# Efficacy of Speed Warning Technologies

## FINAL REPORT

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**16. Abstract**

Research was undertaken to determine the effectiveness of various speed warning technologies across a variety of critical speed-change contexts in order to provide guidance to support future installation and operation of such treatments in Michigan. The speed warning technologies evaluated in this research included dynamic speed feedback signs (DSFS), a flashing LED chevron system, a weather-activated slippery curve warning system, and targeted winter weather messages on changeable message signs (CMS). The speed reduction effectiveness of the selected speed warning technologies was assessed through a series of field evaluations performed at 21 highway locations representing various speed-change contexts, which included: freeway exit ramps (DSFS), mainline freeway curves (DSFS), rural highway curves (DSFS, flashing LED chevrons, weather-activated slippery curve warning system), transition from rural highway into a community (DSFS), transition from freeway to non-freeway (DSFS), and at bridges susceptible to winter icing (CMS messaging). The messaging strategies, warning alerts, and installation positions for each evaluation were selected based on the highway context and warning technology being evaluated. Speeds of free-flowing vehicles were tracked using LIDAR under existing baseline conditions and after the installation of the specified sign treatments. The primary measure of effectiveness was the speed reduction for each test sign condition compared to the existing signing. Overall, the study concluded that enhanced speed warning signing technologies can contribute to meaningful speed reductions in critical areas. The magnitude of the speed reductions varied based on the context, although speed reductions of up to 3.5 mph were observed at both horizontal curves and speed limit transition areas after the installation of the selected enhanced warning sign treatment. Similarly, drivers were 50 to 75 percent less likely to exceed the curve advisory speed or posted speed limit (or some increment above those speeds) after treatment installation. Typically, the greatest speed reductions were observed for drivers approaching at higher-than-average speeds, which is typically the group most targeted by the installation of such treatments. Based on the study findings, the continued use of the tested speed warning technologies is recommended for the highway contexts evaluated in this study. A series of specific recommendations related to sign characteristics, operational performance, and installation details are provided within the project report for each road context. The recommendations comply with the requirements of the 11th Edition of the Manual on Uniform Traffic Control Devices (MUTCD), which provides considerably greater restrictions towards the utilization of DSFS compared to prior editions. The recommendations may be utilized by MDOT and other transportation agencies towards the development of implementable guidelines, standards, and/or provisions for the use of speed warning technologies at freeway and non-freeway horizontal curve applications, speed limit transition areas, and CMS messaging during winter weather conditions.

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dynamic speed feedback sign, DSFS, LED chevrons, enhanced warning sign, horizontal curves, speed transition, roundabout, lane departures, driver behavior, speed reduction, countermeasures

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# EXECUTIVE SUMMARY

Speed-related crashes remain a critical concern in Michigan and across the United States. A substantial proportion of these crashes occur in contexts where drivers are required to quickly adjust their speed to navigate changing roadway geometry or land-use. These critical speed-change areas include freeway exit ramps, horizontal curves, highway transitions into rural communities, and freeway to non-freeway transitions. Excessive speed contributes to crash occurrence and crash severity in such areas, particularly with respect to crashes involving lane departure or pedestrians and bicyclists, and is further exacerbated by adverse weather conditions.

## Research Problem

While traditional warning treatments, including signs, delineation, and beacons have been used for decades, the Michigan Department of Transportation (MDOT) recently expanded the implementation of advanced signing technologies to better warn motorists approaching speed-change areas. Such strategies have the potential to reduce excessive speeds and resulting crashes in speed-change areas. However, for many types of critical speed-change scenarios, little research has been performed on the speed reduction effects of such strategies, and those studies that have been performed have typically only considered daylight and favorable weather conditions.

## Study Design

In response, research was undertaken to determine the effectiveness of various speed warning technologies across a variety of critical speed-change contexts in order to provide guidance to support future installation and operation of such treatments in Michigan. The speed warning technologies evaluated in this research included dynamic speed feedback signs, a flashing LED chevron system for horizontal curves, a weather-activated slippery curve warning system, and targeted winter weather messages on changeable message signs (CMS). The speed reduction effects of the selected speed warning technologies were assessed through field evaluations performed at 21 highway locations representing various speed-change contexts, which included:

- Horizontal curves
    - Freeway ramp (DSFS)
    - Freeway mainline (DSFS)
    - Rural highway (flashing LED chevrons with and without DSFS)
- Speed limit transitions
    - Freeway to non-freeway (DSFS)

  - Roundabout approaching a community (DSFS)
  - Rural highway entering a community (DSFS)
- Winter weather warning
  - Rural highway curve (slippery curve warning system)
  - Freeway bridge overpass (CMS weather warning messages)

The messaging strategies, warning alerts, and installation position for each advanced signing treatment were selected based on the highway context. The primary measure of effectiveness was the speed reduction for each test sign condition compared to the existing signing.

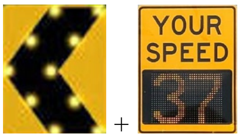
### Summary of Findings

Generally speaking, the dynamic speed feedback signs and flashing LED warning signs (including chevrons) were found to have a statistically significant speed reduction effect on drivers traversing the critical speed change areas investigated in this study. The magnitude of the speed reductions varied based on the site context, although speed reductions of up to 3.5 mph were observed at both horizontal curves and speed limit transition areas after installation of the selected sign treatment. Similarly, drivers were 50 to 75% less likely to exceed the curve advisory speed or posted speed limit (or some increment above those speeds) after treatment installation. Typically, the treatments were found to have the strongest speed reduction effects on drivers approaching the speed-change area at speeds that were higher-than-average, which is typically the driver behavior group most targeted by the installation of such treatments. A summary of the findings from each of the signing treatments and roadway contexts included in the field evaluations is provided in the table on the following page.

### Recommendations for Implementation and Operation of Speed Warning Technologies

Based on the research findings, the continued use of the tested speed warning technologies is recommended for the highway contexts evaluated in this study. A series of specific recommendations related to sign characteristics, operational performance, and installation details for each highway context are provided in Chapter 8 of the final project report. The recommendations comply with the requirements of the 11th Edition of the Manual on Uniform Traffic Control Devices (MUTCD), which provides considerably greater restrictions towards the utilization of DSFS compared to prior editions. The recommendations may be utilized by MDOT and other agencies towards the development of implementable guidelines, standards, and/or provisions for the use of speed warning technologies at freeway and non-freeway horizontal curve applications, speed limit transition areas, and CMS messaging during winter weather conditions.

**Primary Findings from Field Evaluations of Enhanced Warning Sign Technologies**

| Sign Treatment | Roadway Context | No. of Sites | Primary Findings Related to the Sign Treatment |
|---|---|---|---|
|  <br>Dynamic Speed Feedback Sign | Horizontal Curve on Freeway Exit Ramp | 5 | ● Speed reductions at the ramp curve were observed at 3 of 5 sites after DSFS installed. The magnitude of the speed reductions were:<br>○ 1.5 to 2.0 mph during daytime<br>○ 0.6 to 1.8 mph during nighttime<br>● DSFS was considerably more effective at interchanges where the freeway passed over the crossroad due to greater sight distance. |
| | Horizontal Curve on Freeway Mainline | 2 | ● After installation of the DSFS:<br>○ Speed reductions at the curve were up to 1.2 mph greater.<br>○ Drivers were 65% to 71% less likely to exceed curve advisory speed by > 10 mph. |
| | Freeway to Non-Freeway Speed Limit Transition | 1 | ● Speed reductions were up to 3.4 mph greater after installation of the DSFS.<br>● Greater speed reductions were observed:<br>○ with the DSFS 350 ft upstream of the speed limit sign vs. next to the sign and<br>○ for drivers exceeding 75 mph |
| | Roundabout Approaching Community | 4 | ● Greater speed reductions were observed at all four roundabout approaches after installation of the DSFS, ranging from 1.8 to 3.4 mph. |
| | Rural Highway Entering Community | 1 | ● After installation of the DSFS:<br>○ Speed reductions entering the community were up to 2.9 mph greater.<br>○ Drivers were 67% to 76% less likely to exceed the reduced speed limit. |
| <br>Flashing LED Chevrons | Horizontal Curve on Rural Highway | 3 | ● After installation of the LED chevrons:<br>○ Speed reductions at the curve were 1.4 to 2.3 mph greater across all sites<br>○ Drivers were 50% to 60% less likely to exceed curve advisory speed by > 10 mph<br>● Simultaneous flash mode was generally more effective than sequential mode. |
|  <br>Flashing LED Chevrons + DSFS | Horizontal Curve on Rural Highway | 1 | ● Speed reductions were 0.8 to 1.2 mph greater when the DSFS was paired with the flashing LED chevrons vs. the LED chevrons alone.<br>● DSFS had the greatest effect when adjacent to the curve warning sign. |
| <br>Slippery Curve Warning System | Horizontal Curve on Rural Highway During Winter Weather | 2 | ● During winter weather conditions, the flashing LED borders:<br>○ Reduced curve speeds by 0.9 to 1.5 mph<br>○ Reduced occurrence of drivers exceeding the curve advisory speed by 62% to 72%<br>○ Had strongest effect on the fastest drivers |
|  <br>CMS Weather Warning Message | Freeway Bridge During Winter Weather | 3 | ● During winter weather conditions, the CMS weather warning messages:<br>○ Reduced bridge speeds by 0.5 to 0.8 mph<br>○ Increased the number of drivers reducing their speed by 54% to 103%<br>○ Had strongest effect on the fastest drivers<br>● “SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS” had the greatest effect |

# 1. INTRODUCTION AND BACKGROUND

## 1.1 Background

Between 2019 and 2023, 1.42 million crashes occurred on public roadways in Michigan, including 5,054 fatal crashes, 23,694 severe injury crashes, and 229,091 crashes involving other injuries (OHSP 2025). Among the most severe types of crashes are those involving excessive speeds, which accounted for 8.9 percent of total crashes, 19.5 percent of fatal crashes, and 15.3 percent of serious injury crashes in Michigan between 2019 and 2023. Excessive speed is particularly problematic in certain geometric contexts where a speed change is required, such as horizontal curves and freeway ramps, where 35.6 percent and 17.7 percent of crashes, respectively, involved excessive speed. Furthermore, excessive speed was a factor in 42.8 percent of single-vehicle lane departure crashes and 40.0 percent of crashes occurring during winter weather or fog.

These traffic safety issues have been exacerbated by the 2017 speed limit increase in Michigan, which included 900 miles of rural state highways (from 55 to 65 mph) and 600 miles of limited access freeway (from 70 to 75 mph). A recent research project sponsored by the Michigan Department of Transportation (MDOT), found that mean and 85th percentile travel speeds have increased by roughly 2 mph to 4 mph on the freeway and rural state highway segments where speed limits were increased (Savolainen, Gates, and Kassens-Noor 2022). Not surprisingly, crashes in these segments have generally increased after the speed limit was increased. In particular, fatal and A+B-injury crashes on freeway segments where the speed limit was increased have risen by greater than 30 percent following the speed limit increase (Savolainen, Gates, and Kassens-Noor 2022).

Speed-change areas are defined as sections of roadway where a change in speed is required to safely navigate and include (but are not limited to) the following roadway contexts: horizontal curves, freeway ramps, work zones, school zones, isolated rural stop- or signal-controlled intersections, and freeway termini (i.e., where a freeway transitions to a non-freeway). Speed-change areas are particularly vulnerable to traffic safety issues associated with increased travel speeds due to the extreme speed reduction necessary to safely traverse the section. One particularly concerning speed-change scenario where crashes have increased after speed limits were raised are speed transition zones entering rural communities along high-speed roadways. A recent MDOT research project found that A+B-injury crashes increased by 12.9 percent after speed limits were increased along a sample of 321 miles of trunkline speed transition zones (Savolainen, Gates, and Kassens-Noor 2022). Furthermore, field studies performed by members of the Michigan State

University (MSU) research team at multiple speed transition zones have found 85th percentile speeds to greatly exceed the posted speed limit upon entry to the community (Savolainen and Gates 2022; M. S. Mahmud, Johari, et al. 2023). Reducing speeds in communities is particularly critical to ensure the safety of pedestrians and bicyclists, as each of these vulnerable road user types has experienced significant increases in fatal crashes since the start of the COVID-19 pandemic. Specifically, from 2020 to 2023, pedestrian fatalities in Michigan increased by 15.7 percent and bicyclist fatalities increased by 25.7 percent when compared to the prior four-year period of 2016-2019 (OHSP 2025). In keeping with MDOT's commitment to the Safe System Approach and other transportation safety initiatives, strategies must be identified to help reduce speeds and related crashes at critical speed-change areas.

In response, MDOT and other road agencies have deployed various traffic control device strategies to help manage speeds in critical speed-change areas. These devices include traditional warning signs, along with enhanced devices to help alert motorists of the need for speed reduction at critical locations. Some of the more common warning sign enhancements include adding flashing beacons or flashing sign borders to traditional warning signs to alert motorists of a speed-change situation. In many cases, the warning lights on these devices flash continuously. However, driver compliance with flashing warning alerts is improved when the lights are programmed to flash only during certain times of day (e.g., school zones) or during specific weather conditions (e.g., winter warning systems). The effectiveness of these warning alerts can be further improved if the alerts are only activated when approaching vehicles exceed a critical speed threshold.

A common on-demand speed reduction strategy is the dynamic speed feedback sign (DSFS), which utilizes a radar sensor to activate targeted speed warning messages when vehicles exceed a speed threshold. DSFS are particularly effective in reducing excessive speeding in numerous contexts, including highway work zones (Garber et al. 1994; Mattox et al. 2007), school zones (Ullman and Rose 2005), horizontal curves (Ullman and Rose 2005; S. Hallmark et al. 2015; Bertini et al. 2006; S. Mahmud et al. 2022), high-speed arterials (Ullman and Rose 2005; Bertini et al. 2006; Ardeshiri and Jeihani 2014; Karimpour et al. 2021), freeway exit ramps (Gates et al. 2020; Mahmud et al. 2021; Mahmud et al. 2023), and speed transition zones (Hallmark et al. 2015; Ullman and Rose 2005; Cruzado and Donnell 2009; Sandberg et al. 2006; Mahmud et al. 2023)

The promising results of DSFS as a speed-control measure in these contexts have led to widespread utilization of the device across Michigan, mostly as temporary speed control applications, particularly in work zones, school zones, and municipal speed control applications. Recently, MDOT has begun to deploy DSFS as a strategy to reduce speeds and subsequent lane-departures at freeway exit ramps possessing significant horizontal curvature. Recent MDOT conducted by MSU analyzed the effectiveness of DSFS with a series of driver behavior studies at six freeway exit ramps (T. Gates et al. 2018; Timothy J. Gates et al. 2020; M. S. Mahmud et al. 2021; M. S. Mahmud, Gates, et al. 2023). The DSFS were shown to lower ramp speeds by up to 4 mph, on average, compared to when the signs were not present. The research results were used to develop guidance for site selection, sign design and installation, and message design and operation for DSFS at freeway ramps. However, this prior research was limited to the use of DSFS on freeway exit ramps and only during daylight periods and favorable weather.

The promising results of DSFS as a speed reduction countermeasure in the aforementioned contexts warrant further implementation and testing of DSFS and other speed-related warning sign enhancements across other critical speed-change contexts where an additional warning alert is often necessary. Such contexts include horizontal curves on freeway mainlines, freeway to non-freeway transitions, winter roadway conditions, and roundabouts along rural highways, in addition to expanded evaluation of such treatments at horizontal curves on rural highways and freeway exit ramps and speed-reduction zones entering communities along rural highways.

## 1.2 Research Problem

Crashes that occur within speed-change areas continue to be a major safety issue both in Michigan and nationwide. While traditional warning treatments, including signs, delineation, and beacons have been used for decades, MDOT recently expanded the implementation of advanced signing technologies to warn motorists approaching such areas. These signing technologies include DSFS, flashing beacons, flashing sign borders, flashing chevrons, and other warning strategies.

Available warning signing technologies have the potential to reduce excessive speeds and resulting crashes in speed-change areas. However, for many types of critical speed-change scenarios, little research has been performed on the behavioral effects of such strategies, and behavioral studies that have been performed were typically only during the day and in favorable weather conditions. Furthermore, to date, many of MDOT's enhanced speed warning sign deployments have been too recent to allow for a meaningful traffic crash analysis. Thus, research was necessary to determine the driver's behavior and estimate potential traffic safety impacts associated with the use of speed warning signing technologies across a variety of critical roadway contexts, lighting conditions, and weather conditions. The findings and conclusions from this research would ultimately be utilized to provide guidance for MDOT and other agencies towards the deployment and operation of such treatments in critical speed-change areas to support efforts to reduce speed-related crashes and associated injuries and fatalities.

## 1.3 Research Objectives

Research was conducted to evaluate the effectiveness of select warning sign technologies as a speed reduction and traffic safety strategy across a variety of roadway contexts, geometries, lighting conditions, and weather conditions. The specific research objectives are listed as follows:

1. Review literature and nationwide practice on the use of speed warning sign technologies.
2. Determine viable warning signing technologies and roadway contexts for field testing.
3. Evaluate the effectiveness of select speed warning sign technologies on driver behavior across a variety of roadway configurations and weather conditions in Michigan.
4. Perform network screening of target crashes to identify trunkline (freeway and non-freeway) locations for potential future application of speed warning sign technologies.
5. Evaluate installation cost and operational performance of viable warning treatments.
6. Develop guidelines and support tools for the use of speed warning sign technologies.

The study results will provide MDOT and other agencies with critical information when making decisions related to the selection, installation, and operation of appropriate speed warning technologies at critical speed-change areas. It is intended that implementation of the research findings would ultimately lead to more effective utilization of highway safety funding resources.

## 1.4 Report Outline

This report documents all work performed to achieve the study objectives. The report is organized as follows:

- Chapter 1: Introduction and Background
- Chapter 2: Review of Literature and State Agency Practices
- Chapter 3: Field Evaluation Methodology
- Chapter 4: Evaluation of Horizontal Curve Warning Strategies
- Chapter 5: Evaluation of Strategies for Speed Limit Transition Areas
- Chapter 6: Evaluation of Winter Weather Warning Strategies
- Chapter 7: Prioritization of Horizontal Curves for Future Warning Treatment Implementation
- Chapter 8: Conclusions, Recommendations, and Implementation Guidance

# 2. REVIEW OF LITERATURE AND PRACTICE

Previous research has stated that in order to encourage drivers to decrease their speed gradually and without a sudden change in driving speed for safety issues, transitional speed zones need to be well-defined (Dixon et al. 2008). This is especially important when transitioning from a higher-speed rural context to a lower-speed urban context. To reduce speed in advance of and while entering a speed-change area, it is crucial to effectively provide information about reduced speed limits to approaching drivers. Traditional traffic control devices often do not provide enough information to the drivers, and speeding through these speed-change areas becomes an issue leading to the occurrence of crashes. Various strategies have been used to help manage speeds which include median islands, roundabouts, road/lane narrowing, road diets, chicanes, countdown speed signs, transitional speed limits, optical speed bars, pavement markings, speed humps, rumble wave surfaces, gateways, optical lane narrowing, roadside vegetation, flashing warning signs/beacons, and dynamic speed feedback signs (Stamatiadis et al. 2014; Forbes 2011). Many of these treatments were successful in reducing speeds, particularly in low-speed environments. Unfortunately, their effectiveness on high-speed rural highways is not well established, perhaps due to a reluctance towards the implementation of aggressive speed reduction strategies at speed transition zones on rural highways (Forbes 2011).

Horizontal curves are widely understood to experience a higher number of crashes compared to adjacent tangent sections. Horizontal curves account for greater than 25 percent of fatal crashes, where the majority of crashes include roadway departure and are more likely to occur in rural areas due to various reasons, including higher travel speeds (Torbic et al. 2004). The crash rate of curved sections of roadway is three times higher than comparable tangent sections, with crashes on curved sections being typically more severe in nature (Donnell et al. 2019). Data from the Fatality Analysis Reporting System (FARS) has shown that 54% of speed-related crashes occur on horizontal curves (Council et al. 2010). Speeding on the approach to horizontal curves presents the issue, as drivers may not be afforded enough time to react and adjust their speed according to the change of geometric features. Prior research has shown that crash occurrence on horizontal curves is correlated with geometric characteristics (Khan et al. 2012) and driver behavior, including speed, lane positioning, and underestimation of the radius/sharpness of the curve (Charlton 2007; Schneider et al. 2009). These speeding related safety issues are exacerbated by poor road surface conditions caused by inclement weather.

## 2.1 Evaluation of Horizontal Curve Warning Strategies

Various speed reduction strategies have been implemented and tested at highway curves in an attempt to reduce speed-related crashes, including pavement markings, advisory speed signs, advance warning signs, chevron signs, raised pavement markers, flashing beacons and flashing LED border curve warning signs and chevrons (Khan et al. 2012; Gates et al. 2008; Montella et al. 2015; Albin et al. 2016; Hallmark et al. 2020; Stamatiadis et al. 2014). Advance warning signs and pavement markings have been shown to reduce curve speeds (Stamatiadis et al. 2014), but other strategies have been less effective.

The Arkansas State Highway and Transportation Department conducted a study to compare low-cost experimental treatments for horizontal curves. The study compared mean speeds on the approach to the curve with four different treatments including the Pennsylvania DOT's curve advance pavement marking (two transverse bars, "SLOW" legend, and an arrow indicating the curve direction), optical speed bars, fluorescent yellow sheeting on chevron signs, and LED flashing border on the curve warning sign. Overall, no major differences in speed were found for PennDOT curve advance pavement marking, optical speed bars, and fluorescent yellow sheeting. LED flashing border on the curve warning sign was found to be effective in reducing the mean speed (Frierson 2016).

Previous studies have also evaluated the effectiveness of the Sequential Dynamic Chevron Warning System (SDCWS) that included a flashing LED border within chevron signs on horizontal curves. It was found that the installation of SDCWS resulted in a crash modification factor of 0.34 for total crashes (non-intersection) and 0.49 for injury crashes (Shauna Hallmark et al. 2020), and mean speed reduction of 1 – 2 mph (Smadi et al. 2014). However, these prior evaluations did not compare different flashing patterns for the LED chevrons (e.g., simultaneous vs. sequential/chasing), nor did they investigate the effects of pairing multiple treatments (e.g., DSFS plus flashing LED chevrons) at horizontal curves.

Previous MDOT research performed by members of the MSU research team involved the evaluation of a DSFS installed as a speed reduction countermeasure at several freeway exit ramps in Michigan. The results suggested that speeds at the curve entry were on average 1.5 mph to 4 mph lower, compared to when DSFS was not present (Gates et al. 2022). Although comprehensive in the context of freeway ramps, this prior evaluation assessed the DSFS effects over a limited installation period (i.e., two weeks or less) and during the daytime only. Thus, the researchers recommended future work to evaluate DSFS in various other speed-change contexts, in addition to evaluating the long-term and nighttime effects on driver behavior.

Based on the positive speed reduction effects of DSFS at freeway exit ramps, subsequent evaluations of driver response to DSFS were evaluated by the MSU team at five horizontal curves on rural two-lane highways in Michigan (Savolainen and Gates 2022; M. S. Mahmud, Bamney, et al. 2023). The speed-reduction effects of DSFS at these curve locations are shown in **Figure 1**.

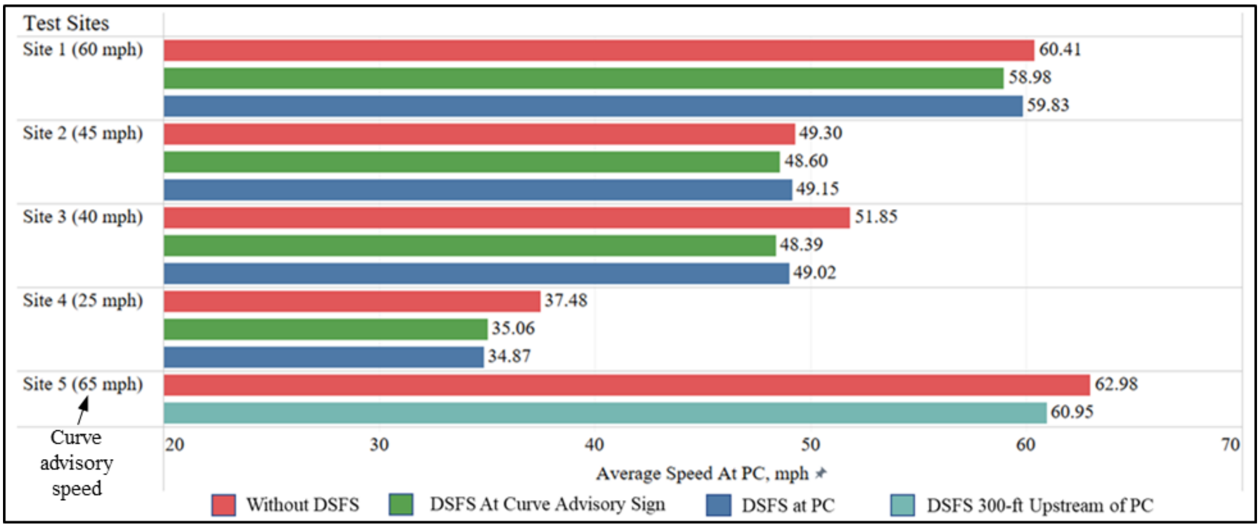


**Figure 1. Average Speeds at Two-Lane Highway Curves, by Site and DSFS Location**
(Savolainen and Gates 2022; M. S. Mahmud, Bamney, et al. 2023)

Another study of DSFS on freeway curves was conducted on Interstate 5 in California, which possessed a speed limit of 65 mph. The DSFS were installed along five horizontal curves with advisory speeds between 50 and 60 mph and were programmed to display approaching vehicle speed alternating with a curve warning sign. The results showed a decrease of 4.5 mph in passenger car speed and 5.4 mph in heavy vehicle speed (Tribbett et al. 2000).

## 2.2 Evaluation of Warning Strategies for Speed Limit Reduction Zones

The use of DSFS at speed transition zones entering rural communities on rural two-lane highways (Savolainen et al. 2022; Mahmud, Johari, et al. 2023) has also been evaluated by the MSU team as a means to improve safety for pedestrians and bicyclists. The speed reduction effects of a DSFS consisting of a radar-activated portable changeable message sign mounted on a trailer were evaluated at four speed limit reduction zones entering communities along rural highways in Michigan. The results of these evaluations are displayed in **Figure 2**, which shows that the DSFS had consistent speed reduction effects at each of the sites where tested with mean speed reductions ranging from 3 to 6 mph across the four sites when the DSFS was present. However, additional research is needed to determine the effects of traditional DSFS in this context.

