is very minimal for most of the equipment that composes a typical ESS or BDWS. **Table 41** depicts typical power consumption (in Watts) per device type required at an ESS/BDWS site.

Table 41. ESS Power Consumption

DEVICE	TYPICAL POWER CONSUMPTION (WATTS)
Surface Sensors	0.005
Sub-Surface Sensors	0.0005
Precipitation Sensor	2
Precipitation Sensor Heater	30
Wind Sensor	0.0025
Wind Sensor Heater	150
Air Temperature & Humidity Sensor	0.15
Visibility Sensor	19
Visibility Sensor Heater	24
PTZ Camera	27
Camera Heater	131
RPU with Back Panel	21.5
IR Illuminator	30
Ethernet Switch	10
Cellular Modem	3.8
Battery Heater	250
Typical Power Consumption Total (no heaters)	114
Peak Power Consumption Total (with heaters)	698

The highest power draw/load comes from the camera (primarily the camera heater). Use of the camera during power outage is not recommended because of its overall purpose at each ESS site location. Additionally, providing backup power to its power draw/load would require a significant number of batteries, cabinet space, and costs; therefore, it is very impractical and not recommended. Without providing backup power to the camera/heater, each site location is anticipated to require just under 115 Watts and can be maintained for several hours (up to 4) with a typical rack/cabinet-mount uninterruptible power supply (UPS) for a very nominal cost.

It is recommended that backup power in the form of a UPS be provided to the cabinet and accompanying field devices (cell modem, RPU, sensors, Ethernet switch, etc.) to always maintain the most critical elements operation and in the most cost-effective manner. This can be achieved with a rack-mounted UPS with battery pack in the ITS cabinet. Typically, UPS's are not very tolerant of low temperatures. The internal and external batteries used for the UPS ae directly affected by low temperatures in the outdoor enclosures. Although the enclosures are sealed, the interior temperature will typically be very close to the outside air temperature. It is recommended using a battery heater inside the enclosure to raise the average temperature of the batteries. The heater to be used should provide a controlled heat while the temperature inside the enclosure reaches below 55ºF. The heater will ensure the batteries have a longer life cycle for the ESS deployment. It is recommended that the heater be placed on its own circuit as the heater is not required to be powered during power outages.

6.2.2 *Grid Power*

Grid power from a local utility company is typically the preferred power source for BDWS as it is the most reliable. On average, a standard 30 AMP service from the utility company is utilized and the meter rack is placed in near proximity to the site-based on coordination with the utility company and where their service feed is located. A new meter meeting the current NEC and MDOT standards should be installed close to the ITS cabinet.

6.2.3 *Alternative Power*

The viability of solar electrical systems is determined by two factors, the amount of available sunlight) and the total daily power consumption (power draw/load) of the device/site location. Providing solar power to any device type and power demand is always achievable with the adequate number of solar panels (at specific power production ratings) and enough battery banks to store the produced power. Theoretically, to be able to operate any solar electrical system year-round the entire system would have to be designed to produce, store, and maintain the full power draw/load within about two to four "sunlight hours. Solar electrical power has been assessed for ESS and BDWS sites and has been determined to be viable, but oftentimes a more expensive alternative to connecting to the power grid due to the need to replace batteries as they age out over time.

6.3 Communications Systems Requirements and Strategies

Communications represents one of the most complex, and often costly, consideration in any ITS deployment. Depending on the specific deployment location, MDOT does have dedicated state-owned communication networks that might be available. For those areas where state-owned networks are not available, cellular, and leased cable are often found to be the most cost-effective solution for the deployment.

6.3.1 *Systems Requirements*

This section presents an analysis of estimated ESS data and image size requirements by device type for the proposed ESS and CCTV camera in order to determine current network requirements and provide for future expectations.

Data rates or the amount of traffic/data on a network segment depends on polling rates, resolutions, frame rates, selected compression parameters, camera resolution and B/W or color, frame-frame changes ("motion"), scene content and noise. **Table 42** outlines the assumptions for estimated bandwidth per projected ITS device type. Streaming video (and control data) is not being recommended at this time but it is provided in the table as a reference to demonstrate rationale. Bandwidth requirements for any network are usually based on video (image) demand versus any data or message sets to/from the actual field devices, as demonstrated in the table. Additionally, data/message sets are typically known as "burst" network traffic and even with a polling rate data is sent/received in short, uneven spurts. Whereas streaming video is data structured and processed in a continuous flow.

Table 42. Estimated ESS and Data/Image Size Calculations per Device

DEVICE	KILOBYTE (KB)	KILOBIT (KB)	MEGABIT (MB)
Set of 8 still 150x150 B/W Images	4	32	0.03
ESS Data Set (Complete Basic ESS Station)	9	72	0.07
Set of 8 still 640x480 Color Images	67.5	540	0.53
Streaming Video & Control Data (MPEG-4)	384	3072	3

6.3.2 *Local Communications*

Locally at the BDWS, most devices are hardwired to the BDWS controller within the ITS cabinet, as shown in **Figure 66**. On occasion, however, wireless communications may be required. This is often seen with pavement condition sensors located near a bridge deck or warning signs that may be located some distance in advance of the bridges. Hardwired communications are usually preferred as they are more reliable.

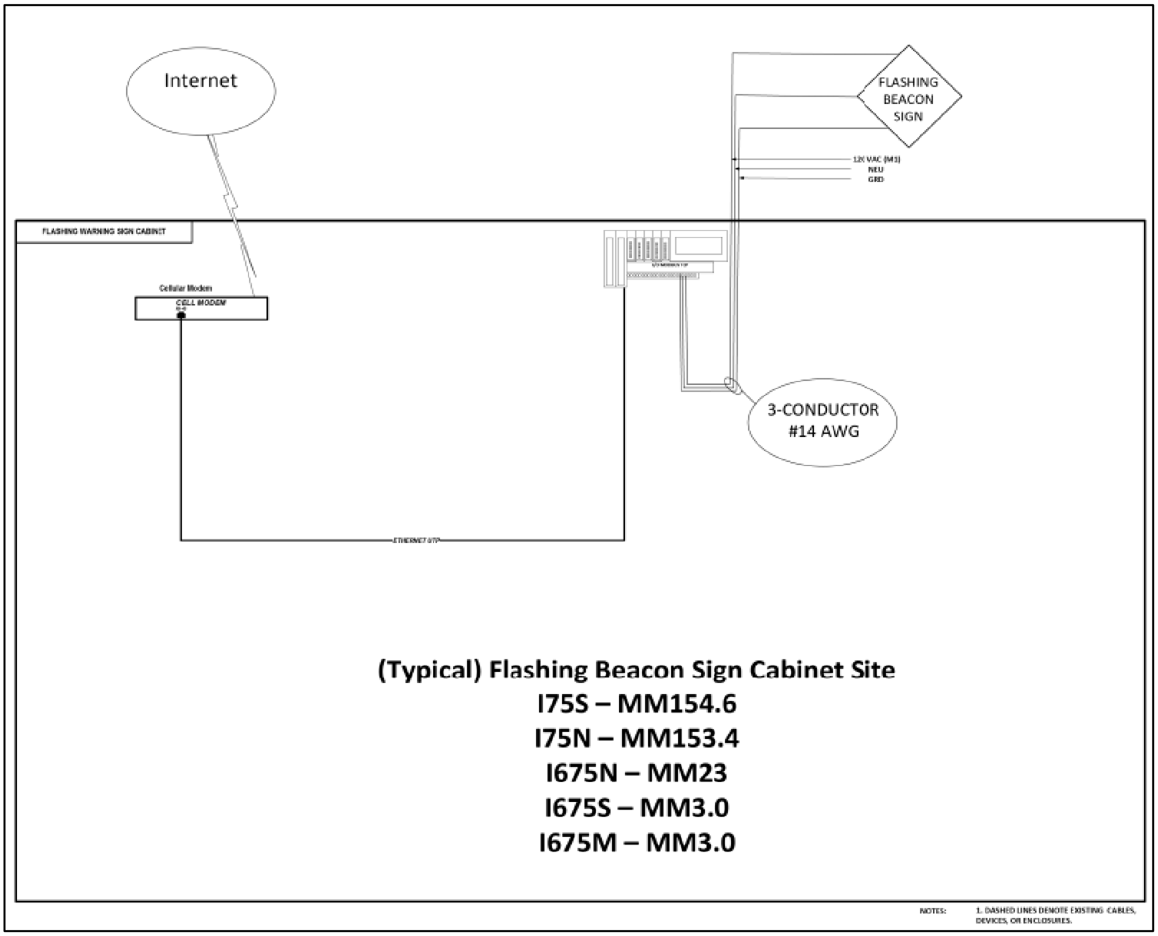


Figure 66. Sample Interconnect Drawing of a Hardwired BDWS Site

6.3.3 *Hybrid Communications*

Alternatively, some sites may use a hybrid approach to communications. **Figure 67** shows wireless radios being used to connect the BDWS signs to the ITS cabinet located near the ESS sensors. To connect the entire site to the MDOT head-end, a cellular modem is employed. This combination of wireless radios and cellular modem is quite common in BDWS throughout the state.

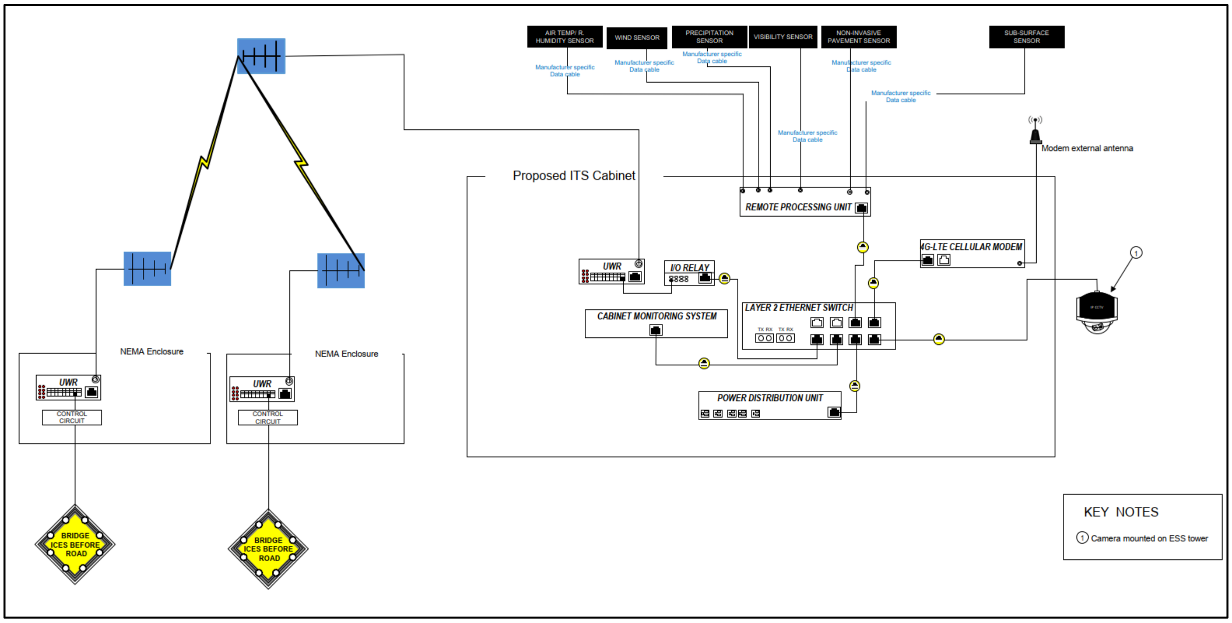


Figure 67. Sample Interconnect Drawing of a BDWS Site with a Hybrid Communication Network

6.3.4 *Remote Control Communications*

A third communications option for BDWS is a remote-control activation. This option is not often used but is available should the site require it. In the event there is a location that MDOT wants to have full activation control over the signing, versus having the signing automatically activate given certain pavement condition criteria, then the system could be remotely activated using an application on the computer.

This type of communications may be desired in locations where there is no camera coverage or staff may not drive by frequently to verify system activations. Knowing exactly when the signs are activated or not activated may eliminate risk of the system defaulting without MDOT's knowledge and the motoring public losing trust in the messaging.

6.4 Warning Sign Strategies

One of the most important pieces of an effective BDWS is the method of messaging to motorists' condition-specific warnings or advisories. Several methods have been used throughout Michigan with various degrees of success. Each of these methods will be discussed below

6.4.1 *Static Signs with Flashing LED Border*

Static signs, with the standard "Bridge Ices Before Road" message, with an imbedded Light Emitting Diode (LED) border that flashes during inclement conditions is one option of messaging that has been used frequently in BDWS. This messaging option has had mixed reviews. Due to the LED border requiring minimal power, the sign can easily be powered using a solar panel and battery. However, many have stated that the LED border can be difficult to see during low visibility or backlit conditions and LEDs became dislodged during early installations of the sign when hit with snow from a passing snowplow. To resolve this issue, MDOT has upgraded to more durable versions of these flashing LED border signs, which should be deployed at future installations in areas where heavy snowfall is experienced.

6.4.2 *Static Signs with Flashing Beacon(s)*

Alternatively, a static sign, with the standard "Bridge Ices Before Road" message, with a single or dual beacon that flashes during inclement conditions is another option of messaging that has been commonly used in BDWS. Similar to the LED border sign, the beacons use LED bulbs which require minimal energy and can be powered using a solar panel and battery. The beacons have been found to attract motorist attention more so than the LED border and tend to cost less to procure and install.

6.4.3 *Static Signs with Speed Feedback Sign Combination*

A third option that was recently tested was a static sign, with the standard "Bridge Ices Before Road" message, with a SFBS panel located below with a pulsing message of "Slow Down". This scenario could also include the LED border or beacons for additional benefit. The SFBS could easily be powered from a solar panel and battery and the dynamic nature of the messaging is very effective at capturing motorist attention and alerting them to reduce their speed.

LED Border

Dual Beacons

Figure 68. Static Sign with LED Border and Dual Beacons

6.4.4 *Dynamic Message Sign*

Another option that has been used when near a BDWS is a DMS – either large or small. The DMS is not typically used solely for messaging for the BDWS, but rather supports the primary messaging by a method discussed above in this section. The benefit of having a DMS available is to provide dynamic messaging that is catered towards the specific condition (i.e., snow, ice, etc.) and provides further detail to motorists of what conditions lie ahead on the roadway. Unfortunately, due to cost, it is not likely to deploy a DMS as a sole messaging method for BDWS.

6.5 ATMS Integration

A BDWS typically consists of an array of ESS devices installed at the roadside which collects current environmental data, a Central Management System (CMS) that receives, stores, processes, and presents this information, and a communications network which links these two components. There is also a Forecasting System component which receives the current information from the CMS, merges this information with previous data and weather forecasting models, and returns a customized weather and road condition forecast to the end users, either directly or via the CMS.