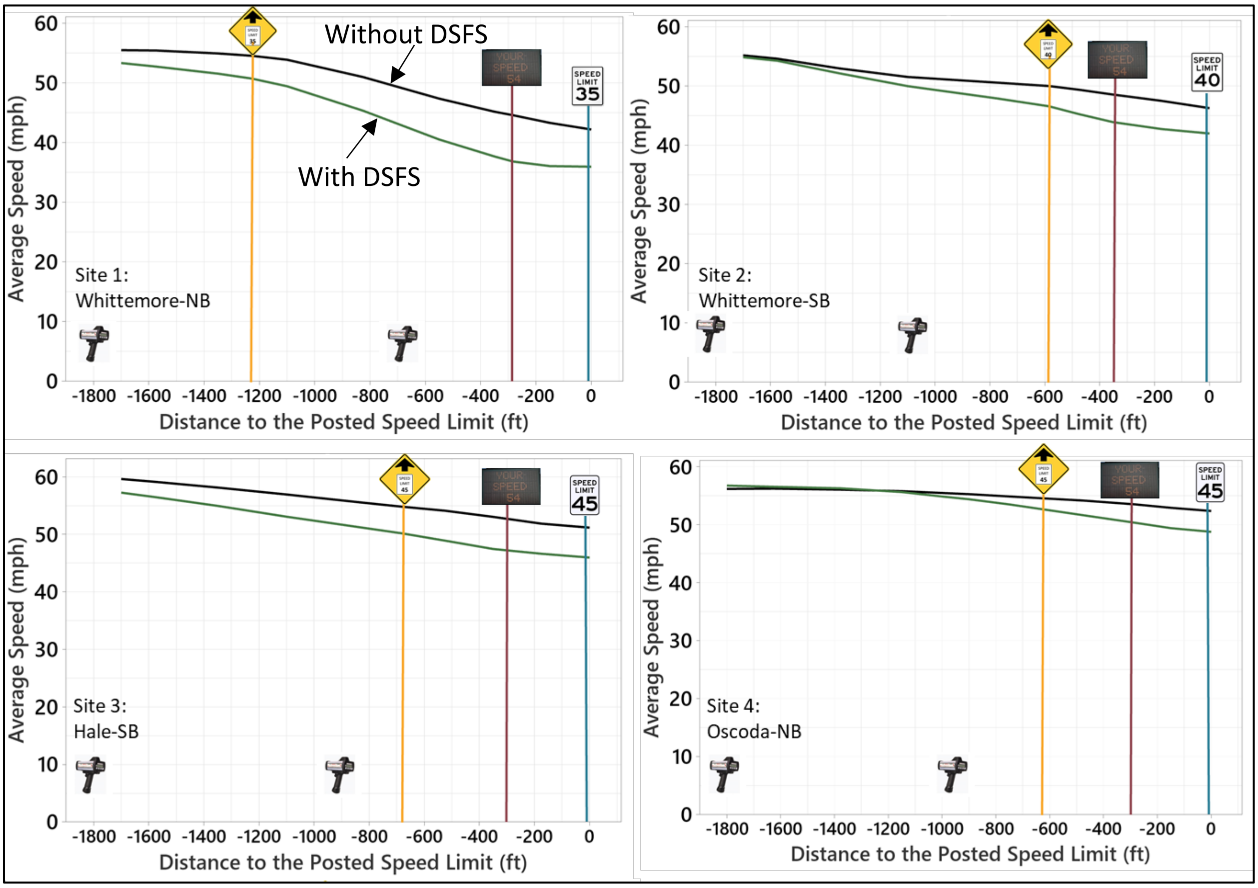


**Figure 2. Speed Trajectories of Vehicles Approaching Rural Towns, by Site and DSFS Use**
(Savolainen et al 2022; Mahmud, Johari, et al. 2023)

## 2.3 Nationwide Practice for Speed Warning Devices at Horizontal Curves

The research team examined agency web pages to identify policies and practices related to speed warning devices, including appropriate highway contexts for deployment, specifications, and message types. The MUTCD serves as the primary reference for traffic control device deployment on horizontal curves. For states that adopt their own versions of the MUTCD, the state-specific manuals were reviewed, while state supplements were examined for states that issue such additions. Overall, very few changes were observed in state MUTCDs or supplements compared to the national MUTCD language regarding speed warning devices in horizontal curves.

Although the 11th Edition of the national MUTCD became effective as of January 2024, states have been given a two-year period to adopt it, meaning that very few supplements specific to this edition are currently available. This is particularly relevant in the case of DSFS usage, as notable changes have been made regarding their general application. The 2009 edition of the MUTCD, as officially interpreted by the FHWA, classified DSFS under Chapter 2L, “Changeable Message Signs”, and prohibited advertising, animation, rapid flashing, dissolving, exploding, scrolling, and other dynamic elements, including flashing displays and strobe light technology

(FHWA 2009; FHWA 2013). Very little additional guidance towards the use of DSFS was provided in the 2009 MUTCD, thereby allowing for considerable flexibility in the types of contexts where DSFS may be utilized in addition to flexibility in the types of messages that could be displayed.

In contrast, the 11th Edition of the MUTCD provides detailed guidance on the use and operation of vehicle speed feedback signs (DSFS) in Section 2C.13 (FHWA 2023). While this edition maintains restrictions against flashing, strobing, color changes, or other animated elements integrated into the DSFS legend display, additional clarity has been provided in that only the vehicle speed may be displayed and all other types of messages, including word messages like "SLOW DOWN", are considered "animated elements". This is highly impactful to MDOT, as the agency's standard practice of displaying the SLOW DOWN message for vehicles traveling a preset increment over the speed limit or advisory speed would be prohibited upon adoption of the 11th Edition MUTCD (via Michigan MUTCD). Furthermore, the 11th Edition MUTCD also specifies that DSFS may only be used to alert drivers of their speed in relation to posted speed limits or horizontal curve warning. In the case of horizontal curves, DSFS should supplement the curve warning sign's advisory speed and be installed as a standalone unit near the point of curvature. When supplementing posted speed limits, the 11th Edition MUTCD requires a shorter DSFS plaque (W13-20aP) posted below the speed limit sign and on the same assembly (FHWA 2023).

The 11th Edition of the MUTCD also expanded on guidance in previous editions towards the use of LEDs to enhance sign conspicuity. Additional guidance is now provided regarding the types of signs and contexts where flashing LEDs elements may be used within the sign face. (FHWA 2023). The LEDs must not extend beyond the sign's border or legend, and their maximum diameter should be no more than ¼ inch. For warning signs, the LEDs must emit either white or yellow light and flash at a steady rate of 50 to 60 times per minute. Notably, the California MUTCD permits only yellow LEDs when used with warning signs (CALTRANS 2023). For chevrons, the MUTCD states that LEDs shall be yellow and outline the chevron symbol (FHWA 2023).

In addition to LED enhancements, the 11th Edition of the MUTCD provides guidelines for the use of flashing beacons to supplement horizontal curve warning signs. These beacons must flash at a rate between 50 and 60 flashes per minute, with allowable nominal diameters of either 8 inches or 12 inches (FHWA 2023). Additionally, the MUTCD permits the use of flashing LED borders to further enhance the visibility of chevron alignment signs. However, states such as Texas, Minnesota, and Indiana have excluded standards related to flashing LEDs on chevron alignment signs (TxDOT 2014; MnDOT 2024; IDOT 2011). Texas DOT, however, issued a specification in 2024 regarding the use of a dynamic LED chevron system (TxDOT 2024).

# 3. FIELD EVALUATION METHODOLOGY

Field evaluations were conducted at 21 highway locations to assess how various speed warning technologies influence driver behavior when approaching various speed-change contexts. The results of these field evaluations would allow for the identification of effective speed warning signing strategies for each of the selected road contexts as well as optimal message strategy, flashing pattern, and/or positioning, if applicable. The following subsections provide a general summary of the field evaluation methods, including the selection of roadway contexts, sign test conditions, study sites, field data collection methods, measures of effectiveness, and analytical methods. Details pertaining to the specific field evaluations are provided in subsequent chapters.

## 3.1 Selected Roadway Contexts

This section provides details about the types of roadway contexts where the field evaluations of speed warning sign technologies were conducted. Several critical speed-change contexts were identified in consultation with the MDOT Research Advisory Panel for the field evaluation of speed warning strategies, which included:

- Horizontal curves
    - Freeway ramp
    - Freeway mainline
    - Rural highway
- Speed limit transitions
    - Freeway to non-freeway
    - Roundabout approaching a community
    - Rural highway entering a community
- Winter weather warning
    - Rural highway curve
    - Freeway bridge overpass

## 3.2 Selected Signing Treatments

Upon selection of the highway contexts where the field studies would be performed, the next step was to select the warning sign technologies for testing at each location. In some cases, the permanent signing treatments had already been installed or were in the process of being implemented during the study period. However, for several of the locations, DSFS signs were temporarily installed for the field evaluation and removed after completion of data collection.

### 3.2.1 Dynamic Speed Feedback Sign

The predominant speed warning sign strategy included in the field evaluations was the DSFS, which was tested at 14 different locations, including both permanent and temporary installations, and across various highway speed-change contexts. Two differently sized DSFS were deployed in the field studies described herein, each manufactured by TraffiCalm. One sign was 40 inches by 31 inches with microprismatic reflective yellow sheeting with black "YOUR SPEED" text and a full matrix amber LED feedback display capable of displaying characters of up to 15 inches in height. The other sign was slightly larger at 48 inches by 36 inches with an 18-inch full matrix amber feedback display. Both signs utilized a radar unit embedded within the LED panel to detect the speed of approaching vehicles. The radar propagated outward in a 30-degree cone and provided a minimum detection range of 400 ft for passenger vehicles and 600 ft for heavy vehicles. There was no difference in the operational performance between the two signs, with the only difference being the size. Examples of the two DSFS signs used in this study are shown in **Figure 3**, which demonstrates the relative size difference between the two signs. Note that prior research performed by the authors confirmed no significant difference in driver performance between the two DSFS sign sizes when applied at rural highway curves and freeway exit ramps.

**Figure 3. Relative Dimensions of 15-inch vs. 18-inch Dynamic Speed Feedback Sign**

During data collection at the roundabout locations, the LED feedback display was removed from the "YOUR SPEED" sign and affixed within a custom bracket, which was mounted between the roundabout warning sign and the advisory speed plaque on the same assembly. At all other sites where the effect of the DSFS was tested, the full DSFS sign was used. The DSFS was able to display a variety of speed feedback messages and could be programmed to display different messages based on the speed of the approaching vehicle. An example of the DSFS messages tested in this study, including the speed digits and “SLOW DOWN”, is provided in **Figure 3**. During the evaluations, signs were powered using a portable battery system which powered the sign for up to one week before depleting.

The DSFS panels were programmed with the proprietary SafetyCalm software using a laptop that communicated with the sign via Bluetooth. Several sign settings were applied to the DSFS across all field evaluations as follows:

1. “Min speed”, which is the minimum speed for activation of the display panel, was set at 15 mph in order to prevent rain and small objects (leaves, debris, animals, etc.) from activating the sign. For this study, except where noted, the measured speed was displayed for vehicles exceeding the minimum speed.
2. “Speed limit” was set to match the speed limit of each site, respectively.
3. Unless noted otherwise, the “Excess speed” was set to match either advisory speed + 10 mph at the site or speed limit + 10 mph, depending on the test site. Vehicles exceeding the excess speed threshold received a “SLOW DOWN” message alternating with the speed digits at 1 Hz.
4. “Max speed” sets the maximum speed, beyond which the sign displays a blank screen to prevent motorists from attempting to achieve high-speed feedback values displayed on the sign. The feedback panel was programmed to go blank for vehicles exceeding 99 mph.
5. The “Squelch” setting can be modified to achieve different vehicle detection ranges. The squelch defines the sensitivity level of the radar embedded in the sign and the values range from 1 to 999, where 1 is the highest sensitivity and 999 is the lowest sensitivity, which essentially provides no vehicular detection. The manufacturer suggests not using a squelch value of less than 50 as this could result in excessive false signals. A squelch of 60 is recommended in the user manual to achieve optimal results, which can be extended up to 100 if needed. For this study, a squelch value of 60 was utilized.
6. The color was set to amber for all speed levels and feedback messages.

### 3.2.2 Flashing LED Chevrons

Flashing LED chevron systems were permanently installed and tested at three horizontal curve locations along US-12 in southeast Michigan. This curve warning treatment includes chevron signs (W1-8) with flashing LEDs around the border of the black chevron arrows. The system is equipped with a radar sensor that was mounted near the initial chevron leading into the curve. The radar detected speeds of approaching vehicles up to 600 ft upstream. The chevrons were programmed to begin flashing if the detected speed of the approaching vehicle was above the set speed threshold, which for this study, was the posted curve advisory speed. The advantage of this type of system is that it only activates for drivers that are traveling too fast on the approach to the curve, thereby providing an on-demand flashing alert, rather than an "always on" flash. An example flashing chevron is displayed in **Figure 4**.

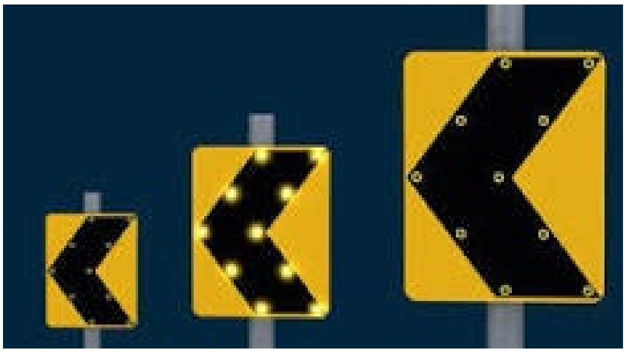


**Figure 4. Example Flashing LED Chevron System**

The LED chevrons could be programmed into two different flashing modes: simultaneous flashing and sequential flashing. In simultaneous mode, all LED chevrons flash at the same time, with the same brightness and frequency. In sequential mode, the LED chevrons go into *chasing flashing,* with a time gap between each successive chevron flashing so that only one chevron flashes at a time. In other words, the first chevron in the curve flashes first, followed by the second, and the third, after which the cycle repeats and the first chevron flashes again. The programming option also allows setting specific flashing frequencies. The flashing LED chevrons used at the sites on US-12 had a frequency of flashing for simultaneous mode of 1 flash per second. For sequential mode, the chevrons flashed for 1/3 of a second, which provided a cycle for the entire flash sequence of 1 second (each site had only the initial three chevrons as a part of the flashing system).

### 3.2.3 Slippery Curve Warning System

A slippery curve warning system (SCWS) was tested during winter conditions at two horizontal curve locations along M-32 west of Gaylord, Michigan. The system, which was installed along this section of highway in 2018, consisted of two W8-5 (slippery when wet) signs and one W1-2 (curve warning) sign positioned on the approach to the horizontal curve. Each sign contained eight LEDs along the sign border and was 48-inches by 48-inches. It should be noted that the supplemental plaques located beneath each sign did not contain LED lights. Fluorescent yellow retroreflective sheeting was affixed to the sign posts beneath both W8-5 signs.

During normal operation, the flashing LED border was automatically activated when the road surface temperature was below 32 degrees Fahrenheit and the road surface friction coefficient was less than 0.4, based on data collected from the environmental sensor located along the segment. However, during the field evaluation, the flashing LED border was manually cycled between "flashing" and "off" every 30 minutes during periods of data collection, which afforded considerable control over any variations in weather conditions, pavement conditions, and general driver behavior throughout the data collection period. When activated, the LED lights would flash at a rate of 1 hertz. An example of the flashing SCWS is displayed in **Figure 5**.

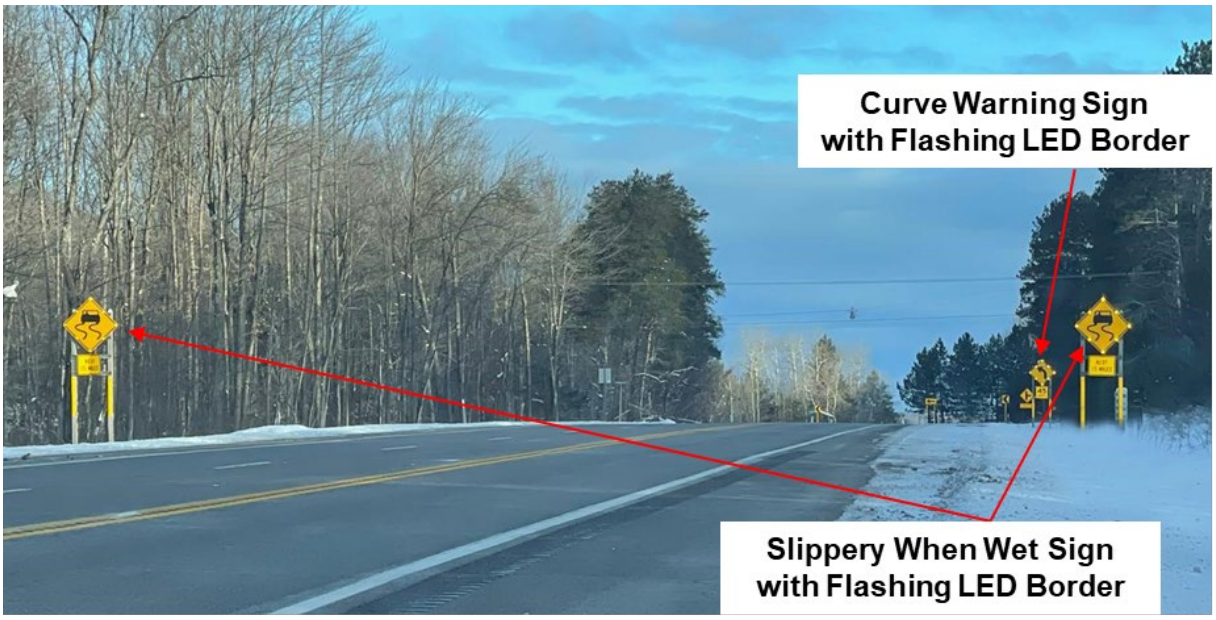


Figure 5. Example Slippery Curve Warning Sign System

### 3.2.4 Winter Weather Warning Message on Changeable Message Signs

The final sign warning treatment included within the field studies were winter weather-related warning messages posted on changeable message signs (CMS) on the approach to bridge overpasses. 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. Two specific winter weather warning messages were evaluated against the travel time message, which served as the baseline. The evaluated messages and message selection rationale are displayed in **Table 1**. Driver speed-selection response to these messages was evaluated during winter weather conditions at three freeway bridge overpass locations in lower Michigan.

**Table 1. CMS Messages and Rationale for Message Selection**

| CMS Message Display | Selection Rationale |
|---|---|
|  | This message represented the default CMS message utilized by MDOT during normal conditions. |
|  | This message reinforces the W8-13 sign message (BRIDGE ICES BEFORE ROAD) while adding the desired action of "REDUCE SPEEDS". |
|  | This message represented MDOT's standard CMS message used during winter weather advisories. |

### 3.3 Site Selection

After identification of the critical highway contexts and warning sign treatments that were of interest to MDOT, specific highway locations were then selected. In addition to satisfying the appropriate highway context, the site was also evaluated for data collection suitability and sign installation capability (for cases where a temporary DSFS installation was to be performed). As previously noted, several permanent treatments, including flashing LED chevrons, a slippery curve warning system, and a DSFS at exit ramps, had already been installed or were in the process of being implemented during the study period. Summaries of all road contexts, locations, signing strategies, and test conditions are presented in **Table 2**. Detailed site descriptions are provided in subsequent chapters. A map of all study sites is provided in **Figure 6**.

**Table 2. Summary of Field Data Collection Sites**

| Site No. | Road Context | Site | Speed Warning Sign Technology | Speed Limit (mph) | Advisory Speed (mph) | Sign Test Conditions |
|---|---|---|---|---|---|---|
| 1 | Freeway Exit Ramp | WB I-94 - Sawyer Rd | DSFS | 70 | 25 | **I)** Standard chevrons and warning signage (baseline), **II)** DSFS displaying: speed digits for vehicles between 25 and 35 mph, speed digits alternating with "SLOW DOWN" for vehicles > 35 mph |
| 2 | | EB I-94 - Sawyer Rd | DSFS | 70 | 25 | |
| 3 | | EB I-94 - Friday Rd | DSFS | 70 | 25 | |
| 4 | | EB I-94 - M-140 | DSFS | 70 | 25 | |
| 5 | | WB I-94 - C-Drive | DSFS | 70 | 25 | |
| 6 | Mainline Freeway Curves | SB US-127 Mt Pleasant | DSFS | 75 | 65 | **I)** Standard chevrons and warning signs (baseline), **II)** DSFS displaying speed digits, **III)** DSFS displaying: speed digits for vehicles < 75 mph, speed digits alternating with "SLOW DOWN" for vehicles > 75 mph |
| 7 | | SB US-127 Mt Pleasant | DSFS | 75 | 70 | **I)** Standard chevrons and warning signs (baseline), **II)** DSFS displaying speed digits, **III)** DSFS displaying: speed digits for vehicles < 80 mph, speed digits alternating with "SLOW DOWN" for vehicles > 80 mph |
| 8 | Rural Horizontal Curves | WB US-12 Deer Run Ct | Flashing LED Chevrons with and without DSFS | 55 | 40 | **I)** Standard chevrons and warning signs (baseline), **II)** LED chevrons simultaneous flashing (Angle I), **III)** LED chevrons simultaneous flashing (Angle II), **IV)** LED chevrons sequential flashing (Angle II), **V)** LED chevrons simultaneous flashing (Angle II) plus DSFS adjacent to the curve warning sign, **VI)** LED chevrons simultaneous flashing (Angle II) plus DSFS near PC<br>Note: LED chevrons and DSFS were activated upon detection of a vehicle exceeding the curve advisory speed. Two DSFS message displays were tested: **i)** speed digits, **ii)** speed digits alternating with "SLOW DOWN" |
| 9 | | EB US-12 Deer Run Ct | Flashing LED Chevrons | 55 | 35 | **I)** Standard chevrons and warning signage (baseline), **II)** LED chevrons simultaneous flashing (Angle I), **III)** LED chevrons simultaneous flashing (Angle II), **IV)** LED chevrons sequential flashing (Angle II)<br>Note: LED chevrons were activated upon detection of a vehicle exceeding the curve advisory speed. |
| 10 | | WB US-12 Person Highway | Flashing LED Chevrons | 55 | 35 | |
| 11 | Freeway to Non-Freeway | NB US-127 St Johns | DSFS | 75/65 | NA | **I)** No DSFS (baseline), **II)** DSFS 350 ft upstream of speed limit sign, **III)** DSFS adjacent to speed limit sign.<br>Note: Three DSFS message displays were tested as follows: **i)** speed digits for vehicles < 65 mph, speed digits alternating with "SLOW DOWN" for vehicles > 65 mph, **ii)** speed digits for vehicles < 70 mph, speed digits alternating with "SLOW DOWN" for vehicles > 70 mph, **iii)** speed digits for vehicles < 75 mph, speed digits alternating with "SLOW DOWN" for vehicles > 75 mph |

| **Site No.** | **Road Context** | **Site** | **Speed Warning Sign Technology** | **Speed Limit (mph)** | **Advisory Speed (mph)** | **Sign Test Conditions** |
|---|---|---|---|---|---|---|
| 12 | Non-Freeway to Community | EB M-115 Farwell | DSFS | 55/45 | N/A | **I)** No DSFS (baseline), **II)** DSFS displaying speed digits, **III)** DSFS displaying: speed digits for vehicles < 45 mph, speed digits alternating with "SLOW DOWN" for vehicles > 45 mph |
| 13 | Roundabout | SB M-52 Chelsea | DSFS and Flashing LED Border Roundabout Warning Sign | 55 | 20 | **I)** Standard warning signs (baseline), **II)** Flashing LED border on the roundabout warning sign, **III)** DSFS displaying speed digits, **IV)** DSFS displaying speed digits alternating with "SLOW DOWN", **V)** DSFS displaying "SLOW DOWN"<br>Note: LED border was disabled during all DSFS test conditions |
| 14 | | EB M-43 Grand Ledge | DSFS | 55 | 20 | **I)** Standard warning signs (baseline), **II)** DSFS displaying speed digits, **III)** DSFS displaying speed digits alternating with "SLOW DOWN", **IV)** DSFS displaying "SLOW DOWN" |
| 15 | | NB US-127 Exit 156 Clare | DSFS | 75 | 20 | **I)** Flashing beacon active (baseline), **II)** DSFS displaying speed digits, **III)** DSFS displaying speed digits alternating with "SLOW DOWN", **IV)** DSFS displaying "SLOW DOWN"<br>Note: The flashing beacon on the roundabout warning sign was active during all DSFS test conditions |
| 16 | | SB US-127 Exit 144 Mt Pleasant | DSFS | 75 | 15 | **I)** Standard warning signs (baseline), **II)** DSFS displaying speed digits, **III)** DSFS displaying speed digits alternating with "SLOW DOWN", **IV)** DSFS displaying "SLOW DOWN" |
| 17 | Rural Horizontal Curves | EB M-32 Gaylord | Slippery Curve Warning System | 55 | 45 | **I)** Standard warning signs (baseline), **II)** Flashing LED borders on advance warning signs |
| 18 | | WB M-32 Gaylord | Slippery Curve Warning System | 55 | 45 | |
| 19 | Freeway Bridge Overpasses | NB US-127 over Willoughby Rd, Lansing | Changeable Message Sign | 70 | N/A | CMS Displays:<br>**I)** Travel times (baseline), **II)** BRIDGES ICE / BEFORE ROAD / REDUCE SPEEDS, **III)** SLIPPERY / ROAD CONDITIONS / REDUCE SPEEDS |
| 20 | | WB I-196 over railroad mile marker 72.5, Grand Rapids | Changeable Message Sign | 70 | N/A | |
| 21 | | EB I-196 over 32nd Ave, Grand Rapids | Changeable Message Sign | 70 | N/A | |

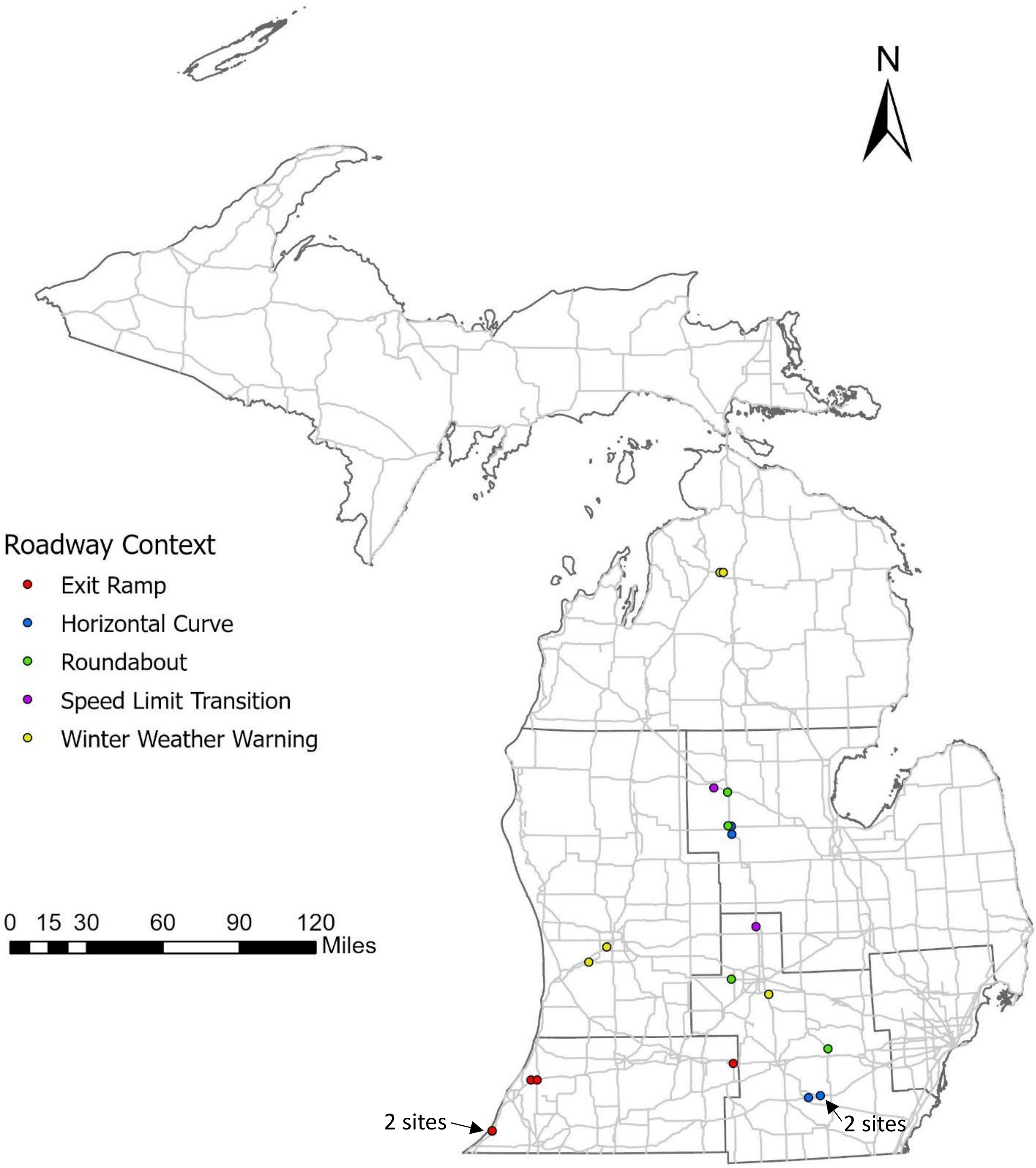


**Figure 6. Map of All Field Evaluation Sites**

## 3.4 Data Collection Methods

The predominant speed data collection method was to utilize LIDAR guns to track the speeds of individual vehicles traversing through the evaluation site. LIDAR guns were utilized at all locations except the five freeway exit ramps along I-94, where data were collected using a trailer-mounted side-firing Wavetronix radar speed sensor installed and operated by MDOT. The LIDAR guns used during field data collection 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 due to geometry and 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. The vehicle was always unmarked and turned off. An example of a LIDAR vehicle position during field data collection is in **Figure 7**. The data collection vehicle was positioned to ensure that the vehicle was away from any critical speed assessment points (e.g., the DSFS, point of curvature, curve or roundabout warning sign, etc.) 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 at a given site. Thus, any speed effect of the data collection vehicle was identical across all test conditions.