MDOT currently utilizes a statewide contract for hosting their ESS repository and forecasting system. This includes a collection of all ESS data from state-owned weather stations and provides a graphical display of all real-time parameters and camera images. The current process for communication to this statewide ESS repository is via Ethernet communications from the field site to the central server. The system must be able to poll the site directly via an IP address that is available on the internet. Since most sites are integrated using a cellular or cable modem, this is easily achievable. However, there are sites that are now being integrated onto MDOT’s private fiber optic communications network which requires the data to be transmitted to an internal MDOT FTP website where the CMS is then able to download the information. This is due to network security protocols that are put in place to reduce the risk of outside parties trying to access MDOT’s private network.

6.6 Connected Vehicles Technologies

RWIS applications combined with connected vehicles technologies can significantly improve road safety and efficiency by providing real-time weather data to drivers and transportation authorities. By integrating RWIS with connected vehicles, road users and transportation agencies can make informed decisions, mitigate weather-related risks, and enhance overall road safety and efficiency in challenging weather conditions. However, it is crucial to ensure the secure and reliable exchange of data between vehicles and infrastructure to make these applications effective. Below are some key applications of RWIS with connected vehicles:

- **Real-time weather updates:** Connected vehicles equipped with sensors can gather real-time weather data, such as temperature, humidity, precipitation, and road surface conditions. This information can be transmitted to a central database, where it is processed and disseminated to other connected vehicles in the vicinity, as well as to transportation agencies and road users.
- **Hazard warnings:** RWIS with connected vehicles can issue warnings to drivers about hazardous weather conditions, such as ice, snow, heavy rain, or strong winds. These warnings can be displayed on the vehicle's dashboard or navigation system, enabling drivers to adjust their driving behavior and avoid potential dangers. For example, sensors mounted on bridge decks could be integrated with connected vehicle roadside unites to provide a Bridge Deck Warning Message to vehicles equipped with CV on board units.
- **Adaptive speed limits:** ESS data can be used to dynamically adjust speed limits on roadways based on current weather conditions. Connected vehicles can receive and respond to these updated speed limits, promoting safer driving practices and reducing the risk of crashes in challenging weather.
- **Road condition monitoring:** Connected vehicles can continuously monitor road surface conditions and provide feedback to the ESS. This data helps transportation authorities assess the effectiveness of road maintenance measures and plan appropriate responses during adverse weather events.
- **Routing and navigation assistance:** RWIS can offer alternative routes to drivers based on weather conditions, helping them avoid areas with severe weather or road closures. Connected vehicles can receive this information and automatically update navigation systems to guide drivers on safer routes.
- **Vehicle-to-vehicle communication:** Connected vehicles can exchange weather-related information with each other, enabling a cooperative awareness of the surrounding

conditions. For instance, a vehicle experiencing slippery road conditions can send warnings to nearby vehicles to exercise caution.

- **Weather-responsive traffic management:** Transportation agencies can utilize ESS data from connected vehicles to optimize traffic flow and manage congestion during inclement weather. Real-time information on road conditions allows for adaptive traffic signal control and dynamic lane management.
- **Road maintenance planning:** ESS data collected from connected vehicles can help authorities prioritize and plan road maintenance activities. For example, identifying areas with a high number of traction-related events can prompt maintenance crews to focus on these sections promptly.

6.7 Cost Estimates

Construction costs will vary depending on which type of BDWS is implemented. **Table 43** provides a comparison of costs for a full deployment of each type of BDWS deployment discussed in this report. A full detailed breakdown of costs can be found in **Appendix C**.

Table 43. Estimated Construction Costs of Each BDWS Deployment

SYSTEM TYPE	ESTIMATED COST
Flashing LED Signs (Solar Powered)	$181,346
Flashing LED Signs (AC Powered)	$276,916
Static Sign with Flashing Beacons (Solar Powered)	$222,597
Static Sign with Flashing Beacons (AC Powered)	$290,613
DMS (One direction)	$306,085
DMS (Two directions)	$404,170

7. CONCLUSIONS AND RECOMMENDATIONS FOR BDWS IMPLEMENTATION AND OPERATION

Research was undertaken to determine the effectiveness of various BDWS strategies in terms of driver behavior and safety performance and to provide guidance to support future installation and operation of BDWS in Michigan. The impacts of BDWS on driver behavior were assessed through a series of field evaluations (**Chapter 3**) performed at existing BDWS installations on NB and SB US-131 near Cadillac, Michigan and a temporary BDWS installation on NB US-127 near Lansing, Michigan. The field evaluations were designed to measure the effectiveness of BDWS as a speed reduction countermeasure for motorists approaching a bridge during winter weather conditions compared to the standard warning signage.

During the field evaluation, two types of BDWS were tested, which included a W8-13 warning sign with a flashing LED border and a flashing amber beacon on top of a W8-13. Also evaluated in the field study were the incremental benefits provided by including a dynamic speed feedback sign (DSFS) panel in combination with the standard BDWS sign. The DSFS was programmed to display an on-demand "SLOW DOWN" or "ICY ROAD" message to approaching vehicles upon detection by the radar embedded within the sign panel. The DSFS messages were displayed to approaching motorists either in steady or pulsing mode. This study design allowed for comparison of the speed reduction effects across the different BDWS warning alerts (flashing LED border vs. flashing overhead beacon vs. inclusion of a DSFS), DSFS messages ("SLOW DOWN" vs. "ICY ROAD"), and DSFS message display strategies (steady vs. pulsing message).

The field evaluation also included assessment of the effects of various winter weather warning messages on a DMS located near the bridge. Three DMS winter weather warning messaging strategies were tested, which included: "BRIDGE ICES BEFORE ROAD / REDUCE SPEEDS"; "SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS" and "SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS" displayed across two-frames (4-second per frame).

Speeds were measured at multiple locations for vehicles traversing the field evaluation sites during each data collection period. This included an initial speed measurement upstream of the test sign, which was used to control for differences in driver behavior between the data collection periods, along with a speed measurement at the start of the study bridge, which was the primary measure of effectiveness. This study design afforded improvements over previous BDWS research by controlling for variations in the general travel speeds between the data collection periods, thereby controlling for differences in road conditions, weather conditions, and drivers. Not surprisingly, because of the added layers of control, the BDWS speed reductions observed here were lower than those observed in prior research (Veneziano et al., 2014).

In addition to the field study, an analysis of target traffic crashes occurring on MDOT bridges during periods of winter-season precipitation was performed (**Chapter 5**). This analysis considered several bridge attributes, including historical traffic crash and volume data, roadway characteristics, and weather data. This dataset was used to benchmark safety performance on snowy or icy bridge decks in Michigan, as well as to conduct a network screening to identify candidate bridge decks that may benefit from future BDWS treatments. A series of analytical tools were developed for evaluation of candidate freeway (mainlines and ramps) and non-freeway bridge decks for BDWS treatments, and a list of candidate sites for further assessment was prepared. Finally, a preliminary before-and-after crash data assessment was conducted for the 20 bridges where BDWS had been installed for at least one winter-season period.

7.1 Conclusions

Based on the findings of the field evaluation (**Chapter 4**), it was concluded that the flashing LED border BDWS had a statistically significant effect on motorist speeds when encountering a bridge during winter weather conditions. The magnitude of the speed reduction for the flashing LED border ranged between 0.7 mph and 1.1 mph for drivers of cars and large trucks, respectively, compared to when the LED border was not flashing. The flashing overhead beacon BDWS did not have a significant impact on speeds at the bridge compared to the inactive beacon.

The inclusion of a radar-activated DSFS panel positioned beneath the BDWS sign provided even greater speed reductions, likely due to the enhanced conspicuity provided by the on-demand message activation as motorists approached the sign. The addition of the DSFS beneath the flashing LED border sign produced speed reductions of 1.9 mph compared to the inactive sign condition, and this effect was consistent for both cars and large trucks. Slightly lower speed reductions were observed when the DSFS paired with the flashing beacon sign. The DSFS was equally effective regardless of the message provided (e.g., SLOW DOWN vs. ICY ROAD). This is consistent with prior research that found that the mere activation of the DSFS panel provided the majority of the speed reduction compared to the actual message displayed (Gates et al., 2020; Mahmud et al., 2021). The addition of a 1 hertz pulse to the DSFS message reduced speeds by an additional 0.4 mph compared to the steady message, suggesting that the pulse provides an additional conspicuity benefit to motorists.

The evaluation of DMS winter weather warning messages showed the strongest speed reduction effects to occur when the "SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS" message was displayed continuously on a single frame. With this message displayed, the speeds at the bridge were 0.6 mph lower for passenger cars compared to when travel time messages were displayed on the DMS (base condition). Notably, the speed reduction effects associated with this message were strongest among the fastest group of drivers. However, the other winter related messages (BRIDGE ICES BEFORE ROAD / REDUCE SPEEDS and SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS in two frames) produced non-significant effects on speeds compared to the base travel time messages.

The analysis of target winter crashes on MDOT bridges identified a number of bridge or road characteristics that influence winter safety performance at bridges, including traffic volume, structure length, the frequency of winter-season precipitation, horizontal curvature, type of intersecting feature, and geographic region. Additionally, the preliminary before-and-after assessment of the current BDWS implementations in Michigan found that winter-season target crash frequencies were lower at 16 of the 20 sites after installation of the BDWS. It is critical to note that this assessment should be interpreted with caution as many of these systems are relatively new, greatly limiting the availability of post-installation data. Nevertheless, the results suggest that BDWS remain a promising option to potentially address crashes related to icy bridge deck conditions.

7.2 Recommendations for BDWS Implementation and Operation

Based on the findings from this study, a series of recommended guidelines were developed to support future implementation and operation of BDWS in Michigan. This included guidance towards selection of sign types, warning alerts and messages, and future implementation locations. Note that recommendations for sensors and other related equipment are provided in detail in **Chapter 6** and are not reiterated here.

7.2.1 *Sign Types and Flashing Warning Alerts*

First, the continued use of BDWS by MDOT is recommended. For future installations, it is recommended that the BDWS include a MUTCD W8-13 sign with either a flashing LED border or dual top flashing amber beacons. The installation location for the BDWS sign with respect to the start of the bridge should be determined according to MDOT/MUTCD placement guidelines. If a single top flashing beacon is utilized, installation of BDWS signs on both sides of the road is recommended for freeways or other divided highways. If a flashing LED border is used, the LEDs should include an auto-dimming sensor to ensure that optimal brightness is achieved during both day and night. If such a sensor is not available, then the LED brightness should be set to achieve optimal brightness during daylight conditions. Doing so will help ensure that the flashing border is visible during daylight, darkness, and low visibility. Further, in areas that regularly experience heavy snowfall, MDOT should continue to use durable LED border signs with LEDs that are designed to withstand snow from passing plows. Finally, while the W8-13 sign is recommended due to its use in this study and broad implementation by MDOT, there may be other warning sign designs or messages strategies worth considering as a part of future BDWS deployments.

7.2.2 *Messaging Strategies for Dynamic Speed Feedback Signs*

To achieve optimal results, the BDWS should be combined with a radar-activated DSFS panel that is capable of displaying characters that are a minimum of 15-inches in height and mounted beneath the warning sign. The DSFS should be programmed to display a message such as “SLOW DOWN”, “ICY ROAD”, or simply “ICE”, and should be interconnected with the ESS/BDWS such that it is activated only during potentially slippery conditions on the bridge deck. To improve conspicuity, the message should be programmed such that it either pulses (i.e., dim to bright) or alternates between messages (e.g., ICE / SLOW DOWN) at a rate of 1 hertz. Note that the MUTCD does not allow flashing messages or strobes DSFS or DMS displays. When active, the DSFS message should be displayed for all approaching vehicles, regardless of speed. These DSFS messaging recommendations are based on signs manufactured by TraffiCalm that are commonly utilized by MDOT. Please check the manufacturer’s specifications and programming capabilities if other DSFS panels are utilized. Although not evaluated here, MDOT may consider adding the DSFS panel as a standalone BDWS treatment beneath standard W8-13 warning signs that do not include the flashing beacon or border. If such a standalone DSFS installation is implemented, it must be interconnected with the ESS such that it is activated only during potentially slippery conditions on the bridge deck.

7.2.3 *Messaging Strategies for Dynamic Message Signs*

At certain critical locations, MDOT should consider implementation of a DMS panel for BDWS messaging rather than the flashing LED border signs, flashing beacon signs, or DSFS. Although more expensive than traditional BDWS, the DMS panel would provide a larger, more visible display, in addition to greater messaging flexibility. DMS messaging for winter driving conditions should use "SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS" on a single frame, which is the message most commonly utilized by MDOT for warning of winter weather conditions. Splitting this message between two panels is not recommended. Discretion should be given towards the use of BDWS-specific DMS panels for other messaging purposes during the winter season, and it may be advisable to include additional flashing beacons on top of the DMS panel to emphasize winter weather warning alerts. MDOT should also continue to post winter weather warning messages on existing full-sized DMS located around the state, particularly those positioned near bridges. These messages may be posted automatically, if interconnected with an ESS, or manually by personnel at the traffic operations center when conditions warrant.

7.2.4 *Site Selection for Future BDWS Treatments*

The safety performance evaluation presented in **Chapter 5** provides MDOT and local roadway agencies with a series of data-driven tools may be used to identify potential candidates for future BDWS treatments. First, the network screening analysis presented in **Section 5.2** identified a total of 100 candidate bridge locations along the trunkline NHS network that could potentially benefit from the installation of a BDWS. Complete details of these 100 candidate locations can be found in **Appendix B**.

It is critical to note that only a preliminary suitability assessment of these bridge locations (beyond the network screening evaluation) was conducted, which included a review of satellite and street view imagery to identify obvious site limitations. In all cases, a more detailed engineering study should ultimately be performed during site selection, considering those factors that were found in the safety performance analysis to influence bridge deck winter safety performance, including: traffic volume, structure length, frequency of winter-season precipitation, horizontal curvature, type of intersecting feature, and geographic region. Horizontal curve superelevation is an important screening factor, as such bridges often experience more frequent moisture on the bridge deck surface due to melting snow on the high side of the curve falling down the superelevated slope across the travel lanes. Climate characteristics also represent an important screening factor, which were represented in this analysis by the number of days of winter-season precipitation and whether the bridge was located in a northern MDOT region (including Bay, Grand, North, and Superior), where temperatures are generally lower. Freeway bridges that cross over another road (as opposed to river, rail, etc.) also tend to experience more target crashes, even after controlling for other influential factors, such as structure length and traffic volume. Finally, the presence of existing ESS technology near candidate bridge decks may allow for potential cost-savings if appropriate sensor systems are already available or can be retrofitted in a cost-effective manner.