**Figure 7. Position of LIDAR Vehicle at SB US-127 Mt Pleasant - Site 1**

The LIDAR gun was connected to a laptop using a serial cable, which allowed for real-time tracking of the time stamp, distance, and speed of each vehicle traversing the site. 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 point of interest with respect to each field data collection site. Using LIDAR for the collection of vehicular speeds provided a significant advantage over other speed data collection methods, as it produces continuous speed measurements over the entire segment of interest, as opposed to spot speeds at fixed points. After completion of the LIDAR tracking for each subject vehicle, data collectors added information regarding the vehicle type, weather, roadway 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 interest were removed from the file along with any vehicles that changed lanes or made any other unusual behavior, as noted in the comments. If more than one LIDAR was used to track vehicles through the site, the two technicians would continuously communicate with each other during data collection. The upstream technician chose the free-flowing vehicle and would provide information about the vehicle's make, type, color, and any other relevant information to the downstream technician. The upstream technician would track the selected vehicle for about 100 ft downstream of the point where the downstream technician was positioned who would then continue tracking the same vehicle beyond the sign or point of interest. This process ensured that the speed data were collected for the same vehicle along the whole stretch of the test site after the collected data from both LIDARs were merged.

### 3.5 Dataset Preparation

The vehicle speed data were compiled separately for each site. Because LIDAR speeds can't be measured at the same locations on the roadway for every vehicle, it was necessary to convert the speed data to a series of spot speeds prior to analysis. Thus, linear interpolation was utilized to convert the raw LIDAR speed data to spot speeds at 50 ft increments in order to allow for speeds to be assessed at specific reference points of interest at each site. As the relative distances between the LIDAR collectors and all of the points of interest were known, all distances were converted relative to the specific point of interest at each site, which included the yield sign at roundabout sites, the speed limit sign at speed limit transition sites, and the point of curvature at all horizontal curve 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, which are summarized in **Table 2** varied from site to site based on the context of the particular location. 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 at the site. The remaining categorical factors were also added as a series of binary variables, which, where applicable, included: vehicle type (passenger vehicle, heavy vehicle) and time of day (daytime, nighttime). 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. Note that data were collected for heavy vehicles across all sites. However, the small sample size of heavy vehicles prevented a separate analysis for heavy vehicles at the majority of non-freeway study sites.

### 3.6 Measure of Effectiveness

The speed of vehicles measured at specific points of interest for all sites (e.g., approaching and entering the curve at horizontal curve sites, location of the initial reduced speed limit sign at speed limit transition sites, roundabout yield sign, start of the bridge) was the primary measure of effectiveness (MOE) related to driver response to the sign test condition. This MOE allowed for the assessment of the magnitude of the speed reduction associated with each sign test condition compared to the base condition for each site. The MOE was analyzed separately for heavy trucks and passenger vehicles, where an adequate sample of trucks was available, and by time of day for locations where data were collected at night.

At select locations, the MOE was further analyzed based on driver types, which were categorized into slower, average, and faster drivers based on the speed measured at the furthest upstream location. To separate the drivers into the three behavioral groups, the vehicle records were first split by site and sign test conditions, then rank-ordered based on the furthest upstream measurement point. The lowest one-third were characterized as slower drivers, the middle one-third were characterized as average drivers and the highest one-third were characterized as faster drivers. Categorizing the vehicle speed data in this manner ensured an equal sample size for each driver behavior group for each of the signing conditions.

### 3.7 Analytical Methods

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

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

where Yi is the measured speed at the point of interest (varies from site to site) for vehicle i, $X_{i1}$ to $X_{ik}$ are independent variables affecting the dependent variables, $\beta_0$ is an intercept, $\beta_1$ to $\beta_k$ are estimated regression coefficients for each independent variable, and $\varepsilon_i$ is a normally distributed error term with variance $\sigma^2$. It should be noted that speed at the furthest upstream measurement location was included as an independent variable (covariate) in each model. Including upstream speed as a covariate control for the variation in the speed selection tendencies of drivers between the data collection periods, 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.

Whereas the linear regression model afforded an assessment of the magnitude of the speed reduction effect, it was also of interest to assess the likelihood of drivers exceeding the advisory speed or speed limit. Since this assessment was binary in nature, thus data were modeled using binary logistic regression. The general form of the binary logistic regression model is given by **Equation 2**:

$$\mathrm{Y_i} = \mathrm{logit}\,(\mathrm{P_i}) = \ln\left(\frac{\mathrm{P_i}}{1-\mathrm{P_i}}\right) = \beta_0 + \beta_1 \mathrm{X_{i1}} + \beta_2 \mathrm{X_{i2}} + \cdots \ldots \ldots \ldots \ldots + \beta_k \mathrm{X_{ik}} \qquad \textbf{(Eq. 2)}$$

where the response variable, $Y_i$, is the logistic transformation of the probability of a vehicle exceeding the advisory speed or speed limit. This probability is denoted as $P_i$. Similar to the linear regression model, $X_{i1}$ to $X_{ik}$ are independent variables, $\beta_0$ is an intercept, and $\beta_1$ to $\beta_k$ are estimated regression coefficients for each independent variable. Similar to the linear regression models, the furthest upstream speed measurement for each subject vehicle was also included as an independent variable in the analysis to account for the general speed behavior of each driver prior to encountering the test sign.

# 4. EVALUATION OF HORIZONTAL CURVE WARNING STRATEGIES

This chapter includes descriptions of the sites, implemented warning signing strategies, test conditions, analyses, and results pertaining to the evaluations of speed warning sign enhancements at horizontal curves. This chapter is organized into three sections based on the roadway context and warning signing strategy tested, which included: freeway exit ramps (DSFS), mainline freeway curves (DSFS), and rural two-lane highway curves (flashing LED chevrons with/without DSFS).

## 4.1 DSFS at Freeway Exit Ramp Curves

The field study was performed at five exit ramps at service interchanges along I-94 in southwest Michigan which are displayed in **Figure 8** and included: WB I-94 at C Drive, EB I-94 at M-140, EB I-94 at Friday Road, WB I-94 at Sawyer Road, and EB I-94 at Sawyer Road. These sites were selected by MDOT for permanent installation of a DSFS based on a high occurrence of lane departure crashes.

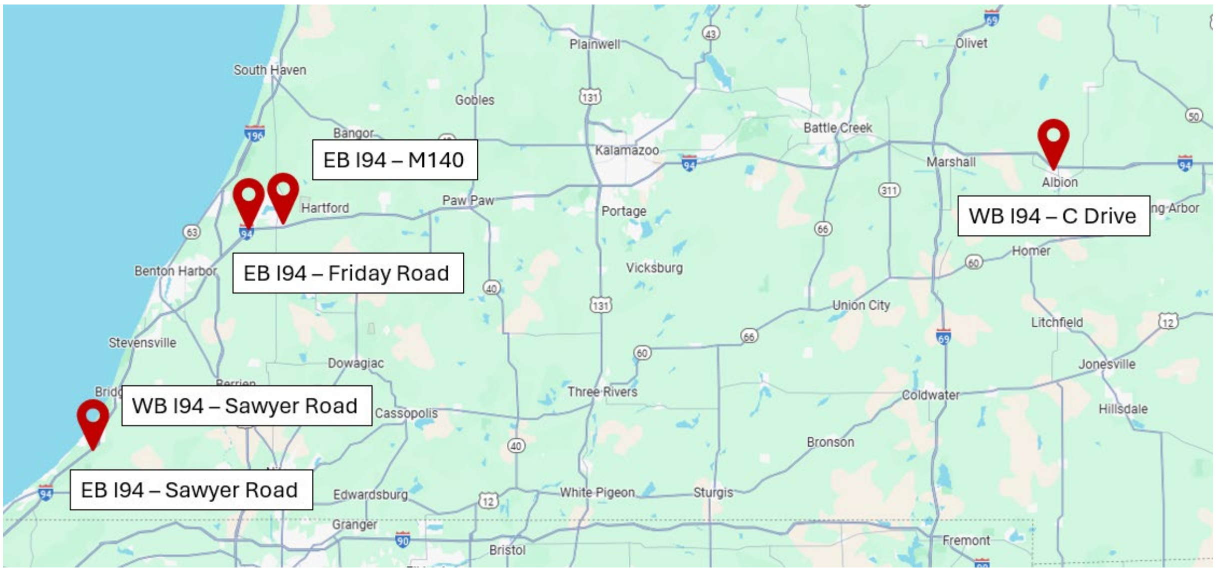


**Figure 8. I-94 Exit Ramp Locations for Evaluation of DSFS**

### 4.1.1 Site Descriptions

The advisory speed at each of the selected exit ramps was 25 mph. The DSFS were installed near the point of curvature at each of the ramp curves in either 2023 or 2024. Data collection was performed before and after DSFS installation in 2022 and 2024, respectively. The position of the DSFS and the Wavetronix data collection sensor are displayed in **Figure 9** (WB I-94 at Sawyer Road), **Figure 10** (EB I-94 at Sawyer Road), **Figure 11** (EB I-94 at Friday Road), **Figure 12** (EB I-94 at M-140), and **Figure 13** (WB I-94 at C Drive), respectively.

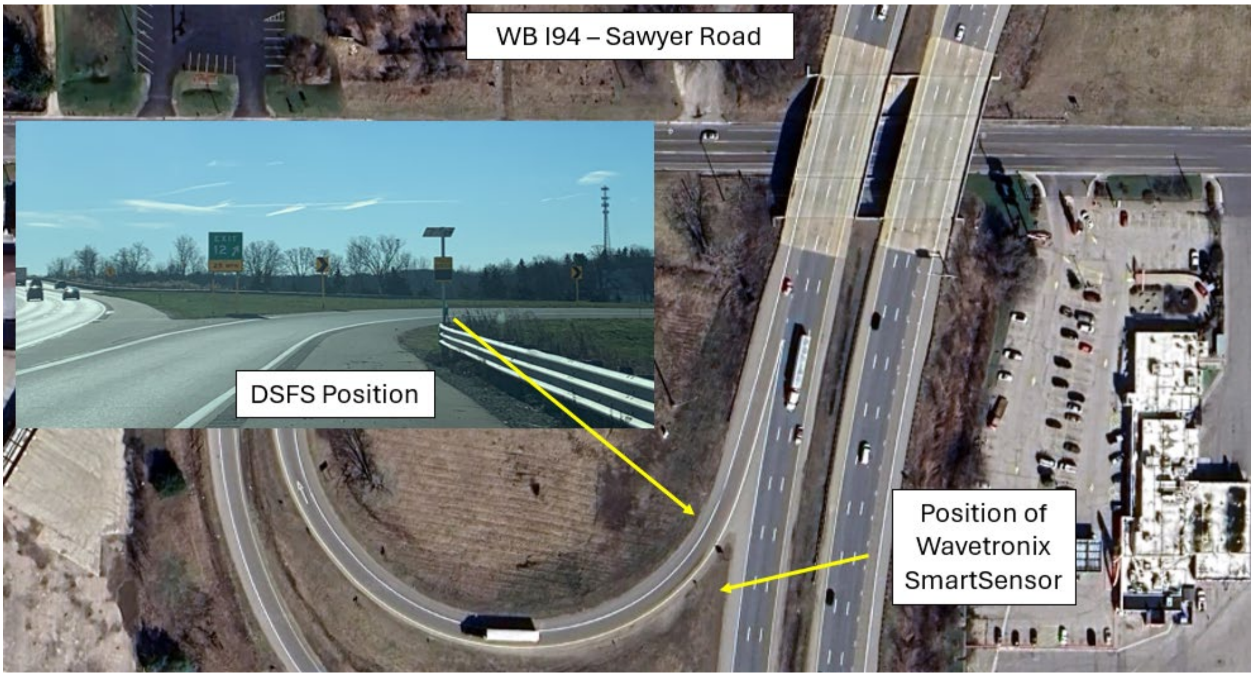


Figure 9. DSFS and SmartSensor Position at WB I-94 - Sawyer Road

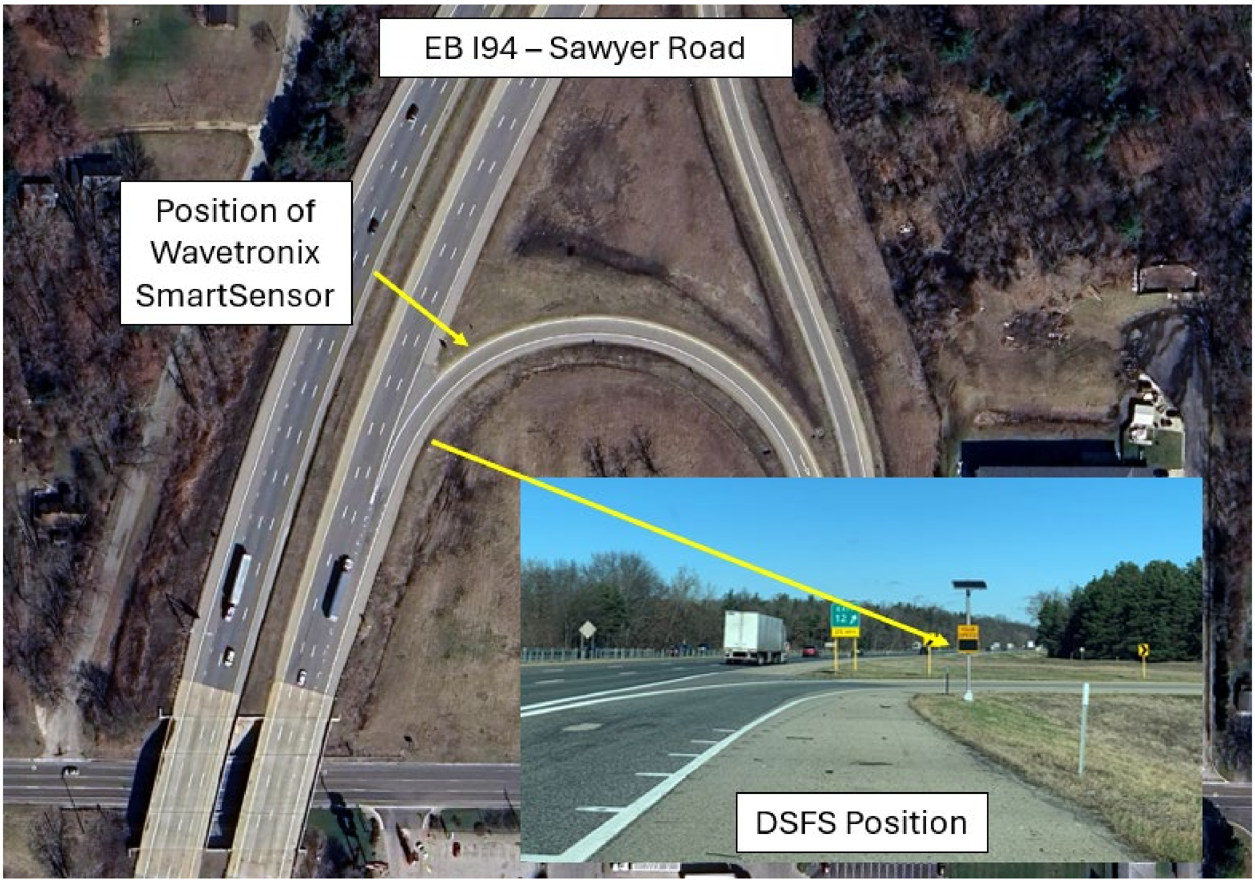


Figure 10. DSFS and SmartSensor Position at EB I-94 - Sawyer Road

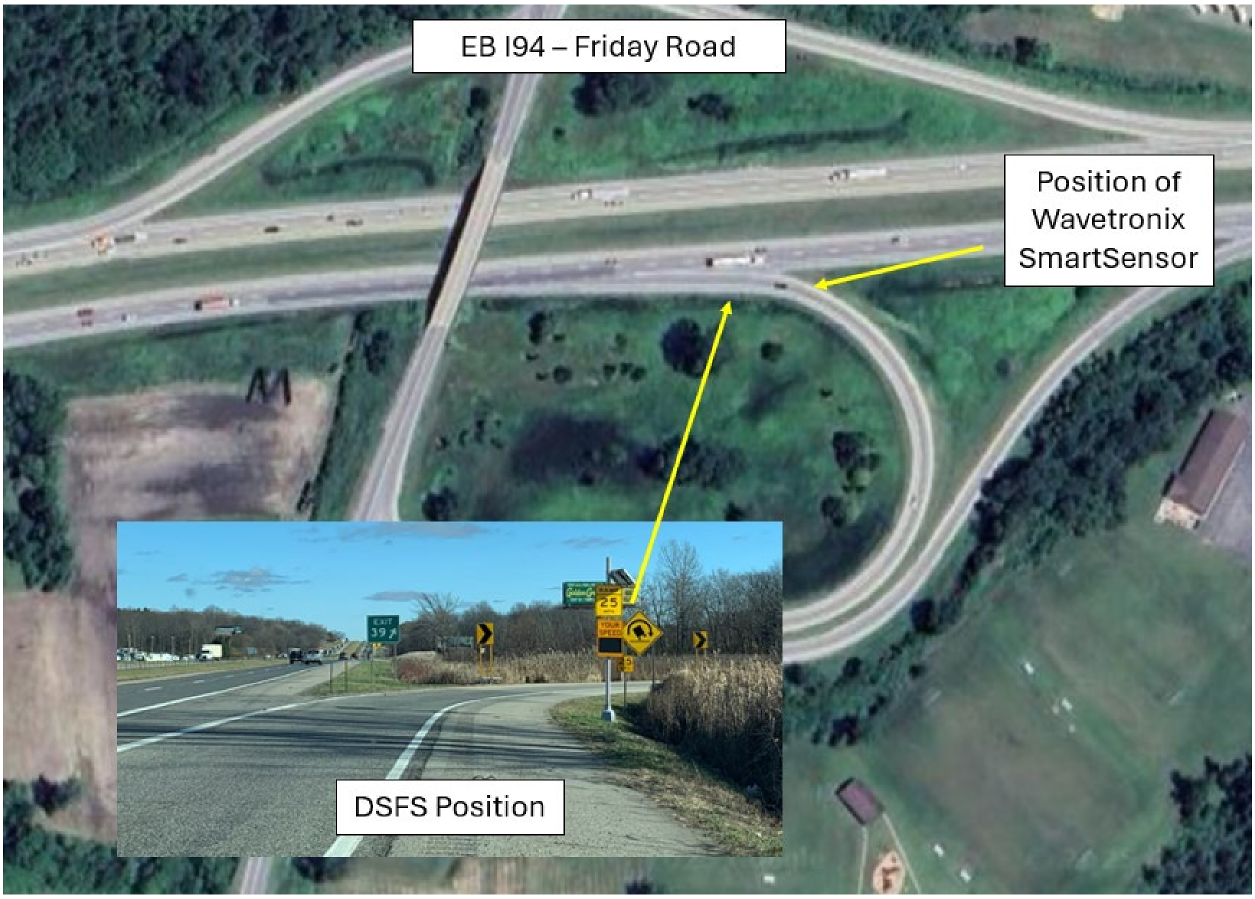


Figure 11. DSFS and SmartSensor Position at EB I-94 - Friday Road

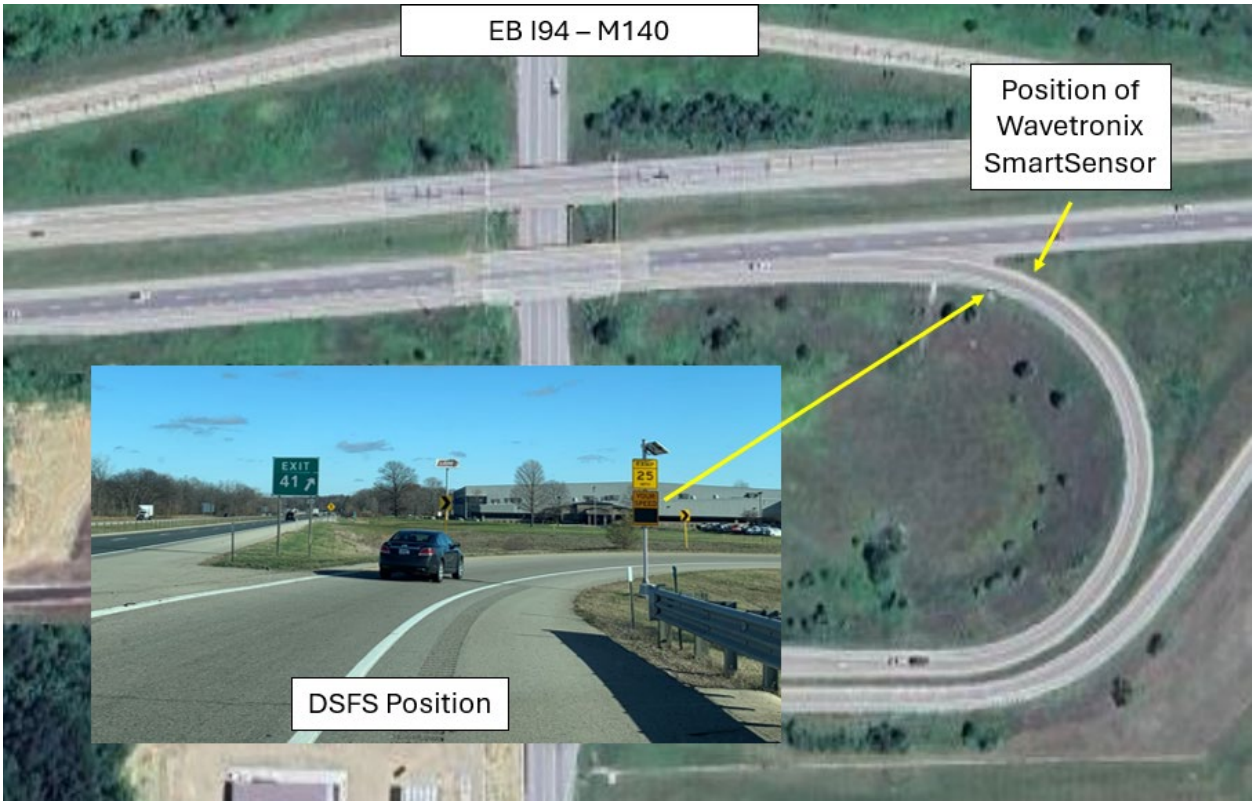


Figure 12. DSFS and SmartSensor Position at EB I-94 – M-140

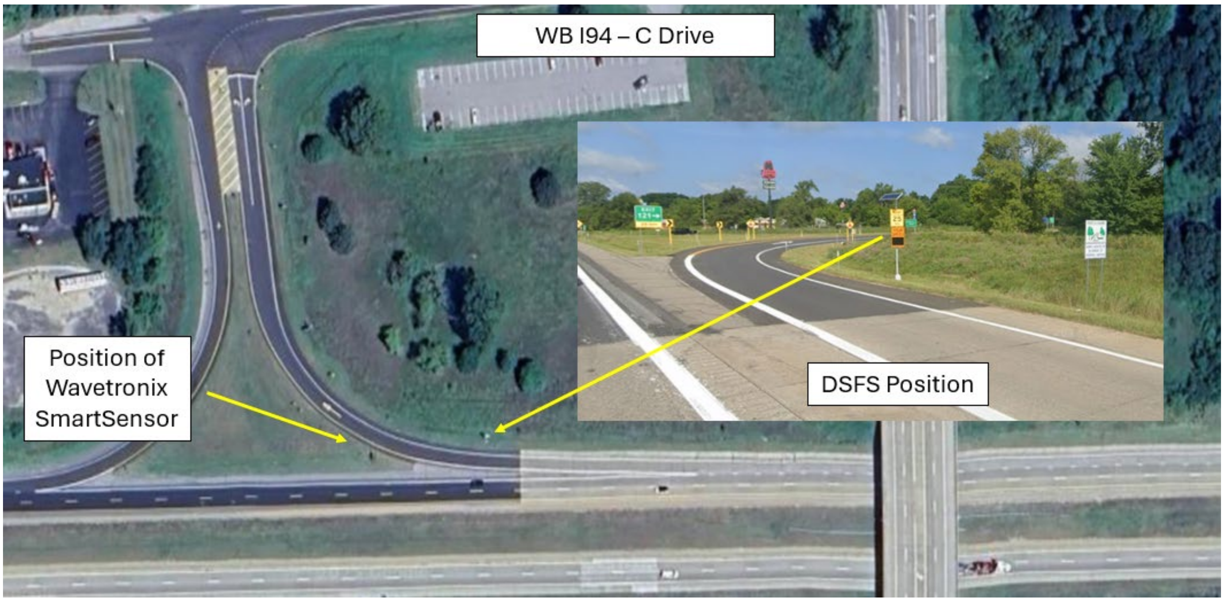


Figure 13. DSFS and SmartSensor Position at WB I-94 - C Drive

### 4.1.2 Data Collection

Vehicle speed data were collected for vehicles exiting the freeway using a trailer-mounted Wavetronix SmartSensor HD, which was positioned on the shoulder of the ramp between 50 and 150 feet downstream of the DSFS. The speed data collection trailer was positioned in the same location during each data collection period at a given site. The SmartSensor was programmed to bin the data into 15-minute intervals and included data for average speed, total volume, detection zone occupancy, headway, gap, date, and time. The sensor also categorized vehicles into predefined classes based on their length. Separate datasets were created for daytime and nighttime by categorizing the data based on sunrise and sunset times. Data collected 30 minutes prior to sunrise and 30 minutes after sunset were removed due to changing light conditions during dawn and dusk.

The average speed data, as well as the daytime and nighttime average speed data for each site, were analyzed and plotted to identify patterns or trends. To further evaluate driver response to the DSFS, a linear regression model was developed using the combined dataset from all sites, providing insights into the effectiveness of the DSFS as a speed reduction countermeasure across various time periods and locations. Though the sensor provided volume data for each class, based on length ranges (C1-10ft, C2-25ft, C3-50ft, C4-60ft, C5-85ft, C6-110, C7-120), the volume data were aggregated into broader vehicle length categories (up to 25 ft, 25-50 ft, and 51-120 ft) for the analysis to represent passenger vehicles, single unit trucks, and semi-trailers, respectively. Note: due to the binning of the data into 15-minute intervals, it was not possible to isolate the speeds of each of the different vehicle length categories. The data collection periods, installation periods, and sample sizes for each location are shown in **Table 3**.

**Table 3. I-94 Exit Ramp Site Information for Evaluation of DSFS**

| Site No. | Site | Freeway Speed Limit/Ramp Advisory Speed (mph) | Pre-Installation Data Collection | DSFS Installation Month, Year | Post-Installation Data Collection | Number of 15-minute Speed Bins (Pre-DSFS) | Number of 15-minute Speed Bins (Post-DSFS) |
|---|---|---|---|---|---|---|---|
| 1 | WB I-94 - Sawyer Road | 70/25 | 8/23 - 8/25, 2022 | April, 2024 | 7/30 - 8/1, 2024 | 177 | 183 |
| 2 | EB I-94 - Sawyer Road | 70/25 | 8/18 - 8/23, 2022 | April, 2024 | 8/1 - 8/6, 2024 | 456 | 462 |
| 3 | EB I-94 - Friday Road | 70/25 | 8/25 - 8/30, 2022 | February, 2023 | 8/8 - 8/13, 2024 | 460 | 462 |
| 4 | EB I-94 - M-140 | 70/25 | 8/30 - 9/1, 2022 | May, 2024 | 8/6 - 8/8, 2024 | 184 | 153 |
| 5 | WB I-94 - C-Drive | 70/25 | 9/13 - 9/15, 2022 | April, 2024 | 8/27 - 8/29, 2024 | 182 | 184 |

### 4.1.3 DSFS Messaging Conditions

The DSFS displayed different messages based on the measured speed of exiting vehicles as they approached the DSFS, which included:

- Blank Display for vehicles traveling below 25 mph
- Speed Digits for vehicles traveling between 25 and 35 mph.
- Speed Digits alternating with “SLOW DOWN” for vehicles traveling above 35 mph (i.e., 10 mph over the ramp advisory speed).

### 4.1.4 Data Summaries for Ramp Curve Speeds by Site

Descriptive statistics (minimum, maximum, mean, and standard deviation) for the binned speed data collected at each exit ramp curve are presented before and after installation of the DSFS for each location in **Table 4** (overall) and **Table 5** (daytime and nighttime). The means of the binned speed data are displayed for each location and data collection period in **Figure 14** (overall), **Figure 15** (daytime), and **Figure 16** (nighttime). Overall mean speeds in the ramp curves were found to decrease at four of the five exit ramp locations after the DSFS was installed, with speed reductions ranging from 0.41 to 1.13 mph. EB I-94 at Friday Road was the lone exception, which saw a 0.3 mph increase in the overall mean speed. Furthermore, the standard deviation of speed was also found to decrease at four of the five sites after the DSFS was installed, suggesting greater uniformity in the speed of vehicles shortly after entry to the exit ramp curve.