7.3 Implementation Action Plan

The prior recommendations may be split into near-term and long-term action items to help guide MDOT with implementation, as follows:

- Near-Term Action Items (i.e., within the next year):
    - For all existing flashing LED border BDWS sign installations, if an auto-dimming sensor is not available, calibrate the LED brightness to achieve optimal brightness during daylight conditions.
    - Continue to post winter weather warning messages on existing full-sized DMS located around the state, particularly those positioned near bridges. These messages may be posted automatically, if interconnected with an ESS, or manually by personnel at the traffic operations center when conditions warrant. DMS messaging for winter driving conditions should use “SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS” on a single frame.
- Long-Term Action Items (i.e., within four years):
    - Implement future BDWS with MUTCD W8-13 sign that includes either a flashing LED border, dual top flashing amber beacons, or single top flashing beacons on both sides of the road (for freeways or other divided highways). Other types of signs may be implemented at MDOT’s discretion, for example, a standalone DMS

or dynamic speed feedback sign panel for BDWS messaging in lieu of flashing LED borders or flashing overhead beacons.

- If a flashing LED border is to be used for the BDWS, the LEDs should:
    - be durable enough to withstand snow from passing plows and
    - include an auto-dimming sensor to ensure that optimal brightness is achieved during both day and night. If such a sensor is not available, then the LED brightness should be set to achieve optimal brightness during daylight conditions.
- For all existing BDWS sign installations on a freeway or divided highway that are only installed on one side of the roadway and only include a single flashing top beacon, implement either:
    - dual top flashing amber beacons or
    - add a second BDWS on the other side of the roadway, directly across from the existing BDWS sign.
- For all existing or future BDWS, to improve driver response, consider adding a radar-activated dynamic speed feedback sign (DSFS) panel beneath the BDWS sign or as a standalone BDWS treatment beneath standard W8-13 warning signs. This DSFS panel should be capable of displaying characters that are a minimum of 15-inches in height, programmed to display a message such as “SLOW DOWN”, “ICY ROAD”, or “ICE”, and interconnected with the ESS/BDWS such that it is activated only during potentially slippery conditions on the bridge deck. The DSFS message should be programmed such that it either pulses (i.e., dim to bright) or alternates between messages (e.g., ICE / SLOW DOWN).
- Perform a detailed engineering study to determine suitability for implementation of future BDWS at candidate locations, considering factors that include: traffic volume, structure length, frequency of winter-season precipitation, horizontal curvature, type of intersecting feature, geographic region, and presence of existing ESS systems near the bridge. Complete details of 100 candidate bridge locations along the trunkline NHS network are provided within Appendix B of this report.

7.4 Limitations and Direction for Future Research

While the conclusions and recommended guidance presented above expand beyond the existing knowledge base related to the use of BDWS presented in **Chapter 2**, it is important to note that several key limitations were present within this evaluation. These limitations are noted below, in addition to suggestions to address these concerns in future research.

- Future field evaluations of BDWS should:
    - Consider evaluating BDWS installations on other roadway contexts, such as along non-freeways and ramps;
    - Provide an expanded analysis of driver behavior to the BDWS during dark conditions; and
    - Provide an expanded analysis of DMS weather warning messaging, including localized messaging at specific target bridges, in addition to area-wide messaging.
- In terms of safety performance, future evaluations should also consider secondary highways, including trunkline non-NHS and local roadways.
- The traffic safety impacts of BDWS, including potential development of CMFs should be expanded after more extensive implementation of such systems has occurred and enough time has elapsed post-installation.

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APPENDIX A: STATE AGENCY SURVEY QUESTIONNAIRE

RWIS/BDWS State Agency Survey Questionnaire

Michigan State University (MSU), in coordination with the Michigan Department of Transportation (MDOT), is performing research on Bridge Deck Warning Systems (BDWS). BDWS are traffic control devices and associated technology designed to provide warning alerts/messages based on real-time weather and surface conditions obtained from a nearby environmental sensor station (ESS) or other road weather information system (RWIS) technology.

As a part of this research, MSU is conducting a survey of transportation agencies with experience in deployment and operation of BDWS including ESS/RWIS. Please read through the following list of survey objectives, and indicate if you are able to help complete any of these objectives:

- Obtain policies, guidelines, and other strategies utilized by agencies for site selection and installation of BDWS or other similar motorist alert systems that rely on RWIS technology to activate weather warning messages.
- Determine details related to the BDWS or other road weather warning systems, including system specifications and associated costs, types of messages or warnings displayed, type of environmental sensor and communication protocols and peripherals, data and decision algorithm used for posting warning messages, speed data collection components, mounting equipment and procedures, installation location with respect to the bridge, sign durability and maintenance, connected vehicle/V2I communication components, and details regarding communication with operations centers.
- Obtain information pertaining to any published or internal evaluations of the safety, operational, and/or economic benefits associated with the use of BDWS or other road weather warning systems. This includes details related to site selection, field data collection and analysis, findings, and recommendations.
    - ○ I am able to help complete one or more of these survey objectives.
    - ○ I am not able to help complete one or more of these survey objectives.

If yes:

- Could you please provide the name and email address of a person or persons within your agency who is/are qualified to complete the survey?
- Name:
- Employer:
- Job Title:
- Preferred Email Address:
- Best phone number and time of day to reach you:
- Feel free to add anything else about yourself here:
- From the list of systems below, please select those with which you have experience:
    - Bridge Deck Warning System (BDWS)
    - Other Weather Activated Motorist Warning Systems
    - Road Weather Information System (RWIS) / Environmental Sensor Stations (ESS)
    - Dynamic/Variable Message Signs (DMS/VMS)
    - Other relevant system or related technology
- How many RWIS/ESS are currently deployed by your agency?
    - 0
    - 1-10
    - 11-20
    - 21-30
    - 31-40
    - 41-50
    - More than 50
    - Unsure
- Are any of these RWIS/ESS connected to a DMS/VMS, activated warning sign/flashing beacon, or other strategy to provide weather related warning messages to motorists?
    - Yes – DMS/VMS
    - Yes – Activated Warning Sign or Flashing Beacon
    - Yes – Other Messaging Strategy (Please explain the medium for communicating weather warning message in the space provided)

  - No (Please explain how the RWIS are used)
  - Unsure
- Regarding the prior question, are any of these connected systems used to provide weather related warning messages to motorists approaching or crossing bridges/overpasses?
  - Yes – DMS/VMS
  - Yes – Activated Warning Sign or Flashing Beacon
  - Yes – Other Messaging Strategy (Please explain the medium for communicating weather warning message in the space provided)
  - No (Please explain how the RWIS are used)
  - Unsure
- Has your agency deployed any projects where RWIS data is utilized in conjunction with a connected vehicle, V2I type of application?
  - Yes (Please explain, provide a link, or upload a document later in this survey)
  - No
  - Unsure

A primary objective of our research is to identify best practices related to information, policies, specifications, and evaluations of RWIS, BDWS, and other related road weather warning system technologies by agencies. The next series of questions will target these aspects.

The questions are all optional; only complete those questions that you are able to answer.

An upload repository is provided for each question; alternatively, files may be emailed to: gatestim@msu.edu

A. Does your agency maintain policies, guidelines, and other strategies for site selection and installation of BDWS or other similar roadway warning systems that rely on RWIS technology for activating motorist warning messages? Examples include:
   - Feasibility studies
   - Strategic plan for deployment of BDWS including key criteria for site selection
   - Concept of operations document
   - Installation details and guidelines
   - Post-installation testing and verification
   - Post-installation studies and performance evaluation results

Explanations, links, file uploads/emails are all acceptable ways to provide info.

  - Upload useful policies, guidelines, etc.