**Table 4. Descriptive Statistics for Overall Speeds in the Ramp Curve, by Site**

| Site | DSFS Condition | Min (mph) | Max (mph) | Mean (mph) | Std. Dev. (mph) |
|---|---|---|---|---|---|
| WB I-94 Sawyer Road | without DSFS | 22.45 | 45.53 | 35.96 | 3.60 |
| | with DSFS | 19.90 | 41.60 | 35.01 | 3.26 |
| EB I-94 Sawyer Road | without DSFS | 22.84 | 42.50 | 34.53 | 3.13 |
| | with DSFS | 21.80 | 39.30 | 33.40 | 2.89 |
| EB I-94 Friday Road | without DSFS | 24.00 | 44.10 | 36.60 | 2.29 |
| | with DSFS | 28.20 | 44.60 | 36.93 | 1.94 |
| EB I-94 M-140 | without DSFS | 28.83 | 45.70 | 39.94 | 2.71 |
| | with DSFS | 31.60 | 43.10 | 39.20 | 1.82 |
| WB I-94 C-Drive | without DSFS | 32.03 | 45.10 | 39.77 | 2.22 |
| | with DSFS | 29.20 | 46.60 | 39.36 | 2.78 |

**Table 5. Descriptive Statistics for Daytime and Nighttime Speeds in the Ramp Curve, by Site**

| Site | DSFS Condition | Mean Speed (mph) | |
|---|---|---|---|
| | | *Daytime* | *Nighttime* |
| WB I-94 Sawyer Road | without DSFS | 37.48 | 34.44 |
| | with DSFS | 36.38 | 33.23 |
| EB I-94 Sawyer Road | without DSFS | 36.75 | 32.20 |
| | with DSFS | 35.09 | 31.37 |
| EB I-94 Friday Road | without DSFS | 37.50 | 35.70 |
| | with DSFS | 37.57 | 36.16 |
| EB I-94 M-140 | without DSFS | 41.47 | 38.37 |
| | with DSFS | 40.02 | 38.16 |
| WB I-94 C-Drive | without DSFS | 40.27 | 39.34 |
| | with DSFS | 40.17 | 38.49 |

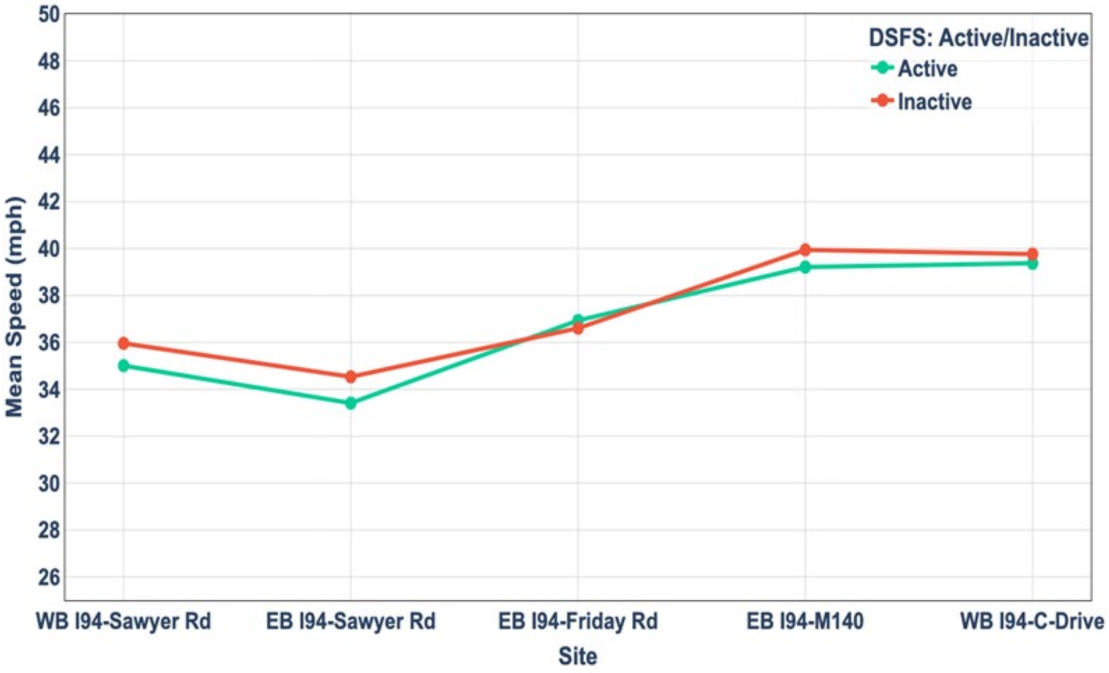


**Figure 14. Overall Mean Speeds at I-94 Exit Ramps**

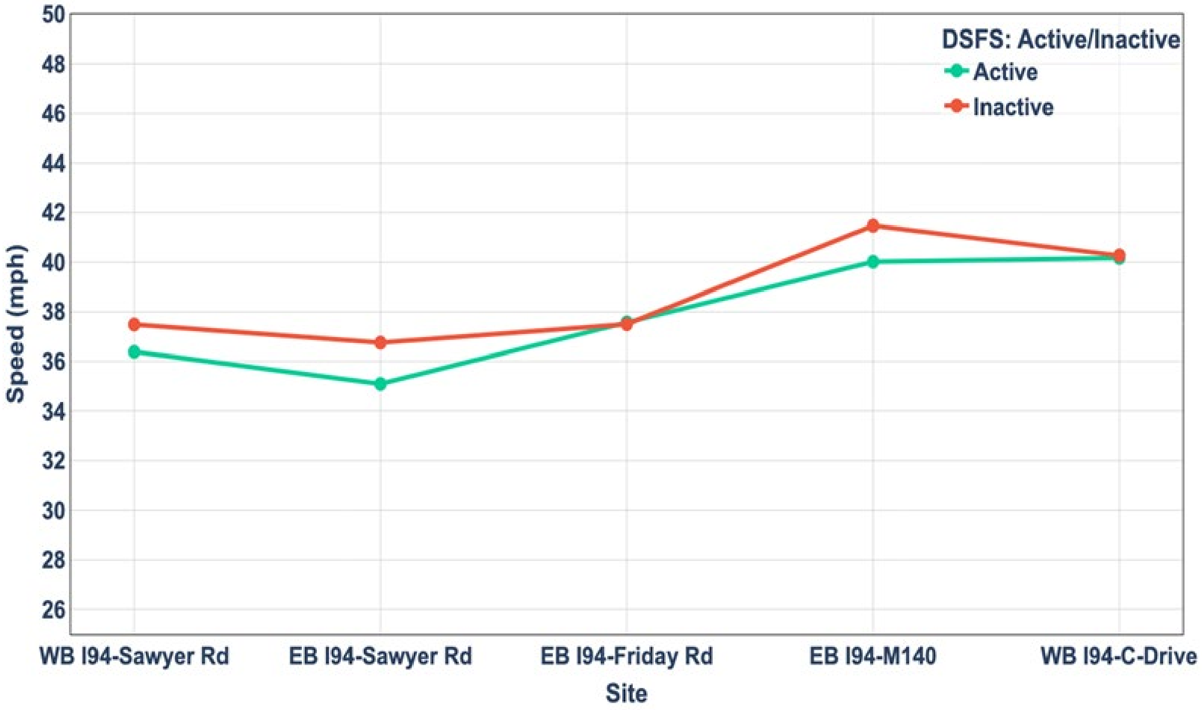


Figure 15. Daytime Mean Speeds at I-94 Exit Ramps

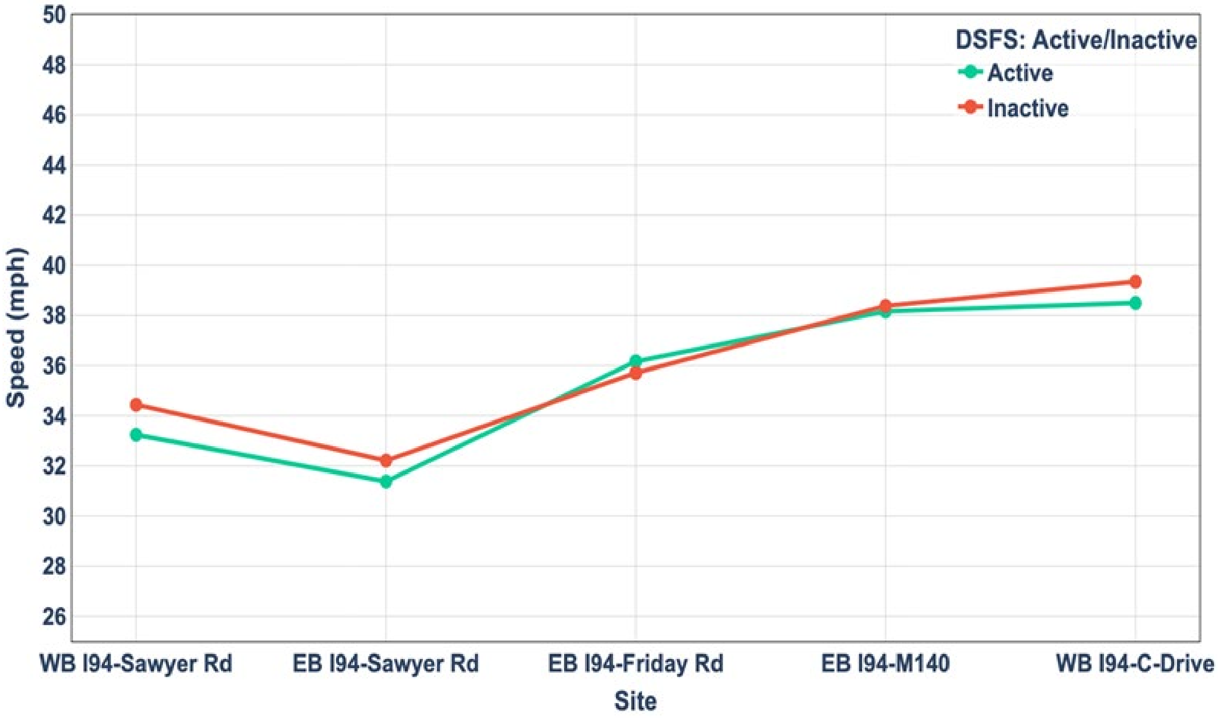


Figure 16. Nighttime Mean Speeds at I-94 Exit Ramps

### 4.1.5 Results for Ramp Curve Speeds by Site, Time of Day, and DSFS Presence

Linear regression models were developed to analyze the relationship between vehicle speed (dependent variable) and multiple explanatory factors (independent variables), including DSFS presence, site, and truck volume as a proportion of the total volume. The models were structured such that the effect of DSFS presence could be assessed on a site-by-site basis while controlling for the proportion of trucks within the aggregated speed data, which as noted previously, had been binned into 15-minute increments. Two separate truck-related variables were utilized, including: 1.) the proportion of vehicles with lengths between 25 and 50 ft and 2.) the proportion of vehicles with lengths greater than 50 ft. The former group would likely include single-unit trucks and passenger vehicles towing trailers, while the latter group would likely mostly include tractor-trailer trucks. Separate models were generated for nighttime and daytime data, the results of which are presented in **Table 6**.

**Table 6. Linear Regression Model for Curve Speed at I-94 Exit Ramps**

| Model | Variable | Coefficient | Std. Error | p-value |
|---|---|---|---|---|
| Daytime | Intercept | 38.461 | 0.111 | 0.000 |
| | Site 1 | 1.822 | 0.136 | <0.001 |
| | Site 3 | -0.219 | 0.123 | 0.074 |
| | Site 4 | 3.764 | 0.131 | <0.001 |
| | Site 5 | 3.170 | 0.142 | <0.001 |
| | Site 1 – DSFS Present | -1.587 | 0.152 | <0.001 |
| | Site 2 – DSFS Present | -1.966 | 0.097 | <0.001 |
| | Site 3 – DSFS Present | -0.018 | 0.095 | 0.853 |
| | Site 4 – DSFS Present | -1.541 | 0.154 | <0.001 |
| | Site 5 – DSFS Present | 0.040 | 0.171 | 0.813 |
| | Proportion of Vehicles 25 to 50 ft | -0.750 | 0.282 | 0.008 |
| | Proportion of Vehicles Longer than 50 ft | -10.161 | 0.363 | <0.001 |
| Nighttime | Intercept | 35.973 | 0.232 | 0.000 |
| | Site 1 | 2.364 | 0.293 | <0.001 |
| | Site 3 | 1.272 | 0.239 | <0.001 |
| | Site 4 | 3.428 | 0.308 | <0.001 |
| | Site 5 | 4.786 | 0.295 | <0.001 |
| | Site 1 – DSFS Present | -1.795 | 0.360 | <0.001 |
| | Site 2 – DSFS Present | -1.364 | 0.228 | <0.001 |
| | Site 3 – DSFS Present | -0.006 | 0.223 | 0.979 |
| | Site 4 – DSFS Present | -0.603 | 0.376 | 0.109 |
| | Site 5 – DSFS Present | -0.240 | 0.347 | 0.489 |
| | Proportion of Vehicles 25 to 50 ft | -0.860 | 0.312 | 0.006 |
| | Proportion of Vehicles Longer than 50 ft | -9.292 | 0.328 | <0.001 |

Note: Site 2 was selected as the baseline condition and excluded from the model due to it possessing the lowest overall speeds.

Considering the effects of the DSFS during daytime conditions, **Table 6** shows significant decreases in the mean speeds after installation of the DSFS at the two Sawyer Road exit ramps (Sites 1 and 2) along with the M140 exit ramp (Site 4). The decrease in daytime speed after installation of the DSFS at these three exit ramp curves ranged from 1.54 to 1.97 mph. No significant changes in daytime speeds were observed at either the Friday Road (Site 3) or C-Drive

(Site 5) exit ramps. Turning to the effects of the DSFS at nighttime, **Table 6** shows that significant speed reductions were again observed after installation of the DSFS at the two Sawyer Road exit ramps (Sites 1 and 2), which ranged from 1.36 mph to 1.80 mph, while a smaller and marginally significant speed reduction of 0.60 mph was observed at the M140 exit ramp (Site 4). Again, no significant changes in nighttime speeds were observed at either the Friday Road (Site 3) or C-Drive (Site 5) exit ramps. Comparison of the daytime vs. nighttime parameter estimates suggests that the DSFS had a greater effect during daytime conditions at the three sites where statistically significant speed reductions were observed after installation of the DSFS. Nevertheless, a comparison of the intercept terms in the regression models suggests that speeds overall were approximately 2.5 mph lower at night than during the day.

The parameter estimates for the two variables related to heavy vehicle proportions suggest that the proportion of vehicles 25-50 ft in length has a somewhat modest, yet statistically significant effect on daytime and nighttime speeds. However, the proportion of vehicles 50 ft and longer has a much larger effect on speeds during both day and night. The negative sign on each of the two parameter estimates indicates an inverse relationship between speed and the proportion of longer vehicles; in other words, the speeds in the ramp curve decrease as the proportion of longer vehicles increases. These results are not surprising, as heavy vehicles, particularly tractor trailer trucks possess a much greater roll-over risk than passenger vehicles at sharp horizontal curves, leading to a greater need for speed reduction in order to safely navigate the curve.

The differences in the DSFS effectiveness between the five exit ramp locations included here may likely have been due to the configuration of the interchanges. As each of the five exit ramps consisted of a ramp that departed from the freeway beyond the overpass or underpass (e.g., a “B” ramp configuration), the visibility of the warning signage, particularly to the DSFS positioned on the right side of the ramp, is greatly influenced by whether the freeway passed over or under the crossroad. Consider that the three exit ramps that experienced significant speed reductions after DSFS installation (Sites 1, 2, and 4) were located at interchanges where the freeway passes over the crossroad. At each of these sites, the exit ramp curve and associated warning signage are clearly visible for a considerable distance leading up to the curve. In contrast, the two sites that did not experience speed reductions (Sites 3 and 5) were at locations where the freeway passed under the crossroad, where the bridge abutment limited the sight distance to the ramp curve and associated warning signage. This was particularly true at EB I-94 and Friday Road, where the relatively short distance between the bridge abutment and the DSFS coupled with the ramp geometry significantly limited the sight distance to the DSFS. Collectively, these results suggest that the DSFS is an effective speed reduction treatment at loop exit ramps, as long an adequate line-of-sight to the DSFS exists along the ramp, including ramps departing a freeway that passes over the crossroad. At exit ramp locations where an adequate line-of-sight cannot be provided to signage mounted on the right side of the ramp, other countermeasures, such as flashing LED chevrons, may serve as an adequate alternative to a DSFS due to their positioning along the outside of the curve.

## 4.2 DSFS at Mainline Freeway Curves

A field study was conducted at two mainline freeway sites to evaluate the effects of a DSFS as a speed reduction strategy at horizontal curves with advisory speeds lower than the speed limit.

### 4.2.1 Site Descriptions

Both test sites were located on southbound US-127 near Mt Pleasant, Michigan and possessed speed limits of 75 mph. Both sites possessed dual curve warning signs (W1-2) and advisory speed plaques (W13-1p) along with four chevrons within each curve. Site 1 (north site) was located near mile marker 143 and had a curve advisory speed of 65 mph, which was posted beneath the curve warning signs located on both sides of the highway 400 ft upstream of the curve. Site 2 (south site) was located near mile marker 139 and had a curve advisory speed of 70 mph, which was posted beneath the curve warning signs located on both sides of the highway 350 ft upstream of the curve. Both locations are shown in **Figure 17**.

### 4.2.2 DSFS Test Conditions and Data Collection Procedures

The DSFS was temporarily installed on the right side of the highway 300 ft upstream of the point of curvature (100 ft downstream of the curve warning sign) at Site 1 and 250 ft upstream of the point of curvature (100 ft downstream of the curve warning sign) at Site 2. The DSFS installation locations align with the positioning requirements for DSFS at horizontal curves found in the 11th edition MUTCD. At Site 1, two different DSFS messaging strategies were tested and compared to the base condition, which was the existing condition at the site prior to installation of the DSFS. The DSFS messaging conditions tested at Site 1 are listed as follows:

1. Baseline Condition: No DSFS
2. DSFS Message 1: Speed digits for all vehicles
3. DSFS Message 2: Speed digits + “SLOW DOWN” for speeds > 75 mph (10 mph above the advisory speed); speed digits for speeds < 75 mph.

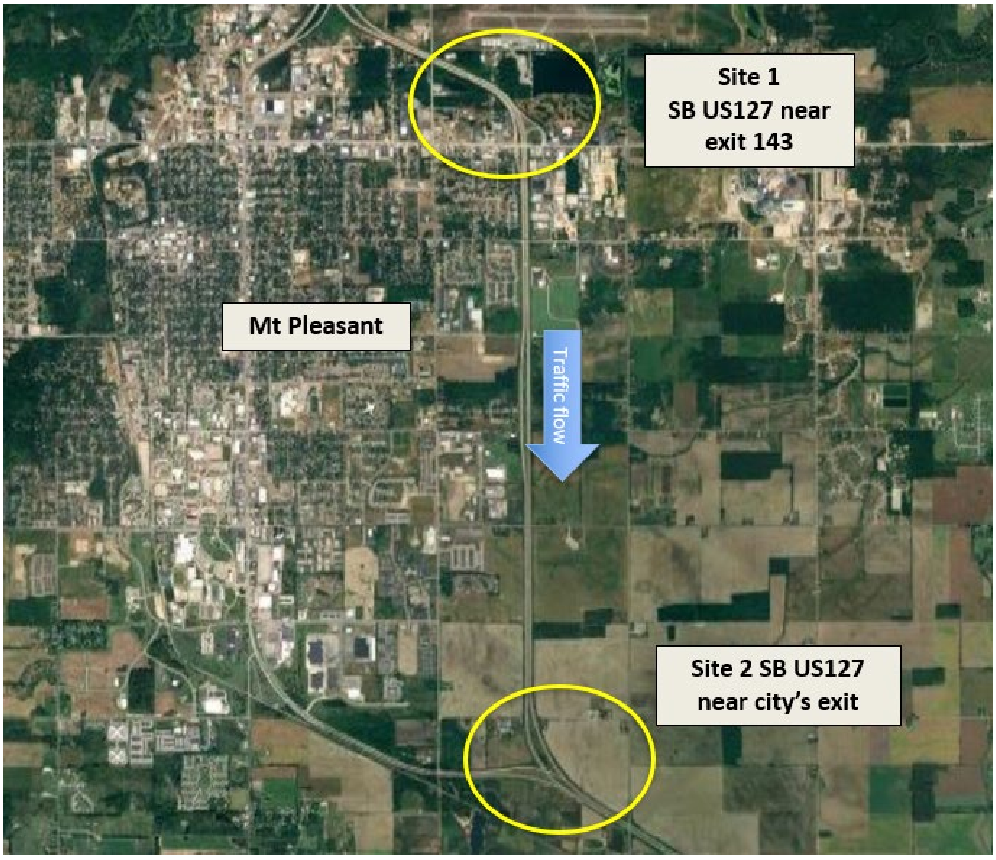


**Figure 17. Location of Freeway Mainline Horizontal Curves for DSFS Testing on SB US-127, Mt Pleasant**

At Site 2 the same message strategies were tested, but since the advisory speed for the curve was higher than at Site 1, the speed threshold for alternating speed digits with "SLOW DOWN" was raised to 80 mph (10 mph above the advisory speed). The DSFS messaging conditions tested at Site 2 are listed as follows:

1. Baseline Condition: No DSFS
2. DSFS Message 1: Speed digits for all vehicles
3. DSFS Message 2: Speed digits + "SLOW DOWN" for speeds > 80 mph (10 mph above the advisory speed); speed digits for speeds < 80 mph.

Speed data were collected on weekdays in September 2024 using a handheld LIDAR gun based on the procedure described in **Section 3.4**. The LIDAR technician was positioned within a vehicle parked on the roadside that was 1,300 ft upstream of the point of curvature for Site 1 and 1,350 ft upstream of the point of curvature for Site 2. The LIDAR vehicle was positioned in identical locations during all data collection periods. Speeds were first collected during the baseline condition (i.e., prior to DSFS installation), after which, the DSFS was installed and programmed to display the speed digits. The DSFS was installed and activated for a minimum of 5 days prior to collecting data for either of the DSFS messaging conditions. Data were collected for the two DSFS message conditions on the same day. After completion of the data collection at Site 1, the DSFS was then moved to Site 2 and the data collection process was repeated. The field evaluation layout and sign test conditions are displayed in **Figure 18** and **Figure 19** for Site 1 and Site 2, respectively. Examples of DSFS display messages at Site 1 and Site 2 are shown in **Figure 20** and **Figure 21**, respectively.

**Figure 18. Field Evaluation Layout and Sign Test Conditions at Freeway Curve Site 1**

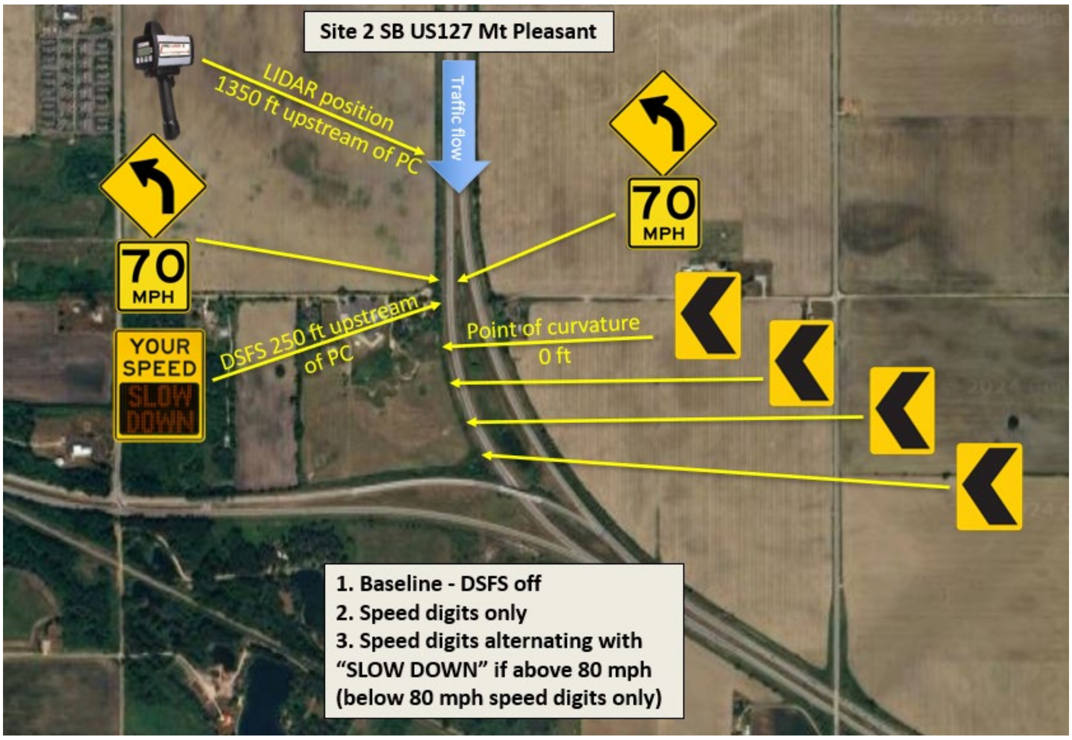


Figure 19. Field Evaluation Layout and Sign Test Conditions at Freeway Curve Site 2

Figure 20. Example DSFS Message Display at Freeway Mainline Curve Site 1

Figure 21. Example DSFS Message Display at Freeway Mainline Curve Site 2

### 4.2.3 Results – Speed Reduction Effect of DSFS at Freeway Mainline Curve Site 1

The datasets were prepared for analysis by first splitting the data by type of vehicle (passenger vehicle and heavy vehicle). The data were further split by speed at 400 ft upstream of DSFS (detection range for DSFS). If the vehicle's speed at 400 ft upstream of DSFS was below 75 mph, in all cases the DSFS would only display speed digits. However, for speeds above 75 mph, the DSFS would display either speed digits only or speed digits alternating with a "SLOW DOWN" message, depending on the programming for that particular data collection period. This split enabled comparison between the various message strategies. Descriptive statistics for speeds below 75 mph are displayed in **Table 7** for passenger vehicles and heavy vehicles. **Table 8** displays the descriptive statistics for approach speeds above 75 mph, which only included passenger vehicles.