B. Regarding BDWS or other similar road weather warning systems used by your agency, please provide any relevant information regarding any of the following items:

  - system specifications and associated costs
  - types of environmental sensors and communication protocols and peripherals
  - types of warning alerts or messages displayed
  - data and decision algorithm used for posting warning messages
  - location of the warning sign with respect to the bridge
  - speed data collection components
  - mounting equipment and installation procedures
  - sign durability and maintenance
  - connected vehicle/V2I communication capabilities
  - details regarding communication with operations centers

Explanations, links, and file uploads are all acceptable ways to provide info.

  - Upload useful policies, guidelines, etc.

C. Does your agency possess any published or internal evaluations of the safety, operational, and/or economic benefits associated with the use of BDWS or other similar road weather warning systems that you would be willing to share? Any details related to site selection, field data collection and analysis, findings, or recommendations would be helpful.

Explanations, links, and file uploads are all acceptable ways to provide info.

  - Upload published or internal evaluations here.

D. Additional File Uploads

  - Are you interested in being contacted for a further interview lasting no more than 30 minutes? Other personnel from your agency would be welcome to join.
  - Yes, via online meeting (Zoom, MS Teams, Skype, etc.)
  - Yes, over the phone.
  - Yes, through email.
  - No, I do not wish to be further interviewed.

APPENDIX B: CANDIDATE BRIDGE INFORMATION

Bridge Information							Mean AADT	Annual Target Crash Metric				Distance to ESS (*Miles*)
Site Name	**County**	**Type**	**Intersects**	**Latitude**	**Longitude**	**Structure Length (*Feet*)**		**Obs.**	**Exp.**	**Pred.**	**Excess**	
US-2 @ Sturgeon River	Dickinson	Non-Freeway	River	45.776749	-87.826977	240.2	5,243	0.90	0.71	0.20	0.51	na
M-37 @ Rail in Chums Corner	Grand Traverse	Non-Freeway	Rail	44.664725	-85.656186	223.8	15,326	0.90	0.84	0.46	0.38	0.5
US-131 @ Manistee River	Wexford	Non-Freeway	River	44.48445	-85.406358	335.0	10,748	0.90	0.82	0.39	0.43	2.0
M-153 EB @ Hines	Wayne	Non-Freeway	Road	42.326931	-83.245103	169.9	29,033	1.10	0.98	0.50	4.76	na
M-153 WB @ Hines	Wayne	Non-Freeway	Road	42.327611	-83.245142	167.7	29,033	0.80	0.74	0.50	0.24	na
US-31 NB @ Grand River	Ottawa	Non-Freeway	River	43.070272	-86.219344	199.8	30,267	0.80	0.76	0.57	0.19	na
US-31 SB @ Grand River	Ottawa	Non-Freeway	River	43.070275	-86.219511	199.8	30,267	1.00	0.92	0.57	0.36	na
M-53 @ Branch Belle River	Lapeer	Non-Freeway	River	42.963428	-83.057258	21.7	16,850	1.10	0.91	0.26	0.66	na
M-53 @ Weston Drain	Lapeer	Non-Freeway	Drain	42.988065	-83.067947	49.9	16,850	0.80	0.71	0.32	0.39	na
M-139 @ St. Joseph River	Berrien	Non-Freeway	River	42.058146	-86.438548	405.8	10,185	0.70	0.68	0.56	0.12	na
M-45 WB @ Grand River	Ottawa	Non-Freeway	River	42.972214	-85.87599	1,595.1	13,414	3.30	na	na	na	na
M-45 EB @ Grand River	Ottawa	Non-Freeway	River	42.97200	-85.87599	1,595.1	13,414	1.80	na	na	na	na
US-127 NB @ Red Cedar	Ingham	Mainline at Interchange	Other	42.7263	-84.509658	263.8	23,673	1.75	1.60	0.46	1.14	0.5
US-127 SB @ Red Cedar	Ingham	Mainline at Interchange	Other	42.726033	-84.510056	272.3	23,637	1.24	1.15	0.46	0.69	0.5
M-8 WB @ M-10	Wayne	Flyover Ramp	Road	42.39824	-83.110357	212.9	46,597	1.30	1.21	0.50	0.71	na
M-39 NB @ M-10	Oakland	Mainline at Interchange	Road	42.457668	-83.219412	273.0	47,578	0.96	0.92	0.56	0.36	na
I-196 EB Ramp @ Buck Creek	Kent	Entrance Ramp	Creek	42.907842	-85.775457	134.8	9,496	1.17	1.06	0.37	0.68	na
I-496 EB Ramp to N US-127	Ingham	Flyover Ramp	Road	42.729058	-84.509825	202.8	13,074	1.10	1.00	0.36	0.63	0.5
M-45 Ramp to I-196 EB	Kent	Flyover Ramp	Road	42.965328	-85.707264	141.7	12,244	0.89	0.82	0.38	0.44	na
I-75 NB Ramp to I-69 EB	Genesee	Flyover Ramp	Road	42.98300	-83.729389	266.1	12,023	1.07	0.96	0.35	0.61	na
I-75 SB Ramp to I-69 EB	Genesee	Flyover Ramp	Road	42.98389	-83.7357	289.0	8,054	0.98	0.82	0.30	0.52	na
I-75 NB Ramp to I-69 WB	Genesee	Flyover Ramp	Road	42.98374	-83.736228	338.9	8,720	0.76	0.69	0.31	0.38	na
I-75 SB Ramp to I-69	Genesee	Flyover Ramp	Creek	42.98733	-83.737686	128.0	8,054	0.53	0.49	0.30	0.19	na
I-69 WB Ramp to I-496 EB	Eaton	Flyover Ramp	Road	42.716397	-84.668947	224.7	11,443	0.84	0.77	0.34	0.42	na
I-469 WB Ramp to I-69 WB	Eaton	Flyover Ramp	Road	42.719839	-84.668792	233.6	6,350	1.14	0.98	0.27	0.71	na
I-94 EB Ramp to I-696 WB	Macomb	Flyover Ramp	Road	42.492981	-82.916852	295.9	24,373	0.73	0.68	0.38	0.30	0.5
I-696 EB Ramp to I-94 EB	Macomb	Flyover Ramp	Road	42.495556	-82.9177	1,122.7	23,699	0.51	0.49	0.38	0.12	0.5
M-6 EB Ramp to I-96 EB	Kent	Flyover Ramp	River	42.887833	-85.485978	1,085.6	11,207	0.75	0.70	0.38	0.32	na
I-96 WB Ramp to M-6 WB	Kent	Flyover Ramp	River	42.888761	-85.485942	1,204.4	11,342	0.62	0.59	0.38	0.21	na
I-75 NB Ramp to I-675 NB	Saginaw	Flyover Ramp	Road	43.433628	-83.890658	270.0	9,865	1.35	1.16	0.29	0.87	na

Bridge Information							Mean AADT	Annual Target Crash Metric				Distance to ESS (*Miles*)
Site Name	County	Type	Intersects	Latitude	Longitude	Structure Length (*Feet*)		Obs.	Exp.	Pred.	Excess	
I-696 WB Ramp to I-275 SB	Oakland	Flyover Ramp	Road	42.485133	-83.431856	628.9	35,027	0.68	0.66	0.49	0.17	na
I-94 WB Ramp to US-127 SB	Jackson	Flyover Ramp	Road	42.276883	-84.358878	165.4	3,737	1.20	0.96	0.19	0.77	na
US-127 NB to I-94 WB	Jackson	Flyover Ramp	Road	42.277033	-84.358642	165.4	10,880	0.60	0.55	0.30	0.25	na
I-96 EB Ramp to US-131 SB	Kent	Flyover Ramp	Other	43.012286	-85.677128	420.9	21,955	1.10	na	na	na	na
I-475 SB Ramp to I-69 EB	Genesee	Flyover Ramp	Road	43.010267	-83.679236	581.0	878	0.48	0.45	0.30	0.15	0.5
I-475 NB @ Grand Traverse/Rail	Genesee	Freeway	Other	42.992672	-83.680897	357.0	22,565	10.40	10.12	2.67	7.45	1.0
I-475 SB @ Grand Traverse/Rail	Genesee	Freeway	Other	42.992672	-83.680897	357.0	22,565	5.10	4.90	1.63	3.27	1.0
I-496 EB/US-127 SB @ Trowbridge/ Rail	Ingham	Freeway	Other	42.720203	-84.504767	305.1	31,261	7.00	6.83	2.50	4.33	0.5
I-94 EB @ Harper	Macomb	Freeway	Road	42.553179	-82.87154	173.6	47,496	4.50	4.43	2.66	1.77	0.5
I-94 EB @ 14 Mile	Macomb	Freeway	Road	42.540348	-82.885941	191.9	48,758	3.20	3.19	2.79	0.40	1.0
I-94 EB @ Clinton River	Macomb	Freeway	River	42.590787	-82.857125	357.9	52,863	3.20	3.13	1.86	1.27	2.5
I-94 WB @ Clinton River	Macomb	Freeway	River	42.590762	-82.857476	357.9	52,863	3.40	3.32	1.86	1.46	2.5
I-94 EB @ Jackson	Washtenaw	Freeway	Road	42.281561	-83.784111	190.9	26,738	3.60	3.53	2.05	1.48	na
I-94 WB @ Jackson	Washtenaw	Freeway	Road	42.281561	-83.784111	190.9	26,738	5.50	5.34	2.05	3.29	na
US-131 NB @ River Dr./Rail	Kent	Freeway	Other	43.041028	-85.661529	474.1	29,919	2.90	2.87	2.23	0.64	na
US-131 SB @ River Dr./Rail	Kent	Freeway	Other	43.040607	-85.661836	474.1	29,919	4.00	3.92	2.23	1.70	na
US-23 NB @ Silver Lake Rd./Rail	Genesee	Freeway	Other	42.804358	-83.727442	333.0	25,052	2.30	2.25	1.49	0.76	0.5
US-23 SB @ Silver Lake Rd./Rail	Genesee	Freeway	Other	42.80445	-83.727742	333.0	25,052	7.10	6.81	1.72	5.08	0.5
I-196 EB @ Market Ave/Grand River	Kent	Freeway	Other	42.948078	-85.710417	999.9	23,095	3.30	3.26	2.35	0.91	na
I-196 WB @ Market Ave/Grand River	Kent	Freeway	Other	42.947914	-85.710858	976.0	23,095	3.60	3.55	2.33	1.22	na
I-75 NB @ Lapeer Road	Oakland	Freeway	Road	42.683569	-83.243297	193.9	54,825	2.30	2.28	1.84	0.43	na
I-75 SB @ Lapeer Road	Oakland	Freeway	Road	42.683347	-83.243556	193.9	54,825	3.90	3.79	1.84	1.95	na
I-96 EB @ Milford	Oakland	Freeway	Road	42.518794	-83.616148	171.3	53,129	3.70	3.59	1.72	1.87	na
I-96 WB @ Milford	Oakland	Freeway	Road	42.519003	-83.616128	171.3	53,129	3.00	2.93	1.72	1.21	na
I-275 SB @ Eight Mile	Oakland	Freeway	Road	42.438986	-83.432339	166.0	87,317	3.40	3.35	2.23	1.12	1.0
US-31 NB @ Laketon	Muskegon	Freeway	Road	43.219708	-86.2048	226.0	28,718	3.60	3.47	1.53	1.94	2.0
US-31 SB @ Laketon	Muskegon	Freeway	Road	43.2195	-86.205119	226.0	28,718	4.00	3.85	1.53	2.32	2.0
I-96 EB @ Grand River	Livingston	Freeway	Road	42.547775	-83.789536	173.9	42,084	4.10	3.93	1.47	2.47	2.5
I-69 WB @ M-54	Genesee	Freeway	Road	43.01216	-83.654313	135.2	38,303	3.50	3.38	1.57	1.82	1.5
I-196 EB @ M-11	Kent	Freeway	Road	42.914292	-85.765044	156.5	32,025	3.20	3.12	1.77	1.36	na
I-196 WB @ Lane	Kent	Freeway	Road	42.972717	-85.692592	126.3	33,346	3.50	3.37	1.44	1.93	na
I-75 NB @ Dixie	Saginaw	Freeway	Road	43.350556	-83.864304	203.1	29,130	3.60	3.45	1.39	2.06	na