**Table 7. Descriptive Statistics for Approach Speeds < 75 mph at Freeway Curve Site 1**

| Data Collection Location | Sign Test Condition | Passenger Vehicles (n=241) | | | Heavy Vehicles (n=85) | | |
|---|---|---|---|---|---|---|---|
| | | Mean (mph) | 85th %tile speed (mph) | Std. Dev. (mph) | Mean (mph) | 85th %tile speed (mph) | Std. Dev. (mph) |
| 250 ft upstream of curve warning sign | Baseline: No DSFS | 69.54 | 73.17 | 4.00 | 65.36 | 68.41 | 3.36 |
| | Speed digits | 68.32 | 74.00 | 4.81 | 64.25 | 67.65 | 3.76 |
| At curve warning sign | Baseline: No DSFS | 68.79 | 73.00 | 4.61 | 65.20 | 68.85 | 3.47 |
| | Speed digits | 67.21 | 73.00 | 5.04 | 63.86 | 67.65 | 3.68 |
| 100 ft downstream of curve warning sign (at DSFS) | Baseline: No DSFS | 68.30 | 73.00 | 4.86 | 65.13 | 68.15 | 3.65 |
| | Speed digits | 66.55 | 72.00 | 5.22 | 63.66 | 67.65 | 3.66 |
| 250 ft downstream of curve warning sign | Baseline: No DSFS | 67.58 | 73.00 | 5.36 | 64.75 | 68.00 | 3.94 |
| | Speed digits | 65.67 | 71.32 | 5.52 | 63.42 | 67.00 | 3.60 |
| 500 ft downstream of curve warning sign (100 ft after first chevron) | Baseline: No DSFS | 65.96 | 72.00 | 6.28 | 63.84 | 68.00 | 4.41 |
| | Speed digits | 64.21 | 70.69 | 6.26 | 62.73 | 66.62 | 3.69 |

**Table 8. Descriptive Statistics for Approach Speeds > 75 mph at Freeway Curve Site 1**

| Data Collection Location | Sign Test Condition | Passenger Vehicles | | |
|---|---|---|---|---|
| | | Mean (mph) | 85th %tile speed (mph) | Std. Dev. (mph) |
| 250 ft upstream of curve warning sign | Baseline: No DSFS (n=29) | 78.20 | 80.50 | 1.90 |
| | Speed digits (n=25) | 78.86 | 82.00 | 2.76 |
| | Alternating speed digits / ”SLOW DOWN” (n=21) | 78.37 | 81.00 | 1.87 |
| At curve warning sign | Baseline: No DSFS (n=29) | 77.84 | 80.50 | 2.28 |
| | Speed digits (n=25) | 78.00 | 82.00 | 3.53 |
| | Alternating speed digits / ”SLOW DOWN” (n=21) | 78.05 | 81.00 | 2.20 |
| 100 ft downstream of curve warning sign (at DSFS) | Baseline: No DSFS (n=29) | 77.69 | 80.50 | 2.52 |
| | Speed digits (n=25) | 77.47 | 82.00 | 4.04 |
| | Alternating speed digits / ”SLOW DOWN” (n=21) | 77.90 | 81.00 | 2.64 |
| 250 ft downstream of curve warning sign | Baseline: No DSFS (n=29) | 77.09 | 80.50 | 3.08 |
| | Speed digits (n=25) | 76.49 | 82.00 | 5.05 |
| | Alternating speed digits / ”SLOW DOWN” (n=21) | 77.33 | 80.96 | 3.26 |
| 500 ft downstream of curve warning sign (100 ft after first chevron) | Baseline: No DSFS (n=29) | 75.73 | 79.76 | 3.78 |
| | Speed digits (n=25) | 75.33 | 80.98 | 5.64 |
| | Alternating speed digits / ”SLOW DOWN” (n=21) | 76.70 | 80.27 | 3.54 |

Prior to analysis, the speeds measured at each 50 ft increment approaching the curve were subtracted from the speed measured at the furthest upstream point, which was 500 ft upstream of the curve warning sign. Doing so converted the raw speed data into speed reduction values and controlled for the normal speeding behavior of each driver prior to encountering the DSFS. This also allowed the regression parameters to be directly interpreted as speed reduction effects (e.g., the DSFS regression parameter would represent the speed reduction effect of the particular DSFS test condition compared to the base condition). Graphical representations of the average speed reduction trajectories for the various DSFS test conditions at Site 1 are displayed in **Figure 22** (for passenger vehicles approaching below 75 mph), **Figure 23** (for all heavy vehicles), and **Figure 24** (for passenger vehicles approaching above 75 mph). The linear regression model results for passenger and heavy vehicles approaching the DSFS below 75 mph are presented in **Table 9**. **Table 10** presents the regression results for passenger vehicles approaching the DSFS above 75 mph.

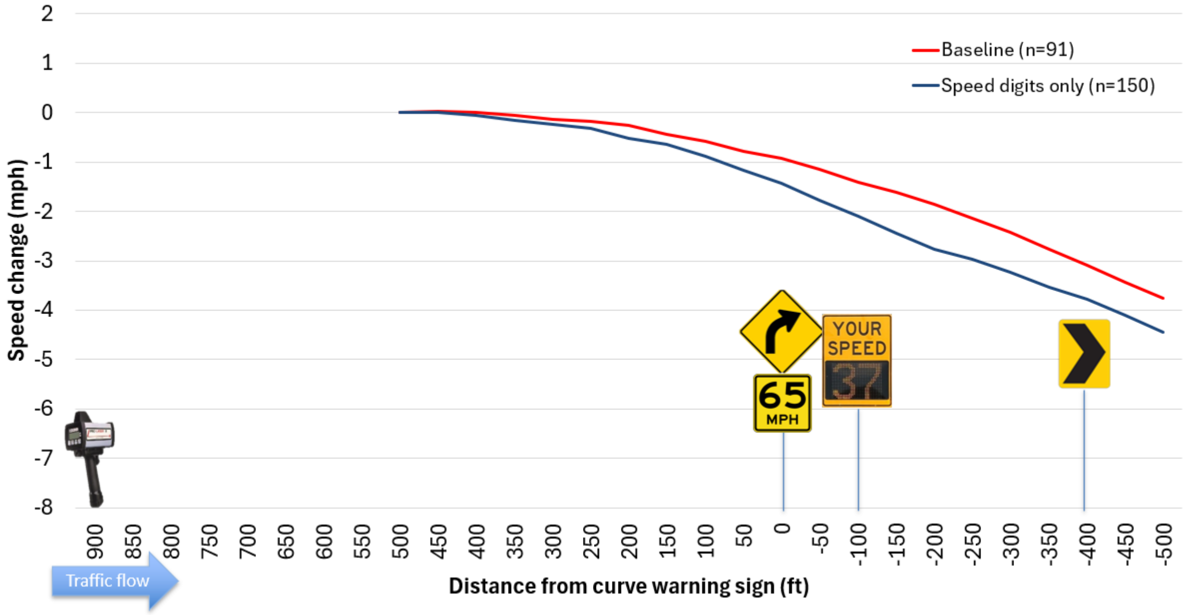


Figure 22. Average Speed Change Trajectories at Freeway Curve Site 1 – Passenger Vehicles < 75 mph

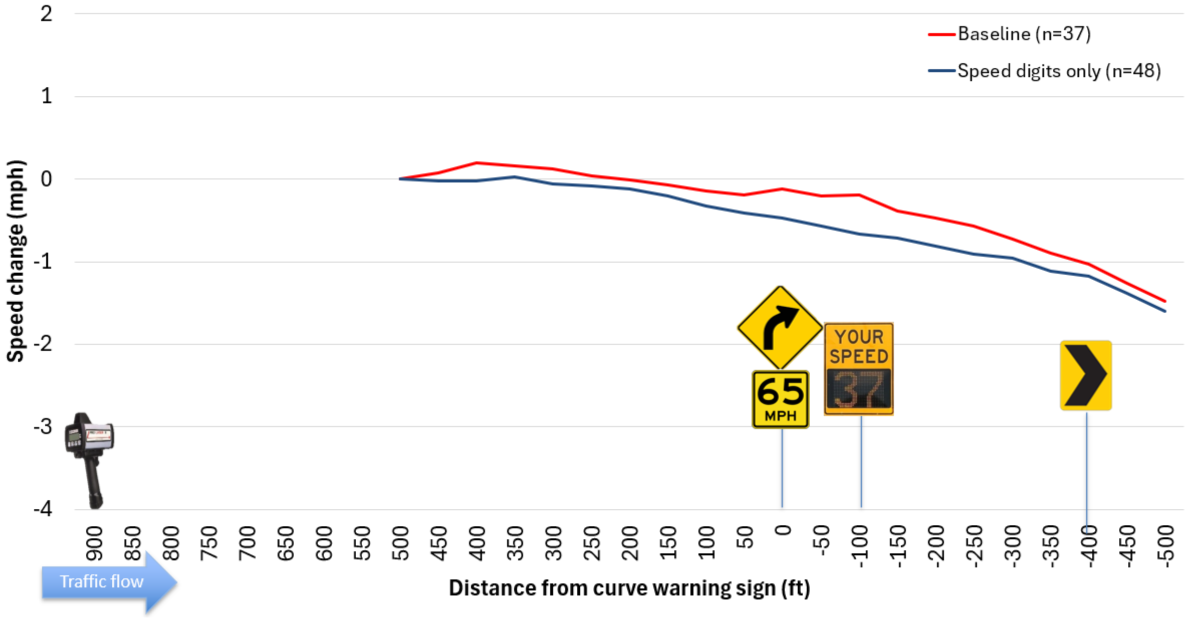


Figure 23. Average Speed Change Trajectories at Freeway Curve Site 1 – Heavy Vehicles

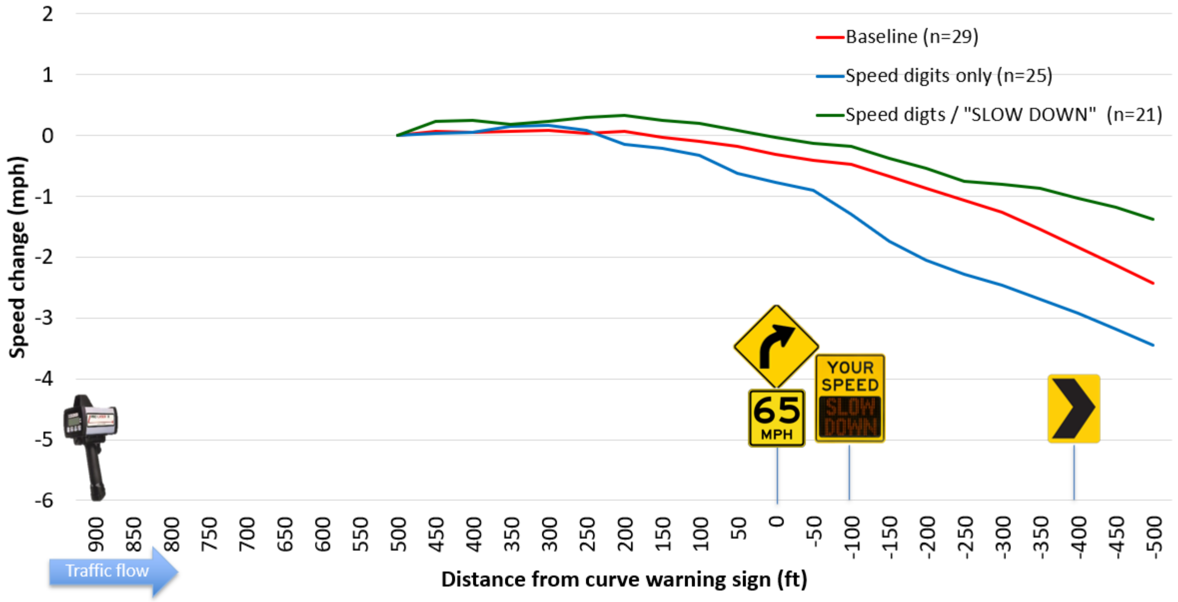


Figure 24. Average Speed Change Trajectories at Freeway Curve Site 1 – Passenger Vehicles > 75 mph

Table 9. Linear Regression Model for Speed Reduction for Vehicles < 75 mph, Freeway Curve Site 1

| Parameters | Passenger Vehicles | | | Heavy Vehicles | | |
|---|---|---|---|---|---|---|
| | **Estimate** | **Std. Error** | **p-Value** | **Estimate** | **Std. Error** | **p-Value** |
| **Speed at 250 ft upstream of curve warning sign** | | | | | | |
| Intercept | -0.172 | 0.107 | 0.108 | 0.042 | 0.107 | 0.692 |
| No DSFS | *Baseline* | | | *Baseline* | | |
| Speed digits | -0.151 | 0.135 | 0.265 | -0.122 | 0.142 | 0.392 |
| **Speed at curve warning sign** | | | | | | |
| Intercept | -0.926 | 0.190 | <0.001 | -0.123 | 0.186 | 0.508 |
| No DSFS | *Baseline* | | | *Baseline* | | |
| Speed digits | -0.502 | 0.241 | 0.039 | -0.351 | 0.247 | 0.159 |
| **Speed at 100 ft downstream of curve warning sign (at DSFS)** | | | | | | |
| Intercept | -1.419 | 0.235 | <0.001 | -0.190 | 0.232 | 0.415 |
| No DSFS | *Baseline* | | | *Baseline* | | |
| Speed digits | -0.677 | 0.298 | 0.024 | -0.477 | 0.309 | 0.126 |
| **Speed at 250 ft downstream of curve warning sign** | | | | | | |
| Intercept | -2.135 | 0.309 | <0.001 | -0.570 | 0.293 | 0.055 |
| No DSFS | *Baseline* | | | *Baseline* | | |
| Speed digits | -0.835 | 0.392 | 0.034 | -0.342 | 0.390 | 0.383 |
| **Speed at 500 ft downstream of curve warning sign (100 ft beyond initial chevron)** | | | | | | |
| Intercept | -3.759 | 0.435 | <0.001 | -1.478 | 0.401 | <0.001 |
| No DSFS | *Baseline* | | | *Baseline* | | |
| Speed digits | -0.679 | 0.551 | 0.220 | -0.125 | 0.533 | 0.815 |

The linear regression model results presented in **Table 9** suggest that the DSFS displaying speed digits had a statistically significant effect on drivers of passenger vehicles approaching the curve below 75 mph, with a maximum speed reduction of 0.84 mph 250 ft downstream of the curve warning sign, which is 150 ft downstream of the DSFS and 150 ft upstream of the point of curvature. For heavy vehicles, the speed reduction effect of the DSFS was small, reaching a maximum of 0.47 mph at the DSFS position (100 ft downstream of the curve warning sign), although this reduction was not statistically significant.

**Table 10. Linear Regression Model for Speed Reduction for Vehicles > 75 mph, Freeway Curve Site 1**

| Parameters | Estimate | Std. Error | p-Value |
|---|---|---|---|
| **Speed at 250 ft upstream of the curve warning sign** | | | |
| Intercept | 0.041 | 0.138 | 0.767 |
| No DSFS | *Baseline* | | |
| Speed digits | 0.050 | 0.203 | 0.805 |
| Alternating speed digits / ”SLOW DOWN” | 0.249 | 0.213 | 0.246 |
| **Speed at the curve warning sign** | | | |
| Intercept | -0.318 | 0.290 | 0.275 |
| No DSFS | *Baseline* | | |
| Speed digits | -0.449 | 0.426 | 0.296 |
| Alternating speed digits / ”SLOW DOWN” | 0.286 | 0.447 | 0.525 |
| **Speed at 100 ft downstream of the curve warning sign (at DSFS)** | | | |
| Intercept | -0.471 | 0.360 | 0.195 |
| No DSFS | *Baseline* | | |
| Speed digits | -0.830 | 0.529 | 0.121 |
| Alternating speed digits / ”SLOW DOWN” | 0.289 | 0.555 | 0.604 |
| **Speed at 250 ft downstream of the curve warning sign** | | | |
| Intercept | -1.066 | 0.500 | 0.036 |
| No DSFS | *Baseline* | | |
| Speed digits | -1.220 | 0.735 | 0.101 |
| Alternating speed digits / ”SLOW DOWN” | 0.314 | 0.771 | 0.686 |
| **Speed at 500 ft downstream of the curve warning sign (100 ft beyond the initial chevron)** | | | |
| Intercept | -2.431 | 0.620 | >0.001 |
| No DSFS | *Baseline* | | |
| Speed digits | -1.013 | 0.911 | 0.270 |
| Alternating speed digits / ”SLOW DOWN” | 1.048 | 0.957 | 0.277 |

The linear regression results for drivers approaching the curve at greater than 75 mph presented in **Table 10,** showed stronger speed reduction effects for the DSFS than for the slower driver group, but only for cases where the speed digits were displayed. The strongest DSFS effect for drivers approaching above 75 mph was observed 250 ft downstream of the curve warning sign, which is 150 ft downstream of the DSFS and 150 ft upstream of the point of curvature. At this location, speeds were 1.22 mph lower with the DSFS displaying the speed digits compared to the baseline condition, and this result was statistically significant at a 90 percent level of confidence. Furthermore, the DSFS display of speed digits alternating with "SLOW DOWN" did not have a statistically significant effect on driver speed compared to the base condition. This may have occurred due to drivers traveling too fast to interpret the DSFS message, which alternated at a frequency of 1 Hz. Furthermore, it is to be noted that the 15-inch DSFS display was used during the study, which could possibly be too small for drivers to interpret at speeds above 75 mph.

A subsequent series of analyses were performed using binary logistic regression to assess the likelihood of drivers exceeding the advisory speed at the point of curvature based on the DSFS message display. This analysis was performed separately for drivers approaching below 75 mph (**Table 11**) and drivers approaching above 75 mph (**Table 12**).

**Table 11. Binary Logistic Regression Model for Likelihood of Exceeding the Advisory Speed at Mainline Freeway Curve Site 1 (Approach Speed < 75 mph)**

| | Parameters | Estimate | Std. Error | p-Value | Exp(B) |
|---|---|---|---|---|---|
| Over advisory speed (65 mph) | Intercept | -36.306 | 5.686 | >0.001 | 0.000 |
| | Speed 500 ft upstream of curve warning sign | 0.532 | 0.082 | >0.001 | 1.703 |
| | No DSFS | *Baseline* | | | |
| | Speed digits | -0.239 | 0.432 | 0.580 | 0.787 |
| 5 mph over advisory speed at the point of curvature | Intercept | -42.288 | 7.776 | >0.001 | 0.000 |
| | Speed 500 ft upstream of curve warning sign | 0.583 | 0.108 | >0.001 | 1.792 |
| | No DSFS | *Baseline* | | | |
| | Speed digits | -1.047 | 0.469 | 0.025 | 0.351 |
| 10 mph over advisory speed at the point of curvature | Intercept | -108.596 | 48.282 | 0.024 | 0.000 |
| | Speed 500 ft upstream of curve warning sign | 1.422 | 0.648 | 0.028 | 4.146 |
| | No DSFS | *Baseline* | | | |
| | Speed digits | -0.032 | 1.369 | 0.981 | 0.968 |

The results of the binary logistic regression model for drivers below 75 mph displayed in **Table 11** indicate that drivers approaching below 75 mph were 64.9 percent (1-Exp(β) = 1-0.351) less likely to exceed the advisory speed by more than 5 mph when the DSFS is displaying speed digits. This result was statistically significant at a 95 percent level of confidence.

**Table 12. Binary Logistic Regression Model for Likelihood of Exceeding the Advisory Speed at Mainline Freeway Curve Site 1 (Approach Speed > 75 mph)**

| | Parameters | Estimate | Std. Error | p-Value | Exp(B) |
|---|---|---|---|---|---|
| 5 mph over advisory speed at the point of curvature | Intercept | -133.176 | 46.790 | 0.004 | 0.000 |
| | Speed 500 ft upstream of curve warning sign | 1.762 | 0.613 | 0.004 | 5.822 |
| | No DSFS | *Baseline* | | | |
| | Speed digits | -0.652 | 1.017 | 0.522 | 0.521 |
| | Alternating speed digits / "SLOW DOWN" | 1.818 | 1.736 | 0.295 | 6.161 |
| 10 mph over advisory speed at the point of curvature | Intercept | -56.517 | 16.239 | 0.001 | 0.000 |
| | Speed 500 ft upstream of curve warning sign | 0.744 | 0.211 | >0.001 | 2.104 |
| | No DSFS | *Baseline* | | | |
| | Speed digits | -1.252 | 0.721 | 0.082 | 0.286 |
| | Alternating speed digits / "SLOW DOWN" | 0.088 | 0.748 | 0.907 | 1.092 |
| 15 mph over advisory speed at the point of curvature | Intercept | -105.658 | 28.336 | >0.001 | 0.000 |
| | Speed 500 ft upstream of curve warning sign | 1.306 | 0.353 | >0.001 | 3.690 |
| | No DSFS | *Baseline* | | | |
| | Speed digits | -0.773 | 1.151 | 0.501 | 0.461 |
| | Alternating speed digits / "SLOW DOWN" | 0.782 | 1.174 | 0.505 | 2.187 |

The results displayed in **Table 12,** suggest that when the speed digits are displayed on the DSFS, drivers approaching at greater than 75 mph are 71.4 percent (1-Exp (β) = 1-0.286) less likely to exceed the curve advisory speed by 10 mph at the point of curvature compared to the baseline condition without the DSFS. This result was statistically significant with a 90 percent level of confidence. When combined with the results from **Table 11** for the lower-speed group of drivers, these findings suggest that the DSFS displaying the speed digits is an effective measure towards reducing excessive speeds on the entry to freeway mainline curves.

### 4.2.4 Results – Speed Reduction Effect of DSFS at Freeway Mainline Curve Site 2

The datasets were prepared for analysis by first splitting the data by type of vehicle (passenger vehicle and heavy vehicle). The data were further split by speed at 400 ft upstream of DSFS (detection range for DSFS). If the vehicle's speed at 400 ft upstream of DSFS was below 80 mph, in all cases the DSFS would only display speed digits. However, for speeds above 80 mph, the DSFS would display either speed digits only or speed digits alternating with a "SLOW DOWN" message, depending on the programming for that particular data collection period. This split enabled comparison between the various message strategies. Descriptive statistics for speeds below 80 mph for passenger and heavy vehicles are displayed in **Table 13. Table 14** displays the descriptive statistics for approach speeds above 80 mph, which only included passenger vehicles.

### Table 13. Descriptive Statistics for Approach Speeds < 80 mph at Freeway Curve Site 2

| Data Collection Location | Sign Test Condition | Passenger Vehicles (n=240) | | | Heavy Vehicles (n=79) | | |
|---|---|---|---|---|---|---|---|
| | | Mean (mph) | 85th %tile speed (mph) | Std. Dev. (mph) | Mean (mph) | 85th %tile speed (mph) | Std. Dev. (mph) |
| 250 ft upstream of curve warning sign | Baseline: No DSFS | 74.79 | 79.00 | 3.87 | 65.19 | 68.59 | 3.39 |
| | Speed digits | 73.91 | 78.85 | 4.36 | 65.83 | 68.41 | 3.11 |
| At curve warning sign | Baseline: No DSFS | 74.65 | 79.00 | 3.95 | 65.24 | 68.95 | 3.32 |
| | Speed digits | 73.80 | 79.00 | 4.44 | 65.78 | 68.87 | 3.13 |
| 100 ft downstream of curve warning sign (at DSFS) | Baseline: No DSFS | 74.50 | 79.00 | 3.98 | 65.07 | 68.65 | 3.39 |
| | Speed digits | 73.66 | 78.58 | 4.47 | 65.75 | 68.16 | 3.13 |
| 250 ft downstream of curve warning sign | Baseline: No DSFS | 74.45 | 79.00 | 4.04 | 65.05 | 68.65 | 3.32 |
| | Speed digits | 73.55 | 78.00 | 4.51 | 65.69 | 68.00 | 3.08 |
| 500 ft downstream of curve warning sign (150 ft after first chevron) | Baseline: No DSFS | 74.22 | 79.00 | 4.08 | 64.79 | 68.00 | 3.31 |
| | Speed digits | 73.21 | 78.00 | 4.48 | 65.45 | 68.00 | 3.16 |

### Table 14. Descriptive Statistics for Approach Speeds > 80 mph at Freeway Curve Site 2

| Data Collection Location | Sign Test Condition | Passenger Vehicles | | |
|---|---|---|---|---|
| | | Mean (mph) | 85th %tile speed (mph) | Std. Dev. (mph) |
| 250 ft upstream of curve warning sign | Baseline: DSFS off (n=13) | 83.74 | 88.68 | 3.05 |
| | Speed digits (n=9) | 83.33 | 86.00 | 1.94 |
| | Alternating speed digits / ”SLOW DOWN” (n=12) | 82.85 | 85.15 | 1.99 |
| At curve warning sign | Baseline: DSFS off (n=13) | 83.73 | 87.90 | 2.98 |
| | Speed digits (n=9) | 83.22 | 86.00 | 1.99 |
| | Alternating speed digits / ”SLOW DOWN” (n=12) | 82.36 | 85.15 | 2.33 |
| 100 ft downstream of curve warning sign (at DSFS) | Baseline: DSFS off (n=13) | 83.74 | 87.90 | 3.11 |
| | Speed digits (n=9) | 83.33 | 86.00 | 1.94 |
| | Alternating speed digits / ”SLOW DOWN” (n=12) | 81.95 | 85.15 | 2.68 |
| 250 ft downstream of curve warning sign | Baseline: DSFS off (n=13) | 83.46 | 86.95 | 3.06 |
| | Speed digits (n=9) | 83.21 | 86.00 | 1.93 |
| | Alternating speed digits / ”SLOW DOWN” (n=12) | 81.55 | 85.15 | 3.14 |
| 500 ft downstream of curve warning sign (150 ft after first chevron) | Baseline: DSFS off (n=13) | 82.99 | 86.86 | 3.15 |
| | Speed digits (n=9) | 83.22 | 85.50 | 1.69 |
| | Alternating speed digits / ”SLOW DOWN” (n=12) | 80.73 | 84.02 | 2.69 |

Prior to analysis, the speeds measured at each 50 ft increment approaching the curve were subtracted from the speed measured at the furthest upstream point, which was 550 ft upstream of the curve warning sign. Doing so converted the raw speed data into speed reduction values and controlled for the normal speeding behavior of each driver prior to encountering the DSFS. This also allowed the regression parameters to be directly interpreted as speed reduction effects (e.g., the DSFS regression parameter would represent the speed reduction effect of the particular DSFS test condition compared to the base condition). Graphical representations of the average speed reduction trajectories for the DSFS test conditions at Site 2 are displayed in **Figure 25** (passenger vehicles below 80 mph), **Figure 26** (heavy vehicles), and **Figure 27** (passenger vehicles above 80 mph). The linear regression model results for passenger vehicles approaching the DSFS below 80 mph are presented in **Table 15**. **Table 16** presents the regression results for heavy vehicles, which all were approaching the DSFS below 80 mph. Regression models were not developed for vehicles approaching the DSFS above 80 mph due to small sample sizes.

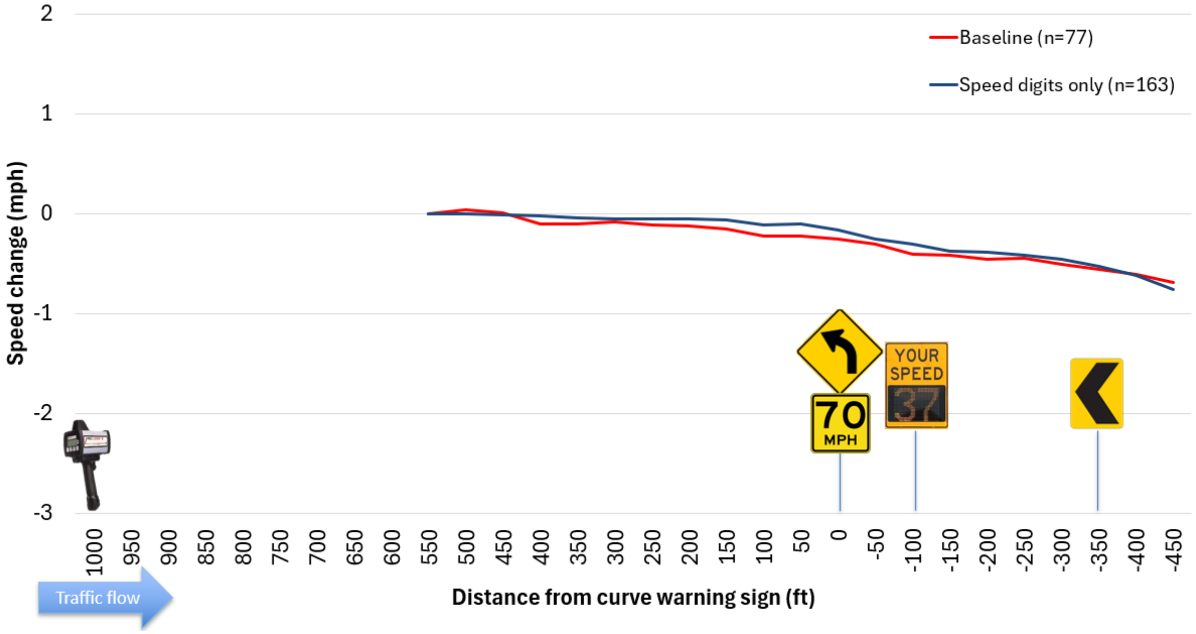


**Figure 25. Average Speed Change Trajectories at Freeway Curve Site 2 – Passenger Vehicles < 80 mph**

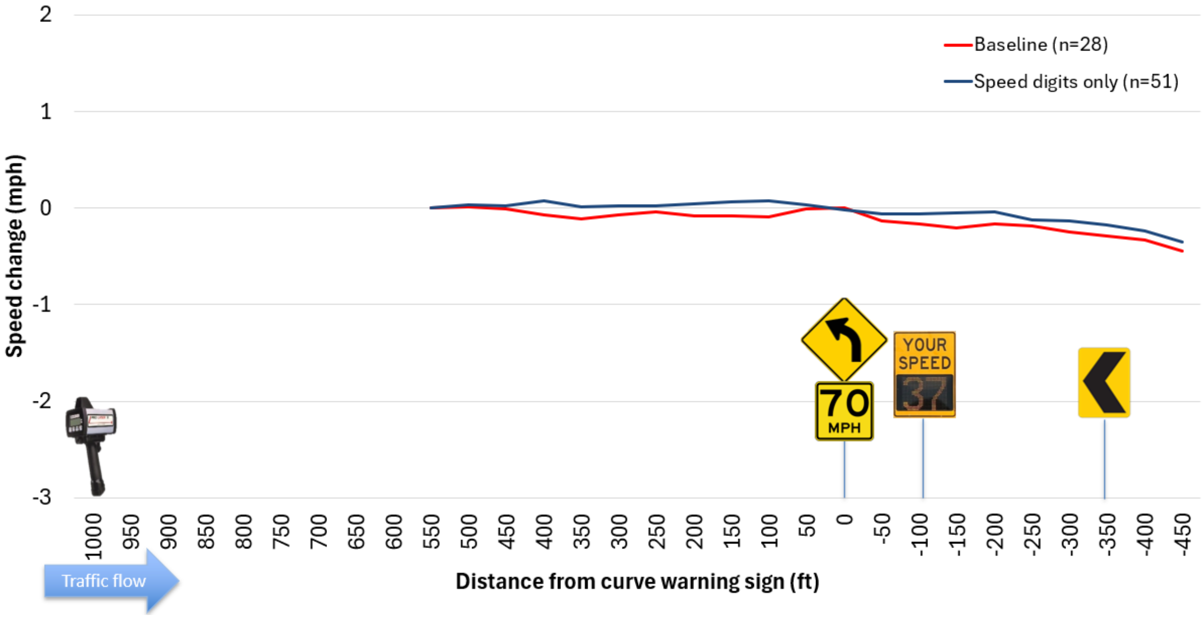


**Figure 26. Average Speed Change Trajectories at Freeway Curve Site 2 – Heavy Vehicles**

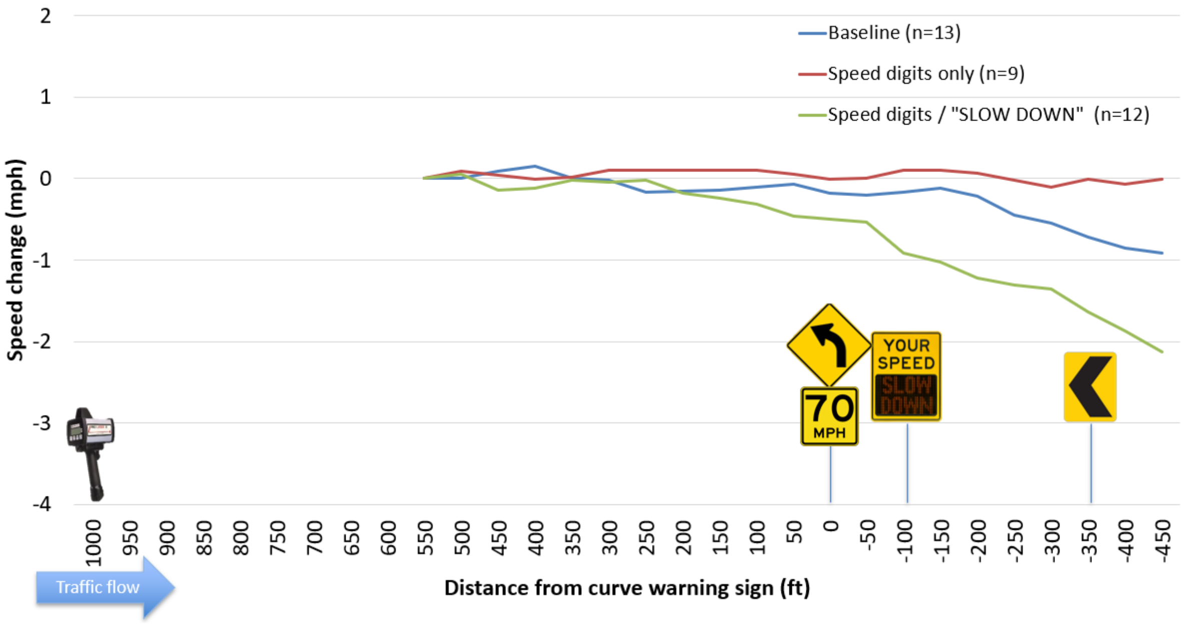


**Figure 27. Average Speed Change Trajectories at Freeway Curve Site 2 – Passenger Vehicles > 80 mph**

**Table 15. Linear Regression Model for Speed Reduction, Passenger Vehicles < 80 mph, Freeway Curve Site 2**

| Parameters | Estimate | Std. Error | p-Value |
|---|---|---|---|
| **Speed at 250 ft upstream of the curve warning sign** | | | |
| Intercept | -0.117 | 0.078 | 0.139 |
| No DSFS | | *Baseline* | |
| Speed digits | 0.063 | 0.095 | 0.512 |
| **Speed at the curve warning sign** | | | |
| Intercept | -0.253 | 0.118 | 0.033 |
| No DSFS | | *Baseline* | |
| Speed digits | 0.088 | 0.143 | 0.541 |
| **Speed at 100 ft downstream of the curve warning sign (at DSFS)** | | | |
| Intercept | -0.401 | 0.142 | 0.005 |
| No DSFS | | *Baseline* | |
| Speed digits | 0.091 | 0.173 | 0.598 |
| **Speed at 250 ft downstream of the curve warning sign** | | | |
| Intercept | -0.450 | 0.168 | 0.008 |
| No DSFS | | *Baseline* | |
| Speed digits | 0.033 | 0.204 | 0.870 |
| **Speed at 450 ft downstream of the curve warning sign** | | | |
| Intercept | -0.688 | 0.187 | <0.001 |
| Dynamic Speed Feedback Sign off | | *Baseline* | |
| Speed digits only | -0.069 | 0.227 | 0.762 |

### Table 16. Linear Regression Model for Speed Reduction, Heavy Vehicles, Freeway Curve Site 2

| Parameters | Estimate | Std. Error | p-Value |
|---|---|---|---|
| **Speed at 250 ft upstream of the curve warning sign** | | | |
| Intercept | -0.042 | 0.095 | 0.656 |
| No DSFS | *Baseline* | | |
| Speed digits | 0.068 | 0.118 | 0.566 |
| **Speed at the curve warning sign** | | | |
| Intercept | 0.003 | 0.142 | 0.982 |
| No DSFS | *Baseline* | | |
| Speed digits | -0.026 | 0.177 | 0.882 |
| **Speed at 100 ft downstream of the curve warning sign (at DSFS)** | | | |
| Intercept | -0.160 | 0.172 | 0.354 |
| No DSFS | *Baseline* | | |
| Speed digits | 0.105 | 0.214 | 0.624 |
| **Speed at 250 ft downstream of the curve warning sign** | | | |
| Intercept | -0.181 | 0.190 | 0.343 |
| No DSFS | *Baseline* | | |
| Speed digits | 0.063 | 0.236 | 0.790 |
| **Speed at 450 ft downstream of the curve warning sign** | | | |
| Intercept | -0.439 | 0.199 | 0.030 |
| No DSFS | *Baseline* | | |
| Speed digits | 0.086 | 0.248 | 0.730 |

As the regression results in **Table 15** and **Table 16** indicate, the DSFS message did not affect the mean speed of drivers approaching or entering the horizontal curve at freeway Site 2. This result was consistent for both passenger vehicles and heavy vehicles. A subsequent series of analyses were performed using binary logistic regression to assess the likelihood of drivers exceeding the advisory speed at the point of curvature based on the DSFS message display. Again, this analysis was only performed for drivers approaching below 80 mph due to the small sample size of drivers approaching above 80 mph. The binary logistic regression results displayed in **Table 17** indicate that the DSFS displaying speed digits did reduce the likelihood of drivers exceeding the 10 mph over the advisory speed at the point of curvature by 45.9 percent (1-Exp (β) = 1-0.541) compared to the base condition. However, this result was not found to be statistically significant.

**Table 17. Binary Logistic Regression Model for Likelihood of Exceeding the Advisory Speed at Mainline Freeway Curve Site 2 (Approach Speed < 80 mph)**

| | Parameters | Estimate | Std. Error | p-Value | Exp(B) |
|---|---|---|---|---|---|
| Over advisory speed (70 mph) | Intercept | -55.034 | 8.253 | 0.000 | 0.000 |
| | Speed 550 ft upstream of the curve warning sign | 0.778 | 0.114 | 0.000 | 2.177 |
| | No DSFS | *Baseline* | | | |
| | Speed digits | -0.270 | 0.545 | 0.620 | 0.763 |
| 5 mph over advisory speed at the point of curvature | Intercept | -99.130 | 13.843 | 0.000 | 0.000 |
| | Speed 550 ft upstream of the curve warning sign | 1.304 | 0.182 | 0.000 | 3.683 |
| | No DSFS | *Baseline* | | | |
| | Speed digits | 0.371 | 0.512 | 0.468 | 1.449 |
| 10 mph over advisory speed at the point of curvature | Intercept | -36.330 | 27.244 | 0.182 | 0.000 |
| | Speed 550 ft upstream of the curve warning sign | 0.417 | 0.349 | 0.232 | 1.517 |
| | No DSFS | *Baseline* | | | |
| | Speed digits | -0.615 | 1.430 | 0.667 | 0.541 |

## 4.3 Flashing LED Chevrons at Horizontal Curves on Rural Highways

The effect of the flashing LED chevrons on driver speed selection while approaching horizontal curves on rural highways was tested at three sites. All three sites were located along US-12 in the area of Brooklyn and Tipton, Michigan. The speed limit at all three sites was 55 mph, while curve advisory speed varied from site to site.

### 4.3.1 Site Descriptions

General site descriptions are provided as follows:

- **Site 1: WB US-12, Deer Run Court.** The curve warning sign (W1-2) was located 350 ft upstream of the point of curvature along with the advisory speed plaque (W13-1P) with a 40 mph advisory speed. A total of six chevron signs (W1-8) were located along the horizontal curve. Only the initial three chevrons in the array included the flashing LED chevrons. The speed detection radar for activation of the LED chevrons was positioned on the first chevron. The radius of the horizontal curve is 500 ft. This location also included testing of a DSFS paired with the flashing LED chevron system. The DSFS was temporarily installed at the site in November 2024, after the completion of data collection with the flashing LED chevrons.
- **Site 2: EB US-12, Deer Run Court.** The site represents the same horizontal curve as Site 1, but for the eastbound approach. The curve warning sign (W1-2) was located 600 ft upstream of the point of curvature along with the advisory speed plaque (W13-1P) with a 35 mph advisory speed. A total of six chevron signs (W1-8) were located along

the horizontal curve. Only the initial three chevrons in the array included the flashing LED chevrons. The speed detection radar for activation of the LED chevrons was positioned on the first chevron.

- **Site 3: WB US-12, Person Highway.** The curve warning sign (W1-4) was positioned 550 ft upstream of the point of curvature on both sides of the road along with an advisory speed plaque (W13-1P) with a 35 mph advisory speed. A continuously flashing amber warning beacon existed on top of both curve warning signs. A total of six chevron signs (W1-8) existed along the horizontal curve. A direction large arrow (W1-6) sign existed between the second and third chevrons. Only the initial three chevrons in the array included the flashing LED chevrons. The speed detection radar for activation of the LED chevrons was positioned on the first chevron. The radius of the horizontal curve is 400 ft.

### 4.3.2 Sign Test Conditions and Data Collection Procedures

Speed data were collected for the existing signing condition (i.e., the baseline condition) prior to installation of the flashing LED chevrons at each of the three sites in July 2023. Thereafter, the flashing LED chevrons were installed, replacing the initial three initial chevrons at each location, in late 2023. The LED chevrons were initially enabled in simultaneous flash mode (all LED chevrons flash at the same time). The speed threshold above which the flashing LED chevrons would begin to flash was set equal to the advisory speed of the curve on all three sites (WB US-12 Deer Run Ct. = 40 mph, EB US-12 Deer Run Ct. = 35 mph, WB US-12 Person Hwy. = 35 mph). The LED chevrons would begin to flash if the speed of the approaching vehicle detected by radar exceeded the curve advisory speed. The LED chevrons would flash at a rate of one flash per second while in simultaneous flash mode. Speed data was again collected at all three sites in May 2024.

Although the LED chevrons had been angled per MDOT specifications, during the May 2024 data collection event, it was noted that the flashing LEDs were of limited visibility to drivers approaching the curve at each location. Thus, the chevrons were re-angled in the summer of 2024 to provide optimal LED visibility for drivers approaching the curve. Technical drawings of the LED chevron angles before and after realignment can be found for the Pearson Highway curve in **Appendix A** and for the Deer Run Court curve in **Appendix B**. After the chevrons were reangled, another round of data collection with the LEDs in simultaneous flash mode was performed at each of the three sites in September 2024. Thereafter, the flashing LED chevrons were set to flash in sequential mode where the LED chevrons would flash one by one, in a *chasing* mode, such that the entire flash sequence would occur once per second. Data collection with the LEDs in sequential mode was performed at each of the three sites in October 2024.

All speed data was collected using a handheld LIDAR gun. When collecting speed data, the technician operating the LIDAR gun was positioned at each site at the same location across all data collection periods. The LIDAR technician was positioned in an unmarked vehicle parked on the side of the road such that the technician had a clear view of vehicles approaching and entering the curve. The LIDAR technician was positioned 700 ft upstream of the point of curvature at Site 1, 1,200 ft upstream of the point of curvature at Site 2, and 750 ft upstream of the point of curvature, at Site 3. The field evaluation layout for Site 1, Site 2, and Site 3 are shown in **Figure 28**, **Figure 29**, and **Figure 30**, respectively. Again note that flashing beacons existed on the top of the curve warning signs during all field data collection periods at Site 3. An example of flashing LED chevrons activated at Site 3 is shown in **Figure 31**.

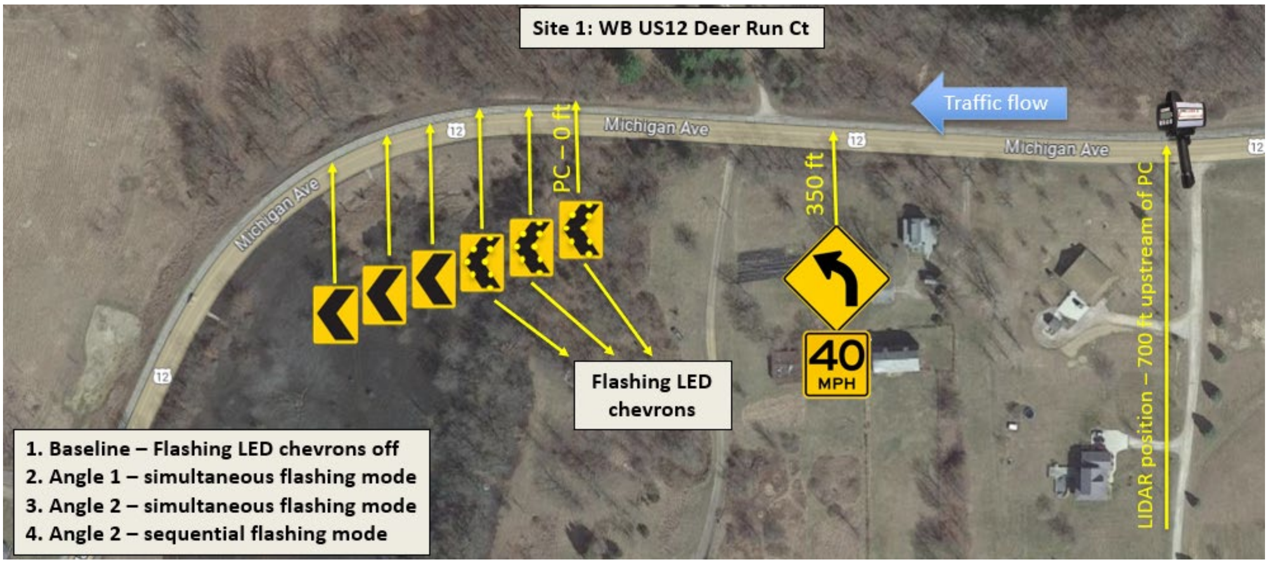


**Figure 28. Site Layout and Sign Test Conditions at WB US-12 Deer Run Ct (Site 1)**

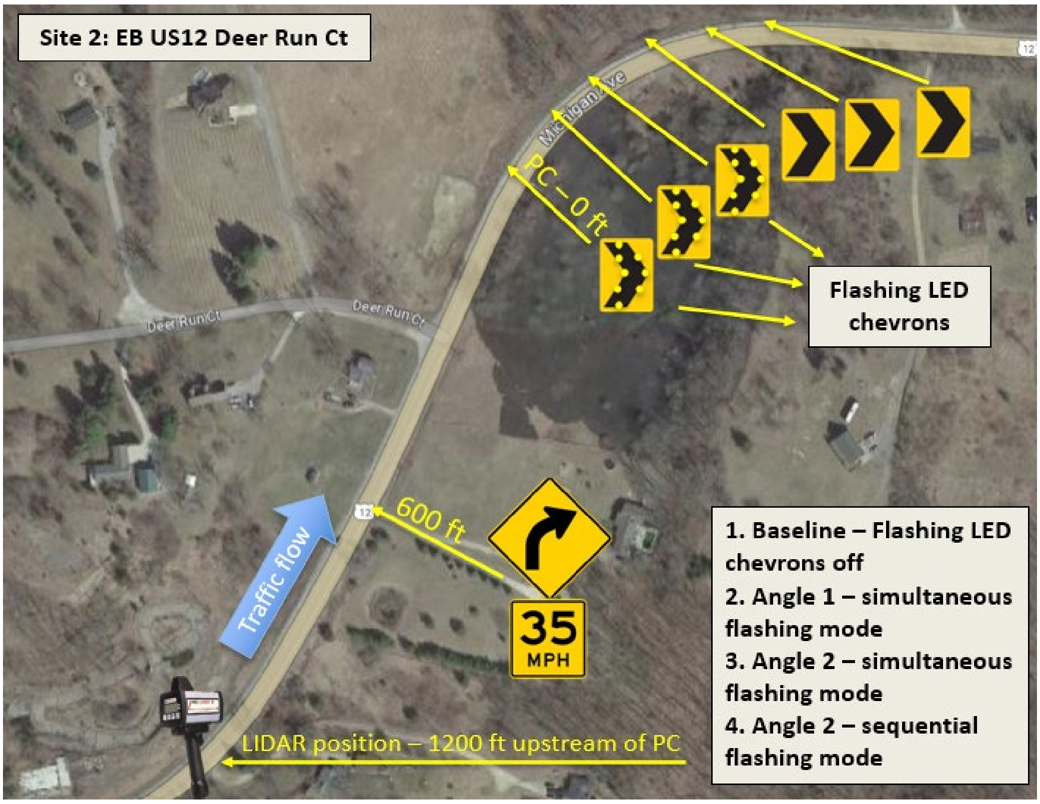


Figure 29. Site Layout and Sign Test Conditions at EB US-12 Deer Run Ct (Site 2)

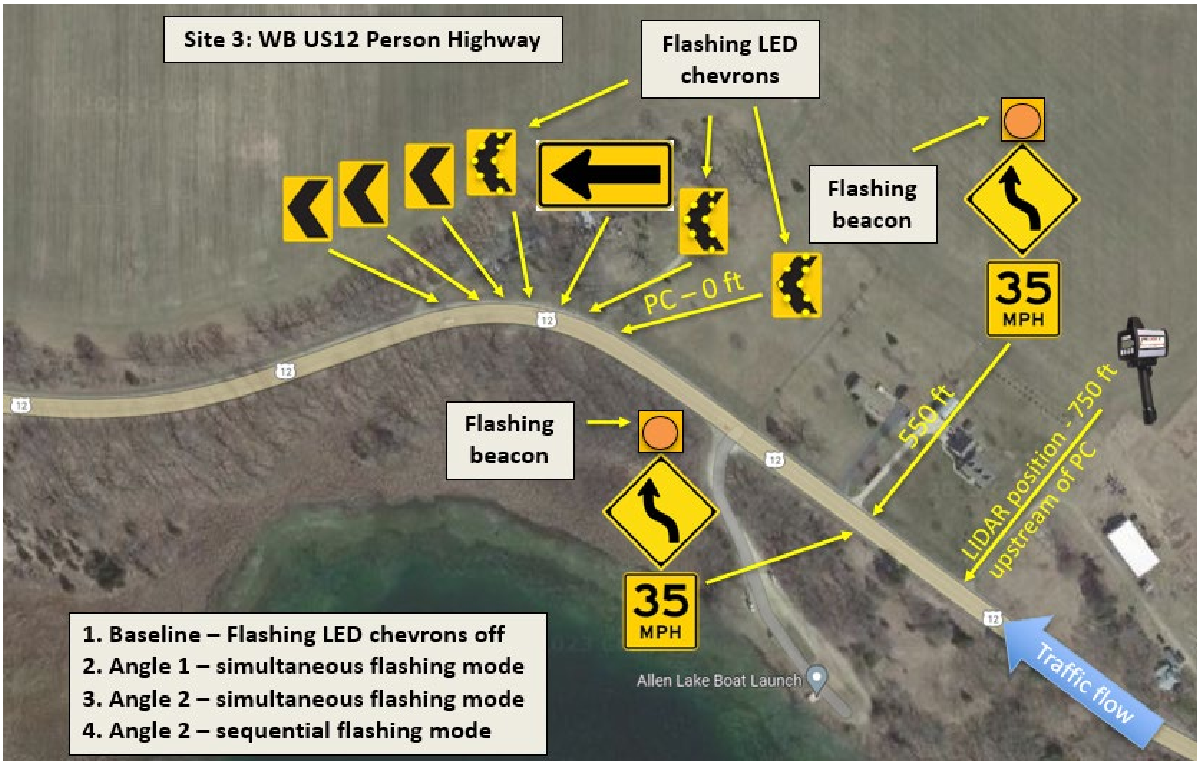


Figure 30. Site Layout and Sign Test Conditions at WB US-12 Person Highway (Site 3)

**Figure 31. Example of Flashing LED Chevrons (background) and Flashing Warning Beacons (foreground) at WB US-12 Person Highway (Site 3)**

MDOT was also interested in evaluation of the incremental effects on driver speed behavior associated with the installation of a DSFS along with the flashing LED chevrons. Testing of the DSFS paired with the flashing LED chevrons signs was performed at the WB Deer Run Ct. location (Site 1). This site was selected for DSFS testing due to the roadside being favorable for installation. The DSFS was installed and tested in two locations at this site: 1.) adjacent to the curve warning sign (350 ft upstream of the point of curvature) and 2.) near the point of curvature (100 ft upstream of the point of curvature). Each of these DSFS positions was compliant with the requirements for installation of DSFS for curve warning application found in the 11th edition MUTCD. Installation of the DSFS was performed in November 2024, after completion of data collection with the flashing LED chevrons as a stand-alone treatment.

LIDAR speed data was collected with the DSFS in the initial position in November 2024, after which DSFS was moved to the second position, and speed data was again collected in December 2024. The flashing LED chevrons were only tested in simultaneous mode when paired with the DSFS. Two messaging strategies were displayed on DSFS during data collection, which included: 1.) DSFS displaying speed digits, LED chevrons in simultaneous flashing mode and 2.) DSFS displaying speed digits alternating with “SLOW DOWN”, LED chevrons in simultaneous flashing mode. The two messages were evaluated at both DSFS installation positions. The DSFS and flashing LED chevrons only activated for vehicles approaching at greater than the curve advisory speed of 40 mph. The field evaluation layout with the DSFS installed in each position at Site 1 is shown in **Figure 32** (Position 1: DSFS installed adjacent to the curve warning sign) and **Figure 33** (Position 2: DSFS installed near the point of curvature). An example of the DSFS installed adjacent to the curve warning sign (Position 1) is shown in **Figure 34**.

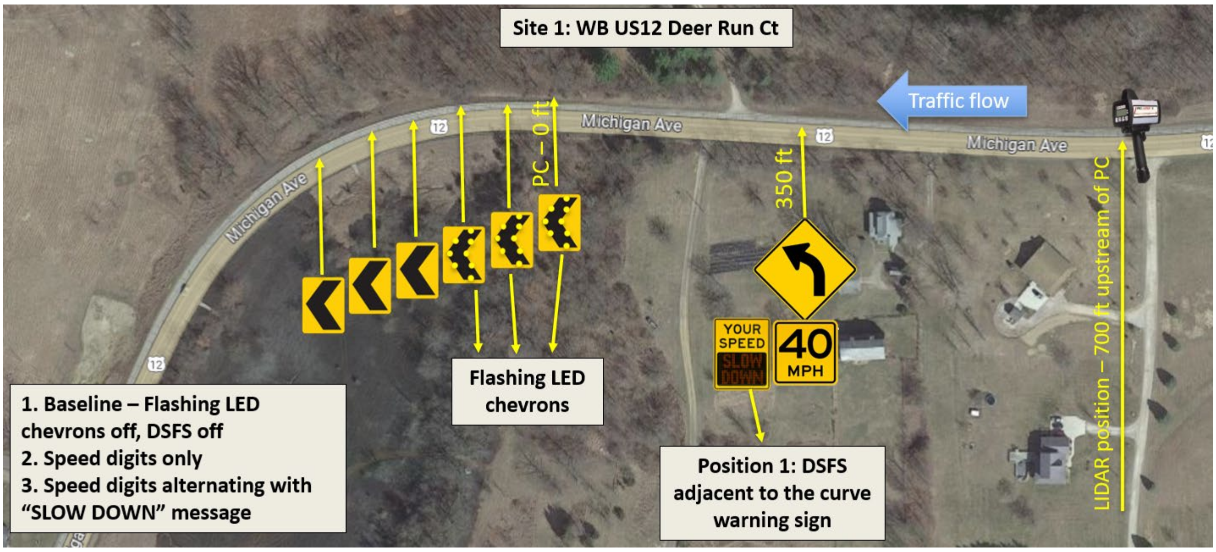


Figure 32. Site Layout and DSFS Messages at WB US-12 Deer Run Ct (DSFS Position 1)

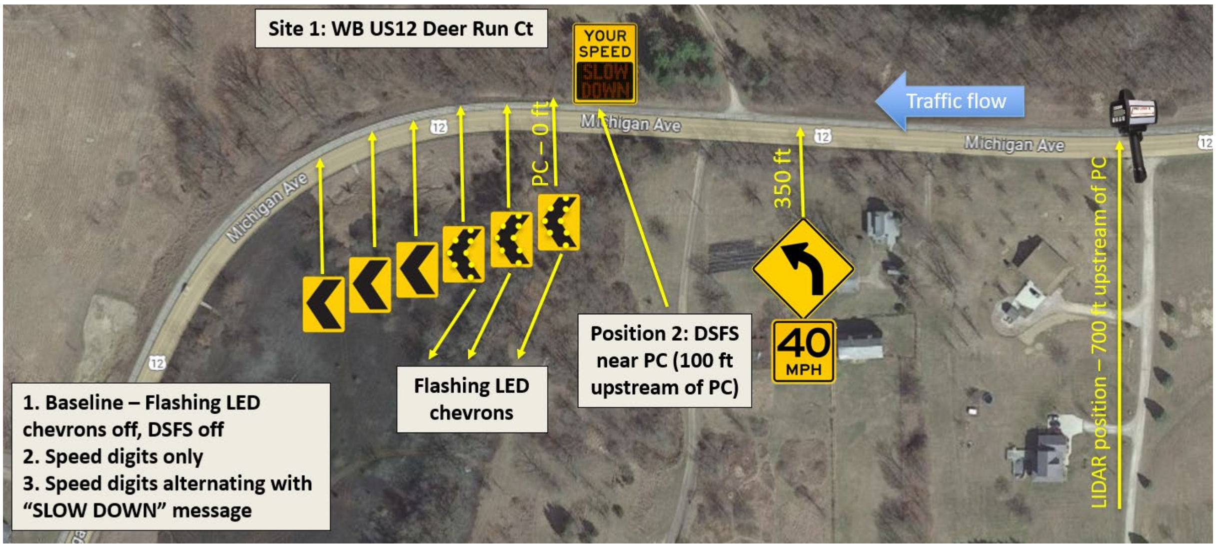


Figure 33. Site Layout and DSFS Messages at WB US-12 Deer Run Ct (DSFS Position 2)

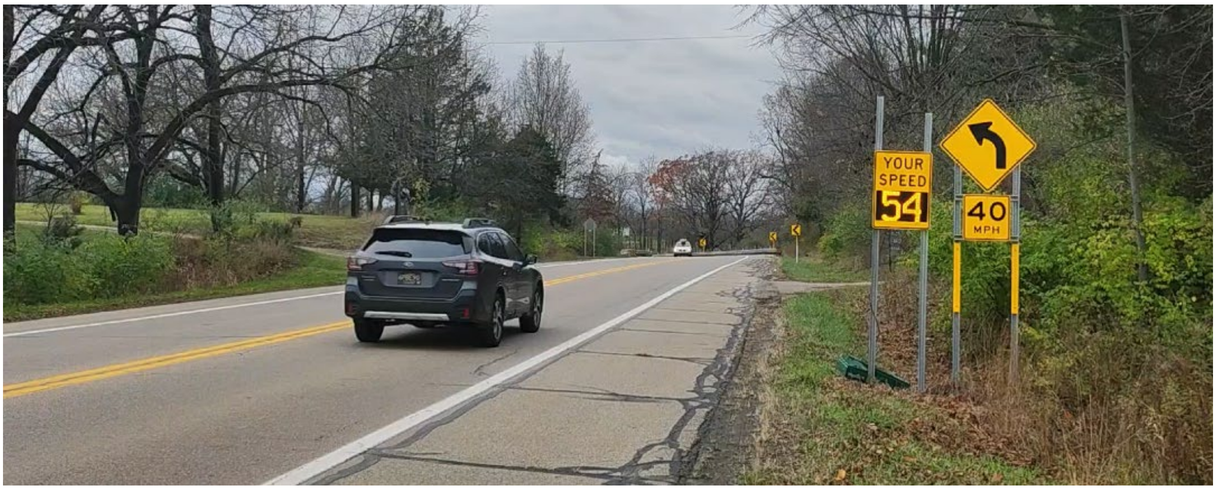


Figure 34. Example DSFS Message Display at WB US-12 Deer Run Ct (DSFS Position 1)

### 4.3.3 Results – Speed Reduction Effect of Flashing LED Chevrons

The speed reduction effect of the flashing LED chevrons was evaluated across the following sign test conditions at each of the three rural horizontal curve sites:

1. Baseline Condition: Standard Chevrons
2. Simultaneous Flashing LED Chevrons – First Angle
3. Simultaneous Flashing LED Chevrons – Second Angle
4. Sequential Flashing LED Chevrons – Second Angle

Descriptive statistics for speed data approaching and entering the horizontal curve at WB US-12 Deer Run Court, EB US-12 Deer Run Court, and WB US-12 Person Highway are provided in **Table 18**, **Table 19,** and **Table 20**, respectively.