Bridge Information							Mean AADT	Annual Target Crash Metric				Distance to ESS (*Miles*)
Site Name	County	Type	Intersects	Latitude	Longitude	Structure Length (*Feet*)		Obs.	Exp.	Pred.	Excess	
I-75 SB @ Dixie	Saginaw	Freeway	Road	43.35075	-83.864689	203.1	29,130	2.30	2.24	1.39	0.85	na
I-75 NB @ Bristol	Genesee	Freeway	Road	42.973497	-83.725639	153.9	47,165	2.80	2.75	1.88	0.87	na
I-75 SB @ Bristol	Genesee	Freeway	Road	42.973497	-83.725639	153.9	47,165	3.10	3.06	2.18	0.88	na
I-94 WB @ Telegraph	Wayne	Freeway	Road	42.265006	-83.270238	246.1	70,287	2.80	2.77	2.18	0.60	na
I-94 EB @ Telegraph	Wayne	Freeway	Road	42.264659	-83.270254	246.1	70,287	2.50	2.49	2.18	0.31	na
I-94 EB @ Westnedge	Kalamazoo	Freeway	Road	42.236754	-85.589533	257.5	39,862	3.00	2.90	1.42	1.47	na
I-94 WB @ Westnedge	Kalamazoo	Freeway	Road	42.236944	-85.589527	257.5	39,862	3.10	2.99	1.42	1.57	na
US-31 NB @ M-120	Muskegon	Freeway	Road	43.292789	-86.207933	195.9	18,489	4.50	4.21	1.08	3.13	3.0
US-31 SB @ M-120	Muskegon	Freeway	Road	43.292503	-86.208617	195.9	17,175	3.90	3.66	1.08	2.58	3.0
I-94 EB @ Pipestone	Berrien	Freeway	Road	42.078836	-86.417064	223.8	27,364	4.30	4.03	1.09	2.94	5.0
I-94 WB @ Pipesone	Berrien	Freeway	Road	42.079217	-86.41707	223.8	27,364	2.90	2.75	1.09	1.66	5.0
I-96 WB @ 28th Street	Kent	Freeway	Road	42.912834	-85.535899	264.8	23,162	2.10	2.05	1.37	0.68	na
I-96 EB @ 28th Street	Kent	Freeway	Road	42.912816	-85.536351	264.8	23,162	2.70	2.61	1.37	1.24	na
I-75 NB @ Dixie Highway	Oakland	Freeway	Road	42.869578	-83.592519	299.9	25,959	3.50	3.30	1.12	2.19	na
I-75 SB @ M-32	Otsego	Freeway	Road	45.027392	-84.688247	133.9	6,371	1.10	0.98	0.44	0.54	1.5
US-131 NB @ Old US-131	Wexford	Freeway	Road	44.328367	-85.403553	190.9	4,182	1.00	0.87	0.38	0.49	6.0
I-96 WB @ Kent	Ionia	Freeway	Road	42.860242	-84.912039	147.0	18,375	3.10	2.94	1.13	1.81	na
I-94 EB @ Red Arrow	Berrien	Freeway	Road	42.030746	-86.514258	190.9	23,645	5.40	4.97	0.94	4.03	na
I-94 WB @ Red Arrow	Berrien	Freeway	Road	42.031066	-86.514242	191.9	23,645	2.40	2.26	0.94	1.32	na
I-675 NB @ Shattuck	Saginaw	Freeway	Road	43.450944	-83.955742	151.9	13,446	2.10	1.97	0.86	1.11	1.0
I-675 SB @ Shattuck	Saginaw	Freeway	Road	43.450944	-83.956061	151.9	13,446	3.90	3.58	0.86	2.73	1.0
I-675 NB @ Michigan	Saginaw	Freeway	Road	43.440642	-83.949472	196.9	13,446	1.90	1.88	1.51	0.37	0.5
I-675 SB @ Michigan	Saginaw	Freeway	Road	43.440367	-83.949536	196.9	13,446	1.90	1.88	1.51	0.37	0.5
I-96 WB @ Airline	Muskegon	Freeway	Road	43.138528	-86.155053	143.0	13,018	3.60	3.28	0.77	2.51	3.5
US-127 NB @ Kalamazoo	Ingham	Freeway	Road	42.729969	-84.510222	139.8	28,041	3.30	3.09	0.98	2.10	1.0
I-75 SB @ Mackinac Trail	Mackinac	Freeway	Road	46.0177	-84.717542	117.5	2,563	0.70	0.56	0.23	0.33	na
I-75 NB @ M-55	Ogemaw	Freeway	Road	44.276381	-84.281614	201.4	6,177	0.90	0.82	0.47	0.36	2.5
I-94 WB @ US-12	Berrien	Freeway	Road	41.799125	-86.708225	239.8	21,735	2.90	2.72	0.96	1.76	3.0
I-94 EB @ US-12	Berrien	Freeway	Road	41.799117	-86.706122	239.8	21,735	3.30	na	na	na	3.0
US-31 NB @ I-96	Muskegon	Freeway	Road	43.171692	-86.206722	220.0	23,856	2.50	na	na	na	0.5
US-31 SB @ I-96	Muskegon	Freeway	Road	43.171692	-86.206722	220.0	23,856	3.60	na	na	na	0.5
I-196 WB @ Butterworth	Kent	Freeway	Road	42.95695	-85.705936	211.9	21,353	6.30	na	na	na	na
I-94 WB @ Niles	Berrien	Freeway	Road	42.058533	-86.457939	320.9	25,975	3.80	na	na	na	na
I-94 EB @ Niles	Berrien	Freeway	Road	42.058533	-86.457939	320.9	25,975	3.40	na	na	na	na
I-75 NB @ Joslyn	Oakland	Freeway	Road	42.701697	-83.284144	213.9	40,925	2.90	na	na	na	na
I-75 SB @ Joslyn	Oakland	Freeway	Road	42.701331	-83.283983	213.9	40,925	4.10	na	na	na	na
I-75 NB @ Huron River	Wayne	Freeway	Road	42.070194	-83.252286	154.2	29,318	3.40	na	na	na	0.5
I-75 SB @ Huron River	Wayne	Freeway	Road	42.070194	-83.252286	154.2	29,318	3.10	na	na	na	0.5

APPENDIX C: BDWS COST ESTIMATE

Section	ITEM DESCRIPTION	UNIT	UNIT COST ($)	Flashing LED (Solar)	Flashing LED (AC)	Static Sign w/ Beacon & Feedback Sign (Solar)	Static Sign w/ Beacon & Feedback Sign (AC)	DMS
				$181346	$276916	$222597	$290613	$306085
Conduit	HH, Round, Comm	Ea	2,500.00	1	1	1	1	2
	HH, Round, Elec	Ea	2,500.00	2	4	2	2	4
	Conduit, DB, 1, 3 inch	Ft	38.00	20	20	20	20	40
	Conduit, DB, 2, 3 inch	Ft	42.00	60	60	60	60	120
	Conduit, DB, 4, 3 inch	Ft	64.00	10	10	10	10	20
	Conduit, Directional Bore, 2 inch	Ft	28.00	100	100	100	100	200
	Conduit, Directional Bore, 1, 3 inch	Ft	32.00	120	1600	120	1600	240
Power & Cabling Cabinet & ITS Equipment	DB Cable, in Conduit, 600V, 1/C#6	Ft	3.00	60	6400	60	6400	360
	Cable, Equipment Grounding Wire, 1/C#6	Ft	3.00	20	1600	20	1600	120
	ITS Grounding, Bonding, and Surge Protection	Ea	1,800.00	1	1	1	1	1
	Power Serv, Underground, 30AMP, 120/240V	Ea	6,500.00	1	1	1	1	2
	ITS Cabinet, Ground Mounted	Ea	15,000.00	1	1	1	1	2
	Uninterruptible Power Supply, ITS Cabinet	Ea	4,000.00	1	1	1	1	2
	Power Distribution Unit	Ea	3,000.00	1	1	1	1	2
	Managed Field Ethernet Switch, Layer 2	Ea	5,500.00	1	1	1	1	2
	Remote Processing Unit	Ea	9,500.00	1	1	1	1	1
	Pavement Sensor, Non-Invasive Condition	Ea	14,000.00	1	1	1	1	1
	I/O Contact Closure	Ea	1,000.00	1	1	2	2	1
	Bridge Deck Warning System	Ea	10,000.00	1	1	1	1	1
	Flashing LED Border Sign, AC	Ea	7,000.00		4			
	Flashing LED Border Sign, Solar	Ea	7,500.00	4				
	Blank Out Sign (Case Sign)	Ea	9,500.00			2	2	
	Sign, Type IIIB	Sft	24.00			64	64	
	Flash Beacon, Solar Power	Ea	5,500.00			4	4	
Warning Displays	Post, Wood, 4 inch by 6 inch	Ft	25.00	96	96	96	96	
	Dynamic Message Sign, Amber, 46mm, 27 by 95	Ea	48,000.00					1

	Small Dynamic Message Sign, Support Structure	Ea	18,000.00					1
	Column, Breakaway, W8x18	Ea	1,200.00					3
	Fdn, Breakaway, W8x18	Ea	950.00					3
	Lightning Protection, Structure, Small Dynamic Message Sign	Ea	3,000.00					1
Display Comms Structures	Wireless Intercn, Sign Mtd Flasher, Solar Power, Remote	Ea	6,000.00	2		2		
	Wireless Intercn, Sign Mtd Flasher, Master	Ea	6,800.00	1		1		
	Strain Pole Fdn, 6 Bolt	Ft	800.00	1	1	1	1	1
	Strain Pole, Steel, 6 Bolt, 40 foot	Ea	15,000.00	1	1	1	1	1
	Light Std, Fdn	Ea	1,800.00					
	Light Std Shaft, 30 foot or less	Ea	3,200.00					
	Lightning Protection, Pole	Ea	1,800.00	1	1	1	1	1
Landscaping	Slope Restoraton, Type A	Syd	4.50	65	65	65	65	120
Integration	System Integration and Testing	LS	N/A					
	System Testing	LS	N/A					
	Integration, Advance Traf Management System Software	LS	N/A					
Contingency	Contingency (MOT, Mobilization)	%	15%	23653.88	31951.88	25684.28	33532.28	35317.5