**Table 18. Descriptive Statistics for Speed, WB US-12 Deer Run Court**

| Data Collection Location | Sign Test Condition | Sample Size | Mean (mph) | 85th %tile speed (mph) | Std. Dev. (mph) |
|---|---|---|---|---|---|
| Speed at 600 ft upstream of the first chevron | Standard chevrons (Baseline) | 98 | 53.35 | 58.00 | 4.16 |
| | Simultaneous flashing LED chevrons – 1st angle | 94 | 54.28 | 58.99 | 4.95 |
| | Simultaneous flashing LED chevrons – 2nd angle | 94 | 54.32 | 59.00 | 4.52 |
| | Sequential flashing LED chevrons – 2nd angle | 92 | 54.42 | 59.05 | 4.80 |
| Speed at 350 ft upstream of the first chevron (at curve warning sign) | Standard chevrons (Baseline) | 98 | 53.55 | 58.00 | 4.06 |
| | Simultaneous flashing LED chevrons – 1st angle | 94 | 54.67 | 58.00 | 4.41 |
| | Simultaneous flashing LED chevrons – 2nd angle | 94 | 54.31 | 58.55 | 4.27 |
| | Sequential flashing LED chevrons – 2nd angle | 92 | 54.47 | 60.00 | 4.86 |
| Speed at 150 ft upstream of the first chevron | Standard chevrons (Baseline) | 98 | 52.55 | 57.00 | 4.41 |
| | Simultaneous flashing LED chevrons – 1st angle | 94 | 53.40 | 58.00 | 4.38 |
| | Simultaneous flashing LED chevrons – 2nd angle | 94 | 52.66 | 57.00 | 4.57 |
| | Sequential flashing LED chevrons – 2nd angle | 92 | 53.02 | 57.63 | 4.66 |
| Speed at first chevron/PC | Standard chevrons (Baseline) | 98 | 50.64 | 55.00 | 4.35 |
| | Simultaneous flashing LED chevrons – 1st angle | 94 | 50.99 | 55.38 | 4.56 |
| | Simultaneous flashing LED chevrons – 2nd angle | 94 | 50.10 | 55.00 | 4.64 |
| | Sequential flashing LED chevrons – 2nd angle | 92 | 50.83 | 55.21 | 4.60 |
| Speed at 200 ft downstream of the first chevron | Standard chevrons (Baseline) | 98 | 47.52 | 52.56 | 4.67 |
| | Simultaneous flashing LED chevrons – 1st angle | 94 | 47.57 | 52.16 | 4.86 |
| | Simultaneous flashing LED chevrons – 2nd angle | 94 | 46.14 | 50.68 | 4.65 |
| | Sequential flashing LED chevrons – 2nd angle | 92 | 47.37 | 51.02 | 4.46 |

## Table 19. Descriptive Statistics for Speed, EB US-12 Deer Run Court

| Data Collection Location | Sign Test Condition | Sample Size | Mean (mph) | 85th %tile speed (mph) | Std. Dev. (mph) |
|---|---|---|---|---|---|
| Speed at 800 ft upstream of the first chevron | Standard chevrons (Baseline) | 118 | 51.05 | 55.00 | 4.06 |
| | Simultaneous flashing LED chevrons – 1st angle | 97 | 52.40 | 56.42 | 4.16 |
| | Simultaneous flashing LED chevrons – 2nd angle | 93 | 51.14 | 56.00 | 4.53 |
| | Sequential flashing LED chevrons – 2nd angle | 85 | 51.64 | 55.00 | 4.39 |
| Speed at 600 ft upstream of the first chevron (at curve warning sign) | Standard chevrons (Baseline) | 118 | 51.05 | 55.75 | 4.31 |
| | Simultaneous flashing LED chevrons – 1st angle | 97 | 52.11 | 57.00 | 4.31 |
| | Simultaneous flashing LED chevrons – 2nd angle | 93 | 50.91 | 57.00 | 4.87 |
| | Sequential flashing LED chevrons – 2nd angle | 85 | 51.58 | 56.00 | 4.65 |
| Speed at 450 ft upstream of the first chevron | Standard chevrons (Baseline) | 118 | 50.90 | 56.00 | 4.33 |
| | Simultaneous flashing LED chevrons – 1st angle | 97 | 51.74 | 56.99 | 4.40 |
| | Simultaneous flashing LED chevrons – 2nd angle | 93 | 50.54 | 56.13 | 5.01 |
| | Sequential flashing LED chevrons – 2nd angle | 85 | 51.33 | 56.00 | 4.72 |
| Speed at 300 ft upstream of the first chevron | Standard chevrons (Baseline) | 118 | 50.48 | 55.15 | 4.33 |
| | Simultaneous flashing LED chevrons – 1st angle | 97 | 51.04 | 56.00 | 4.77 |
| | Simultaneous flashing LED chevrons – 2nd angle | 93 | 50.12 | 55.48 | 4.85 |
| | Sequential flashing LED chevrons – 2nd angle | 85 | 51.09 | 55.06 | 4.69 |
| Speed at 150 ft upstream of the first chevron | Standard chevrons (Baseline) | 118 | 49.35 | 54.12 | 4.31 |
| | Simultaneous flashing LED chevrons – 1st angle | 97 | 49.72 | 54.62 | 4.83 |
| | Simultaneous flashing LED chevrons – 2nd angle | 93 | 48.86 | 53.40 | 4.79 |
| | Sequential flashing LED chevrons – 2nd angle | 85 | 50.14 | 54.09 | 4.52 |
| Speed at first chevron/PC | Standard chevrons (Baseline) | 118 | 47.59 | 52.00 | 4.10 |
| | Simultaneous flashing LED chevrons – 1st angle | 97 | 47.77 | 52.24 | 4.48 |
| | Simultaneous flashing LED chevrons – 2nd angle | 93 | 46.50 | 51.00 | 4.56 |
| | Sequential flashing LED chevrons – 2nd angle | 85 | 48.08 | 52.02 | 4.51 |
| Speed 50 ft downstream of the first chevron | Standard chevrons (Baseline) | 118 | 46.91 | 51.07 | 4.18 |
| | Simultaneous flashing LED chevrons – 1st angle | 97 | 47.15 | 51.45 | 4.39 |
| | Simultaneous flashing LED chevrons – 2nd angle | 93 | 45.58 | 50.80 | 4.57 |
| | Sequential flashing LED chevrons – 2nd angle | 85 | 47.29 | 51.98 | 4.64 |

**Table 20. Descriptive Statistics for Speed, WB US-12 Person Highway**

| Data Collection Location | Sign Test Condition | Sample Size | Mean (mph) | 85th %tile speed (mph) | Std. Dev. (mph) |
|---|---|---|---|---|---|
| Speed at 650 ft upstream of the first chevron | Standard chevrons (Baseline) | 104 | 54.48 | 59.00 | 3.85 |
| | Simultaneous flashing LED chevrons – 1st angle | 102 | 56.01 | 60.00 | 3.54 |
| | Simultaneous flashing LED chevrons – 2nd angle | 100 | 55.77 | 60.00 | 4.46 |
| | Sequential flashing LED chevrons – 2nd angle | 98 | 55.93 | 59.00 | 3.57 |
| Speed at 550 ft upstream of the first chevron (at curve warning sign) | Standard chevrons (Baseline) | 104 | 54.51 | 59.00 | 3.86 |
| | Simultaneous flashing LED chevrons – 1st angle | 102 | 56.13 | 60.00 | 3.52 |
| | Simultaneous flashing LED chevrons – 2nd angle | 100 | 56.01 | 60.00 | 4.35 |
| | Sequential flashing LED chevrons – 2nd angle | 98 | 55.92 | 59.00 | 3.54 |
| Speed at 350 ft upstream of the first chevron | Standard chevrons (Baseline) | 104 | 54.07 | 58.02 | 3.98 |
| | Simultaneous flashing LED chevrons – 1st angle | 102 | 55.88 | 59.85 | 3.52 |
| | Simultaneous flashing LED chevrons – 2nd angle | 100 | 55.54 | 59.03 | 4.36 |
| | Sequential flashing LED chevrons – 2nd angle | 98 | 55.49 | 59.00 | 3.57 |
| Speed at 150 ft upstream of the first chevron | Standard chevrons (Baseline) | 104 | 51.85 | 56.00 | 4.17 |
| | Simultaneous flashing LED chevrons – 1st angle | 102 | 54.04 | 58.00 | 3.76 |
| | Simultaneous flashing LED chevrons – 2nd angle | 100 | 53.19 | 57.97 | 4.48 |
| | Sequential flashing LED chevrons – 2nd angle | 98 | 53.06 | 56.25 | 3.50 |
| Speed at first chevron/PC | Standard chevrons (Baseline) | 104 | 48.69 | 53.21 | 4.23 |
| | Simultaneous flashing LED chevrons – 1st angle | 102 | 50.83 | 54.84 | 3.68 |
| | Simultaneous flashing LED chevrons – 2nd angle | 100 | 49.90 | 53.94 | 4.70 |
| | Sequential flashing LED chevrons – 2nd angle | 98 | 49.71 | 53.00 | 3.59 |
| Speed at 200 ft downstream of the first chevron | Standard chevrons (Baseline) | 104 | 41.96 | 46.27 | 4.43 |
| | Simultaneous flashing LED chevrons – 1st angle | 102 | 43.43 | 47.43 | 3.76 |
| | Simultaneous flashing LED chevrons – 2nd angle | 100 | 42.75 | 46.28 | 4.47 |
| | Sequential flashing LED chevrons – 2nd angle | 98 | 41.94 | 46.00 | 4.03 |

Prior to analysis, the speeds measured at each 50 ft increment approaching the curve were subtracted from the speed measured at the furthest upstream point, which was 600 ft upstream of the first chevron at WB US-12 Deer Run Ct, 800 ft upstream of the first chevron at EB US-12 Deer Run Court, and 650 ft upstream of the first chevron at WB US-12 Person Highway. Doing so converted the raw speed data into speed reduction values and controlled for the normal speeding behavior of each driver prior to encountering the DSFS. This also allowed the regression parameters to be directly interpreted as speed reduction effects (e.g., the chevron regression parameter estimate would represent the speed reduction effect of the particular flashing LED test condition compared to the base condition). Graphical representations of the average speed reduction trajectories for the various chevron test conditions are displayed in are in **Figure 35** (WB US-12 Deer Run Court), **Figure 36** (EB US-12 Deer Run Court), and **Figure 37** (WB US-12 Person Highway). Linear regression models were developed separately for each of the three sites, as presented in **Table 21** (WB US-12 Deer Run Court), **Table 22** (EB US-12 Deer Run Court), and **Table 23** (WB US-12 Person Highway).

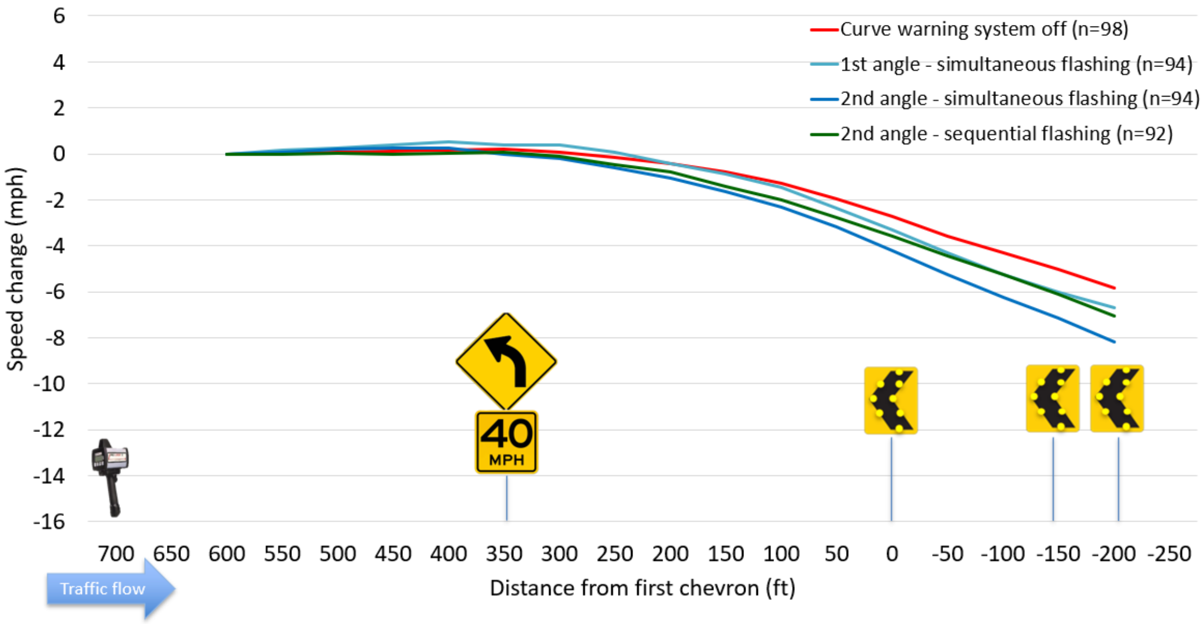


**Figure 35. Average Speed Change Trajectories, WB US-12 Deer Run Court**

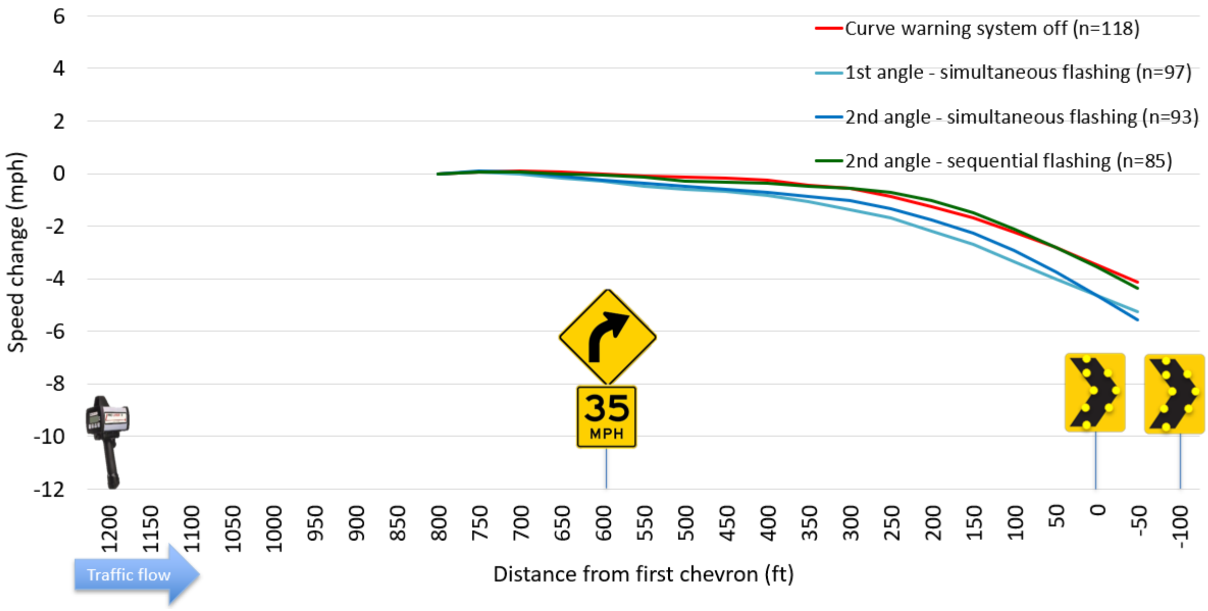


**Figure 36. Average Speed Change Trajectories, EB US-12 Deer Run Court**

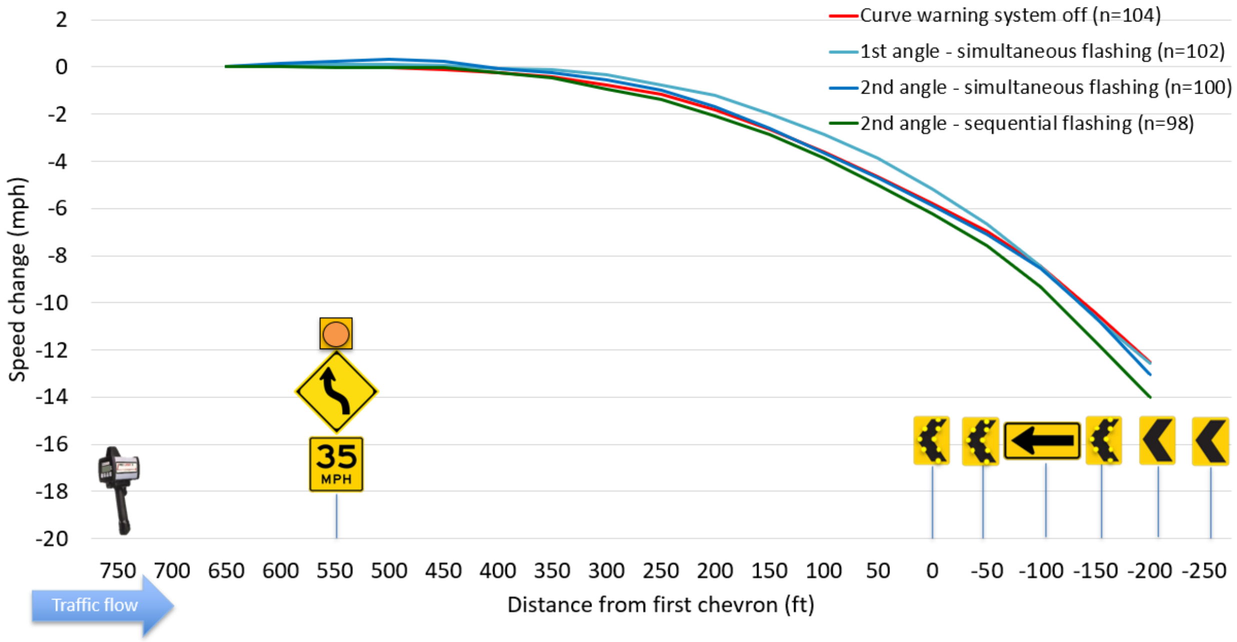


Figure 37. Average Speed Change Trajectories, WB US-12 Person Highway

Table 21. Linear Regression Model for Speed Reduction, WB US-12 Deer Run Court

| **Parameters** | **Estimate** | **Std. Error** | **p-Value** |
|---|---|---|---|
| **Speed at 350 ft upstream of the first chevron (at curve warning sign)** | | | |
| Intercept | 0.195 | 0.119 | 0.102 |
| Standard chevrons | *Baseline* | | |
| Simultaneous flashing LED chevrons – 1st angle | 0.198 | 0.170 | 0.246 |
| Simultaneous flashing LED chevrons – 2nd angle | -0.209 | 0.170 | 0.221 |
| Sequential flashing LED chevrons – 2nd angle | -0.145 | 0.171 | 0.398 |
| **Speed at 150 ft upstream of the first chevron** | | | |
| Intercept | -0.805 | 0.228 | <0.001 |
| Standard chevrons | *Baseline* | | |
| Simultaneous flashing LED chevrons – 1st angle | -0.076 | 0.326 | 0.816 |
| Simultaneous flashing LED chevrons – 2nd angle | -0.851 | 0.326 | 0.009 |
| Sequential flashing LED chevrons – 2nd angle | -0.600 | 0.328 | 0.068 |
| **Speed at first chevron/PC** | | | |
| Intercept | -2.718 | 0.302 | <0.001 |
| Standard chevrons | *Baseline* | | |
| Simultaneous flashing LED chevrons – 1st angle | -0.578 | 0.432 | 0.182 |
| Simultaneous flashing LED chevrons – 2nd angle | -1.502 | 0.432 | 0.001 |
| Sequential flashing LED chevrons – 2nd angle | -0.880 | 0.435 | 0.044 |
| **Speed at 200 ft downstream of the first chevron** | | | |
| Intercept | -5.837 | 0.407 | <0.001 |
| Standard chevrons | *Baseline* | | |
| Simultaneous flashing LED chevrons – 1st angle | -0.877 | 0.582 | 0.133 |
| Simultaneous flashing LED chevrons – 2nd angle | -2.344 | 0.582 | <0.001 |
| Sequential flashing LED chevrons – 2nd angle | -1.221 | 0.585 | 0.038 |

## Table 22. Linear Regression Model for Speed Reduction, EB US-12 Deer Run Court

| Parameters | Estimate | Std. Error | p-Value |
|---|---|---|---|
| **Speed at 600 ft upstream of the first chevron (at curve warning sign)** | | | |
| Intercept | -0.008 | 0.109 | 0.944 |
| Standard chevrons | *Baseline* | | |
| Simultaneous flashing LED chevrons – 1st angle | -0.287 | 0.163 | 0.078 |
| Simultaneous flashing LED chevrons – 2nd angle | -0.228 | 0.165 | 0.167 |
| Sequential flashing LED chevrons – 2nd angle | -0.050 | 0.169 | 0.766 |
| **Speed at 450 ft upstream of the first chevron** | | | |
| Intercept | -0.159 | 0.156 | 0.308 |
| Standard chevrons | *Baseline* | | |
| Simultaneous flashing LED chevrons – 1st angle | -0.505 | 0.232 | 0.030 |
| Simultaneous flashing LED chevrons – 2nd angle | -0.442 | 0.234 | 0.060 |
| Sequential flashing LED chevrons – 2nd angle | -0.155 | 0.240 | 0.520 |
| **Speed at 300 ft upstream of the first chevron** | | | |
| Intercept | -0.575 | 0.198 | 0.004 |
| Standard chevrons | *Baseline* | | |
| Simultaneous flashing LED chevrons – 1st angle | -0.782 | 0.294 | 0.008 |
| Simultaneous flashing LED chevrons – 2nd angle | -0.443 | 0.298 | 0.137 |
| Sequential flashing LED chevrons – 2nd angle | 0.020 | 0.305 | 0.947 |
| **Speed at 150 ft upstream of the first chevron** | | | |
| Intercept | -1.705 | 0.234 | <0.001 |
| Standard chevrons | *Baseline* | | |
| Simultaneous flashing LED chevrons – 1st angle | -0.978 | 0.349 | 0.005 |
| Simultaneous flashing LED chevrons – 2nd angle | -0.579 | 0.353 | 0.102 |
| Sequential flashing LED chevrons – 2nd angle | 0.207 | 0.362 | 0.568 |
| **Speed at first chevron/PC** | | | |
| Intercept | -3.463 | 0.263 | <0.001 |
| Standard chevrons | *Baseline* | | |
| Simultaneous flashing LED chevrons – 1st angle | -1.163 | 0.391 | 0.003 |
| Simultaneous flashing LED chevrons – 2nd angle | -1.174 | 0.396 | 0.003 |
| Sequential flashing LED chevrons – 2nd angle | -0.096 | 0.406 | 0.813 |
| **Speed at 50 ft downstream of the first chevron** | | | |
| Intercept | -4.147 | 0.286 | <0.001 |
| Standard chevrons | *Baseline* | | |
| Simultaneous flashing LED chevrons – 1st angle | -1.102 | 0.427 | 0.010 |
| Simultaneous flashing LED chevrons – 2nd angle | -1.409 | 0.432 | 0.001 |
| Sequential flashing LED chevrons – 2nd angle | -0.205 | 0.443 | 0.644 |

**Table 23. Linear Regression Model for Speed Reduction, WB US-12 Person Highway**

| Parameters | Estimate | Std. Error | p-Value |
|---|---|---|---|
| **Speed at 550 ft upstream of the first chevron (at curve warning sign)** | | | |
| Intercept | 0.033 | 0.043 | 0.444 |
| Standard chevrons | *Baseline* | | |
| Simultaneous flashing LED chevrons – 1st angle | 0.093 | 0.061 | 0.129 |
| Simultaneous flashing LED chevrons – 2nd angle | 0.202 | 0.061 | 0.001 |
| Sequential flashing LED chevrons – 2nd angle | -0.039 | 0.061 | 0.521 |
| **Speed at 350 ft upstream of the first chevron** | | | |
| Intercept | -0.411 | 0.121 | 0.001 |
| Standard chevrons | *Baseline* | | |
| Simultaneous flashing LED chevrons – 1st angle | 0.284 | 0.173 | 0.100 |
| Simultaneous flashing LED chevrons – 2nd angle | 0.177 | 0.173 | 0.306 |
| Sequential flashing LED chevrons – 2nd angle | -0.032 | 0.174 | 0.856 |
| **Speed at 150 ft upstream of the first chevron** | | | |
| Intercept | -2.630 | 0.219 | <0.001 |
| Standard chevrons | *Baseline* | | |
| Simultaneous flashing LED chevrons – 1st angle | 0.657 | 0.312 | 0.036 |
| Simultaneous flashing LED chevrons – 2nd angle | 0.047 | 0.312 | 0.881 |
| Sequential flashing LED chevrons – 2nd angle | -0.235 | 0.314 | 0.455 |
| **Speed at first chevron/PC** | | | |
| Intercept | -5.790 | 0.304 | <0.001 |
| Standard chevrons | *Baseline* | | |
| Simultaneous flashing LED chevrons – 1st angle | 0.608 | 0.434 | 0.163 |
| Simultaneous flashing LED chevrons – 2nd angle | -0.079 | 0.434 | 0.856 |
| Sequential flashing LED chevrons – 2nd angle | -0.433 | 0.436 | 0.322 |
| **Speed at 200 ft downstream of the first chevron** | | | |
| Intercept | -12.522 | 0.412 | <0.001 |
| Standard chevrons | *Baseline* | | |
| Simultaneous flashing LED chevrons – 1st angle | -0.060 | 0.588 | 0.919 |
| Simultaneous flashing LED chevrons – 2nd angle | -0.503 | 0.588 | 0.393 |
| Sequential flashing LED chevrons – 2nd angle | -1.466 | 0.591 | 0.014 |

As can be observed from the linear regression models presented in **Table 21**, **Table 22**, and **Table 23**, the flashing LED chevrons had a statistically significant speed reduction effect on drivers upon entry to the curve. In all cases when the flashing LED system was activated, the speed reductions increased compared to the baseline as the vehicle approached the curve, with the greatest speed reductions observed after the vehicle had passed the initial chevron. Furthermore, the re-aiming of the chevrons to improve LED visibility for approaching drivers (i.e., 2nd angle) produced consistently greater speed reductions than the initial angle. However, when comparing the two different flashing modes (simultaneous vs. sequential), the effectiveness varied between the three sites. The greatest speed reductions were associated with the simultaneous flashing mode after the chevrons had been re-aligned to improve LED visibility at both WB and EB US-12 Deer Run Court. At WB Deer Run Court, when vehicles were 200 ft downstream of the first chevron, the simultaneous flashing LED chevrons produced speed reductions that were 2.34 mph greater than with the standard chevrons (baseline condition), compared to 1.22 mph speed reductions when the LEDs were in sequential mode. Similarly, at EB US-12 Deer Run Court, when vehicles were 50 ft downstream of the first chevron, the simultaneous flashing LED chevrons produced speed reductions that were 1.41 mph greater than with the standard chevrons (baseline condition), compared to a non-significant 0.21 mph speed reductions when the LEDs were in sequential mode.

In contrast, at WB US-12 Person Highway, when vehicles were 200 ft downstream of the first chevron, the sequential flashing mode produced speed reductions that were 1.46 mph greater than with the standard chevrons (base condition), compared to a non-significant 0.50 mph speed reductions when the LEDs were in simultaneous flashing mode. Speed reductions at this site were generally lower in magnitude and not statistically significant. This may be due to the presence of constant-flashing amber beacons on top of the two curve warning signs on the approach, which may have dampened the driver warning effect of the flashing LED chevrons.

A subsequent series of analyses were performed using binary logistic regression to assess whether the flashing LED chevrons reduced the likelihood of drivers exceeding the advisory speed by greater than 5 mph or 10 mph at the point of curvature compared to the standard chevrons (baseline). The speed at the point of curvature for each vehicle was coded into separate binary variables based on whether the curve advisory speed was exceeded by more than 5 mph or 10 mph. The likelihood of the vehicle exceeding advisory speed is calculated as 1–Exp (β). The model results are presented in **Table 24** (WB US-12 Deer Run Court), **Table 25** (EB US-12 Deer Run Court), and **Table 26** (WB US-12 Pearson Hwy).

The binary logistic model for WB US-12 Deer Run Court presented in **Table 24** indicates that drivers are 60.2 percent (1-Exp (β) = 1-0.398) less likely to exceed the advisory speed of 40 mph by more than 10 mph when the chevrons were flashing simultaneously. The model also indicates that drivers are 46.6 percent less likely to exceed the advisory speed by 10 mph when the system is flashing sequentially. **Table 25** shows that similar results were found for EB US-12 Deer Run Court, as drivers were 49.7 percent less likely to exceed the advisory speed of 35 mph by more than 10 mph when the chevrons were flashing simultaneously. **Table 26** shows that WB US-12 Person Highway did not produce statistically significant reductions in the likelihood of drivers exceeding the curve advisory speed by more than 5 or 10 mph.

## Table 24. Binary Logistic Model for WB US-12 Deer Run Court

| | Parameters | Estimate | Std. Error | p-Value | Exp(B) |
|---|---|---|---|---|---|
| **5 mph over advisory speed at the point of curvature** | Intercept | -23.562 | 3.136 | <0.001 | 0.000 |
| | Speed 600 ft upstream of the point of curvature | 0.497 | 0.063 | <0.001 | 1.643 |
| | Standard chevrons | *Baseline* | | | |
| | Simultaneous flashing LED chevrons – 1st angle | 0.181 | 0.591 | 0.760 | 1.198 |
| | Simultaneous flashing LED chevrons – 2nd angle | -0.146 | 0.549 | 0.790 | 0.864 |
| | Sequential flashing LED chevrons – 2nd angle | 0.131 | 0.586 | 0.823 | 1.140 |
| **10 mph over advisory speed at the point of curvature** | Intercept | -28.291 | 3.136 | <0.001 | 0.000 |
| | Speed 600 ft upstream of the point of curvature | 0.539 | 0.059 | <0.001 | 1.714 |
| | Standard chevrons | *Baseline* | | | |
| | Simultaneous flashing LED chevrons – 1st angle | -0.588 | 0.398 | 0.140 | 0.555 |
| | Simultaneous flashing LED chevrons – 2nd angle | -0.922 | 0.399 | 0.021 | 0.398 |
| | Sequential flashing LED chevrons – 2nd angle | -0.627 | 0.393 | 0.111 | 0.534 |

## Table 25. Binary Logistic Model for EB US-12 Deer Run Court

| | Parameters | Estimate | Std. Error | p-Value | Exp(B) |
|---|---|---|---|---|---|
| **5 mph over advisory speed at the point of curvature** | Intercept | -21.403 | 4.269 | <0.001 | 0.000 |
| | Speed 800 ft upstream of the point of curvature | 0.512 | 0.093 | <0.001 | 1.668 |
| | Standard chevrons | *Baseline* | | | |
| | Simultaneous flashing LED chevrons – 1st angle | -0.681 | 0.772 | 0.378 | 0.506 |
| | Simultaneous flashing LED chevrons – 2nd angle | -0.585 | 0.694 | 0.399 | 0.557 |
| | Sequential flashing LED chevrons – 2nd angle | 0.232 | 0.845 | 0.783 | 1.262 |
| **10 mph over advisory speed at the point of curvature** | Intercept | -27.606 | 3.043 | <0.001 | 0.000 |
| | Speed 800 ft upstream of the point of curvature | 0.570 | 0.062 | <0.001 | 1.768 |
| | Standard chevrons | *Baseline* | | | |
| | Simultaneous flashing LED chevrons – 1st angle | -0.388 | 0.401 | 0.333 | 0.678 |
| | Simultaneous flashing LED chevrons – 2nd angle | -0.688 | 0.393 | 0.080 | 0.503 |
| | Sequential flashing LED chevrons – 2nd angle | 0.214 | 0.431 | 0.620 | 1.238 |

## Table 26. Binary Logistic Model for WB US-12 Person Highway

| | Parameters | Estimate | Std. Error | p-Value | Exp(B) |
|---|---|---|---|---|---|
| **5 mph over advisory speed at the point of curvature** | Intercept | -18.598 | 5.294 | <0.001 | 0.000 |
| | Speed 650 ft upstream of the point of curvature | 0.429 | 0.107 | <0.001 | 1.535 |
| | Standard chevrons | *Baseline* | | | |
| | Simultaneous flashing LED chevrons – 1st angle | - | - | - | - |
| | Simultaneous flashing LED chevrons – 2nd angle | -0.678 | 0.874 | 0.438 | 0.508 |
| | Sequential flashing LED chevrons – 2nd angle | -0.393 | 1.007 | 0.697 | 0.675 |
| **10 mph over advisory speed at the point of curvature** | Intercept | -25.498 | 3.594 | <0.001 | 0.000 |
| | Speed 650 ft upstream of the point of curvature | 0.505 | 0.069 | <0.001 | 1.657 |
| | Standard chevrons | *Baseline* | | | |
| | Simultaneous flashing LED chevrons – 1st angle | 1.007 | 0.546 | 0.065 | 2.738 |
| | Simultaneous flashing LED chevrons – 2nd angle | 0.478 | 0.476 | 0.315 | 1.614 |
| | Sequential flashing LED chevrons – 2nd angle | -0.030 | 0.467 | 0.948 | 0.970 |

### 4.3.4 Results – Effect of Adding DSFS to the Flashing LED Chevron System

At WB US-12 Deer Run Court, a DSFS with a 15-inch display panel was paired with the flashing LED chevron system to assess if the DSFS would provide further speed reductions. The LED chevrons had been re-aligned for improved driver visibility by the time the DSFS was installed and were only tested in simultaneous flashing mode for this evaluation. The DSFS was programmed to match the activation setting of the flashing LED chevrons, which was to only activate when approaching vehicles exceeded the curve advisory speed of 40 mph. Speed data were collected with a LIDAR gun from the same roadside vantage point during each of the sign test conditions, which were as follows:

1. Baseline Condition: No DSFS
2. Simultaneous Flashing LED Chevrons
3. DSFS Installation: near the point of curvature; DSFS Message: Speed digits
4. DSFS Installation: near the point of curvature; DSFS Message: Speed digits alternating with "SLOW DOWN"
5. DSFS Installation: adjacent to curve warning sign; DSFS Message: Speed digits
6. DSFS Installation: adjacent to curve warning sign; DSFS Message: Speed digits alternating with "SLOW DOWN"

Prior to analysis, the speeds measured at each 50 ft increment approaching the curve were subtracted from the speed measured at the furthest upstream point, which was 600 ft upstream of the first chevron at WB US-12 Deer Run Ct. Doing so converted the raw speed data into speed reduction values and controlled for the normal speeding behavior of each driver prior to encountering the DSFS. This also allowed the regression parameters to be directly interpreted as speed reduction effects (e.g., the DSFS regression parameter estimate would represent the speed reduction effect of the particular test condition compared to the base condition). Graphical representations of the average speed reduction trajectories for the various chevron test conditions are displayed in **Figure 38**. The linear regression model developed for the speed data collected during this field evaluation is presented in **Table 27**.

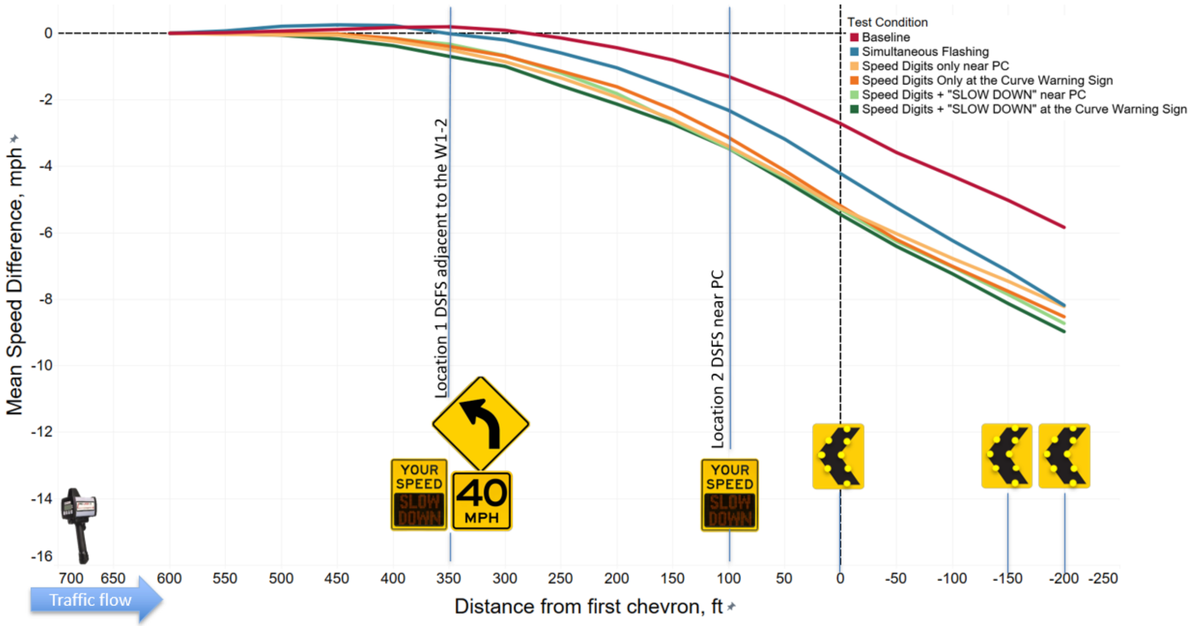


Figure 38. Average Speed Change Trajectories with DSFS, WB US-12 Deer Run Court

Results from the linear regression model suggest that adding the DSFS to the flashing LED chevrons elicited an additional speed reduction effect for drivers approaching and entering the curve. Note that the LEDs were flashing in simultaneous mode when DSFS was active. The incremental effect of DSFS was determined by subtracting the estimated coefficients for the DSFS test conditions from the coefficients for the simultaneous flashing LED chevrons without the DSFS. These values are presented in the last column of **Table 27** for each of the DSFS test conditions. The incremental speed reduction effect of the DSFS was strongest near the point of curvature and was relatively consistent between each of the DSFS installation locations and messaging conditions. Near the point of curvature, the magnitude of the incremental speed reduction provided by the DSFS paired with the flashing LED chevrons ranged between 0.82 and 1.23 mph compared to the flashing LED chevrons without the DSFS. Compared to the standard chevrons, the overall speed reductions near the point of curvature for the DSFS/flashing LED combination ranged from 2.47 to 2.73 mph. The greatest incremental effect associated with the DSFS occurred with the DSFS positioned adjacent to the curve warning sign and displaying speed digits alternating with a "SLOW DOWN" message.

## Table 27. Linear Regression Model for WB US-12 Deer Run Court, with DSFS

| Parameters | Estimate | Std. Error | p-Value | DSFS effect |
|---|---|---|---|---|
| **Speed at 350 ft upstream of the first chevron (at curve warning sign)** | | | | |
| Intercept | 0.195 | 0.116 | 0.092 | |
| Standard chevrons | *Baseline* | | | |
| Simultaneous flashing LED chevrons | -0.209 | 0.165 | 0.207 | |
| Speed digits only (DSFS adjacent to the curve warning sign) | -0.592 | 0.163 | >0.001 | -0.384 |
| Speed digits only (DSFS near PC) | -0.688 | 0.177 | >0.001 | -0.479 |
| Speed digits with "SLOW DOWN" (DSFS adjacent to the curve warning sign) | -0.890 | 0.163 | >0.001 | -0.681 |
| Speed digits with "SLOW DOWN" (DSFS near PC) | -0.523 | 0.177 | 0.003 | -0.314 |
| **Speed at 100 ft upstream of the first chevron** | | | | |
| Intercept | -1.305 | 0.233 | >0.001 | |
| Standard chevrons | *Baseline* | | | |
| Simultaneous flashing LED chevrons | -1.015 | 0.333 | 0.002 | |
| Speed digits only (DSFS adjacent to the curve warning sign) | -1.834 | 0.328 | >0.001 | -0.819 |
| Speed digits only (DSFS near PC) | -2.093 | 0.357 | >0.001 | -1.078 |
| Speed digits with "SLOW DOWN" (DSFS adjacent to the curve warning sign) | -2.159 | 0.329 | >0.001 | -1.144 |
| Speed digits with "SLOW DOWN" (DSFS near PC) | -2.154 | 0.357 | >0.001 | -1.138 |
| **Speed at first chevron/PC** | | | | |
| Intercept | -2.718 | 0.286 | >0.001 | |
| Standard chevrons | *Baseline* | | | |
| Simultaneous flashing LED chevrons | -1.502 | 0.409 | >0.001 | |
| Speed digits only (DSFS adjacent to the curve warning sign) | -2.472 | 0.403 | >0.001 | -0.970 |
| Speed digits only (DSFS near PC) | -2.545 | 0.438 | >0.001 | -1.043 |
| Speed digits with "SLOW DOWN" (DSFS adjacent to the curve warning sign) | -2.734 | 0.404 | >0.001 | -1.232 |
| Speed digits with "SLOW DOWN" (DSFS near PC) | -2.582 | 0.438 | >0.001 | -1.081 |
| **Speed at 200 ft downstream of the first chevron** | | | | |
| Intercept | -5.837 | 0.373 | >0.001 | |
| Curve warning system off | *Baseline* | | | |
| Simultaneous flashing | -2.344 | 0.533 | >0.001 | |
| Speed digits only (DSFS adjacent to the curve warning sign) | -2.689 | 0.524 | >0.001 | -0.345 |
| Speed digits only (DSFS near PC) | -2.381 | 0.570 | >0.001 | -0.037 |
| Speed digits with "SLOW DOWN" (DSFS adjacent to the curve warning sign) | -3.135 | 0.526 | >0.001 | -0.791 |
| Speed digits with "SLOW DOWN" (DSFS near PC) | -2.888 | 0.570 | >0.001 | -0.545 |

# 5. EVALUATION OF STRATEGIES FOR SPEED LIMIT TRANSITION AREAS

This chapter includes descriptions of the sites, implemented warning signing strategies, test conditions, analyses, and results pertaining to the evaluations of speed warning sign enhancements for speed limit transition areas. This chapter is organized into three subchapters based on the roadway context where evaluations were performed, which included the following speed limit transition areas: 1.) freeway to non-freeway, 2.) rural highway entering a community, 3.) roundabout approaching a community, including freeway and non-freeway cases. The DSFS was the primary speed warning sign countermeasure evaluated at each site.

## 5.1 DSFS at the Transition from Freeway to Non-Freeway

A DSFS was tested at northbound US-127 north of St. Johns, Michigan where the speed limit reduces from 75 to 65 mph as the freeway transitions to a non-freeway. The existing warning signage for the end of the freeway began approximately 1 mile upstream of the 65 mph speed limit, where a W19-1 ("FREEWAY ENDS 1 MILE") sign with two alternating flashing amber beacons on top of each sign were present on both sides of the freeway. Approximately one-half mile downstream from the initial sign was a W19-1 ("FREEWAY ENDS ½ MILE") warning sign on both sides of the road. Finally, the last existing warning sign before speed limit reduction was a W19-3 ("FREEWAY ENDS") sign on both sides of the road with a plaque stating "1/4 MILE".

### 5.1.1 Sign Test Conditions and Data Collection Procedures

A DSFS with a 15-inch display panel was temporarily installed for testing at two different roadside locations with respect to the speed limit sign, which included.

1. 350 ft upstream of the speed limit sign
2. Adjacent to the speed limit sign

Three different DSFS messaging strategies were tested at each of the installation locations and compared to the base condition, which was the period prior to installation of the DSFS. The tested DSFS messaging conditions are listed as follows:

1. Baseline: No DSFS
2. Speed digits + "SLOW DOWN" for speeds > 65 mph; speed digits for speeds < 65 mph
3. Speed digits + "SLOW DOWN" for speeds > 70 mph; speed digits for speeds < 70 mph
4. Speed digits + "SLOW DOWN" for speeds > 75 mph; speed digits for speeds < 75 mph

Speed data for passenger vehicles was collected using two handheld LIDAR guns in December 2023. Only passenger vehicles were collected due to the small sample of heavy vehicles along this segment. The LIDAR technicians were parked unmarked vehicles at the same roadside position across all test conditions. The upstream LIDAR technician was located 1,850 ft upstream of the 65 mph speed limit sign, while the downstream LIDAR was located 800 ft upstream of the 65 mph speed limit sign. The upstream LIDAR technician would track the speed of vehicles beyond the downstream LIDAR technician, at which point the vehicle tracking responsibilities would be "handed-off" to the downstream technician, who would continue tracking the vehicle beyond the 65 mph speed limit sign. The field evaluation layout and sign test conditions for both DSFS positions are displayed in **Figure 39** and **Figure 40**. Photos of the DSFS installed at Positions 1 and 2 are shown in **Figure 41** and **Figure 42**, respectively. Descriptive statistics for passenger vehicle speeds are displayed in **Table 28** for the DSFS placed 350 ft upstream of the 65 mph speed limit sign and **Table 29** for the DSFS adjacent to the 65 mph speed limit sign.

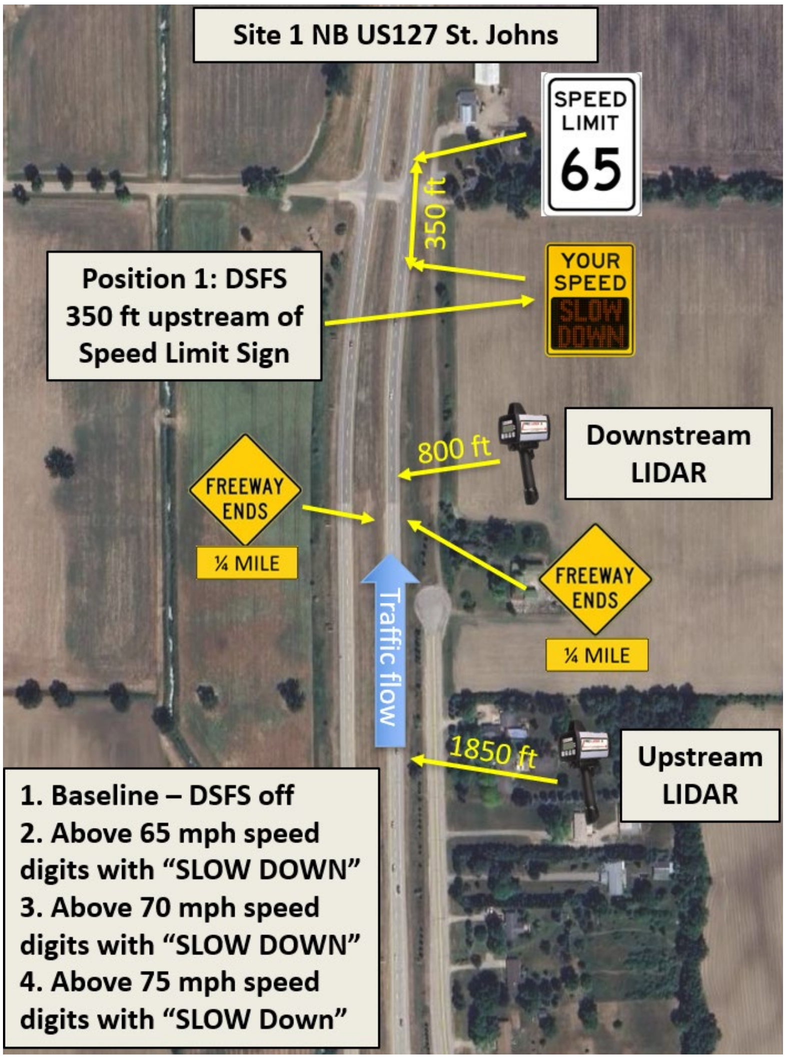


**Figure 39. Field Layout and Sign Test Conditions at NB US-127 St. Johns, DSFS Position 1**

**Figure 40. Field Layout and Sign Test Conditions at NB US-127 St. Johns, DSFS Position 2**

**Figure 41. Example of DSFS Message Display at NB US-127 St. Johns, Position 1**

Figure 42. Example of DSFS Message Display at NB US-127 St. Johns, Position 2

**Table 28. Descriptive Statistics for Passenger Vehicle Speed with DSFS Positioned Upstream of the 65 mph Speed Limit Sign, NB US-127 St. Johns**

| Data Collection Location | DSFS Test Condition | Sample Size | Mean (mph) | 85th%tile speed (mph) | Std. Dev. (mph) |
|---|---|---|---|---|---|
| 1500 ft upstream of speed limit sign (furthest upstream measurement) | No DSFS (Baseline) | 119 | 75.24 | 81.00 | 5.55 |
| | DSFS speed threshold = 65 mph | 85 | 74.14 | 80.00 | 5.36 |
| | DSFS speed threshold = 70 mph | 85 | 73.11 | 79.00 | 5.61 |
| | DSFS speed threshold = 75 mph | 92 | 74.42 | 80.00 | 4.94 |
| 1050 ft upstream of speed limit sign (location of "FREEWAY ENDS 1/4 MILE" sign) | No DSFS (Baseline) | 119 | 74.79 | 81.00 | 5.85 |
| | DSFS speed threshold = 65 mph | 85 | 73.29 | 80.00 | 5.67 |
| | DSFS speed threshold = 70 mph | 85 | 71.98 | 78.10 | 5.83 |
| | DSFS speed threshold = 75 mph | 92 | 73.24 | 79.00 | 5.26 |
| 700 ft upstream of speed limit sign | No DSFS (Baseline) | 119 | 73.89 | 79.75 | 5.68 |
| | DSFS speed threshold = 65 mph | 85 | 72.00 | 77.51 | 5.65 |
| | DSFS speed threshold = 70 mph | 85 | 71.08 | 77.70 | 5.83 |
| | DSFS speed threshold = 75 mph | 92 | 71.44 | 77.14 | 5.15 |
| 350 ft upstream of speed limit sign (DSFS location) | No DSFS (Baseline) | 119 | 72.98 | 79.00 | 5.56 |
| | DSFS speed threshold = 65 mph | 85 | 70.84 | 76.03 | 5.62 |
| | DSFS speed threshold = 70 mph | 85 | 69.97 | 76.00 | 5.85 |
| | DSFS speed threshold = 75 mph | 92 | 69.73 | 74.07 | 4.82 |
| At speed limit sign | No DSFS (Baseline) | 119 | 72.46 | 78.00 | 5.34 |
| | DSFS speed threshold = 65 mph | 85 | 70.03 | 76.00 | 5.43 |
| | DSFS speed threshold = 70 mph | 85 | 69.47 | 75.00 | 5.57 |
| | DSFS speed threshold = 75 mph | 92 | 69.12 | 73.83 | 4.23 |
| 500 ft downstream of speed limit sign | No DSFS (Baseline) | 119 | 71.63 | 77.16 | 5.35 |
| | DSFS speed threshold = 65 mph | 85 | 69.14 | 74.51 | 5.07 |
| | DSFS speed threshold = 70 mph | 85 | 68.90 | 74.00 | 5.12 |
| | DSFS speed threshold = 75 mph | 92 | 68.91 | 73.00 | 3.88 |

**Table 29. Descriptive Statistics for Passenger Vehicle Speed with DSFS Positioned Adjacent to the 65 mph Speed Limit Sign, NB US-127 St. Johns**

| Data Collection Location | Sign Test Condition | Sample Size | Mean (mph) | 85th%tile speed (mph) | Std. Dev. (mph) |
|---|---|---|---|---|---|
| 1500 ft upstream of speed limit sign (furthest upstream measurement) | No DSFS (Baseline) | 78 | 73.90 | 80.00 | 5.43 |
| | DSFS speed threshold = 65 mph | 100 | 72.97 | 78.74 | 5.91 |
| | DSFS speed threshold = 70 mph | 102 | 73.35 | 79.00 | 5.32 |
| | DSFS speed threshold = 75 mph | 97 | 73.41 | 79.00 | 5.40 |
| 1050 ft upstream of speed limit sign (location of "FREEWAY ENDS 1/4 MILE" sign) | No DSFS (Baseline) | 78 | 73.43 | 79.98 | 5.68 |
| | DSFS speed threshold = 65 mph | 100 | 72.27 | 78.95 | 6.07 |
| | DSFS speed threshold = 70 mph | 102 | 72.73 | 78.00 | 5.37 |
| | DSFS speed threshold = 75 mph | 97 | 72.36 | 78.30 | 5.54 |
| 700 ft upstream of speed limit sign | No DSFS (Baseline) | 78 | 72.66 | 79.57 | 5.73 |
| | DSFS speed threshold = 65 mph | 100 | 71.11 | 77.43 | 5.82 |
| | DSFS speed threshold = 70 mph | 102 | 71.82 | 77.65 | 5.40 |
| | DSFS speed threshold = 75 mph | 97 | 71.52 | 77.78 | 5.44 |
| 350 ft upstream of speed limit sign (DSFS location) | No DSFS (Baseline) | 78 | 72.13 | 78.15 | 5.54 |
| | DSFS speed threshold = 65 mph | 100 | 69.91 | 76.00 | 5.40 |
| | DSFS speed threshold = 70 mph | 102 | 70.99 | 76.71 | 5.07 |
| | DSFS speed threshold = 75 mph | 97 | 70.59 | 77.00 | 5.30 |
| At speed limit sign | No DSFS (Baseline) | 78 | 71.65 | 77.00 | 5.47 |
| | DSFS speed threshold = 65 mph | 100 | 68.94 | 75.00 | 5.04 |
| | DSFS speed threshold = 70 mph | 102 | 70.04 | 75.00 | 5.11 |
| | DSFS speed threshold = 75 mph | 97 | 69.81 | 75.30 | 4.81 |
| 500 ft downstream of speed limit sign | No DSFS (Baseline) | 78 | 70.90 | 76.67 | 5.02 |
| | DSFS speed threshold = 65 mph | 100 | 68.30 | 73.74 | 4.63 |
| | DSFS speed threshold = 70 mph | 102 | 69.14 | 73.69 | 4.78 |
| | DSFS speed threshold = 75 mph | 97 | 68.94 | 73.52 | 4.58 |

### 5.1.2 Results – Speed Reduction Effect of DSFS at Transition from Freeway to Non-Freeway based on DSFS Position and Messaging Strategy

Prior to analysis, the speeds measured at each 50 ft increment on the approach were subtracted from the speed measured at the furthest upstream point, which was 1500 ft upstream of the 65 mph speed limit sign. Doing so converted the raw speed data into speed reduction values and controlled for the normal speeding behavior of each driver prior to encountering the DSFS. This also allowed the regression parameters to be directly interpreted as speed reduction effects (e.g., the regression parameter estimate for the particular DSFS condition would represent the speed reduction effect of the DSFS compared to the base condition without the DSFS).

The first step was to compare the DSFS combined across all messaging conditions to the baseline (without the DSFS). The dataset was formatted into binary form with variables indicating the status of DSFS: 1 for active DSFS (data combined across the three messaging conditions) and 0 for inactive DSFS (baseline condition). The average speed change trajectories for the upstream position of DSFS are in **Figure 43** and for DSFS adjacent to the speed limit sign in **Figure 44**.

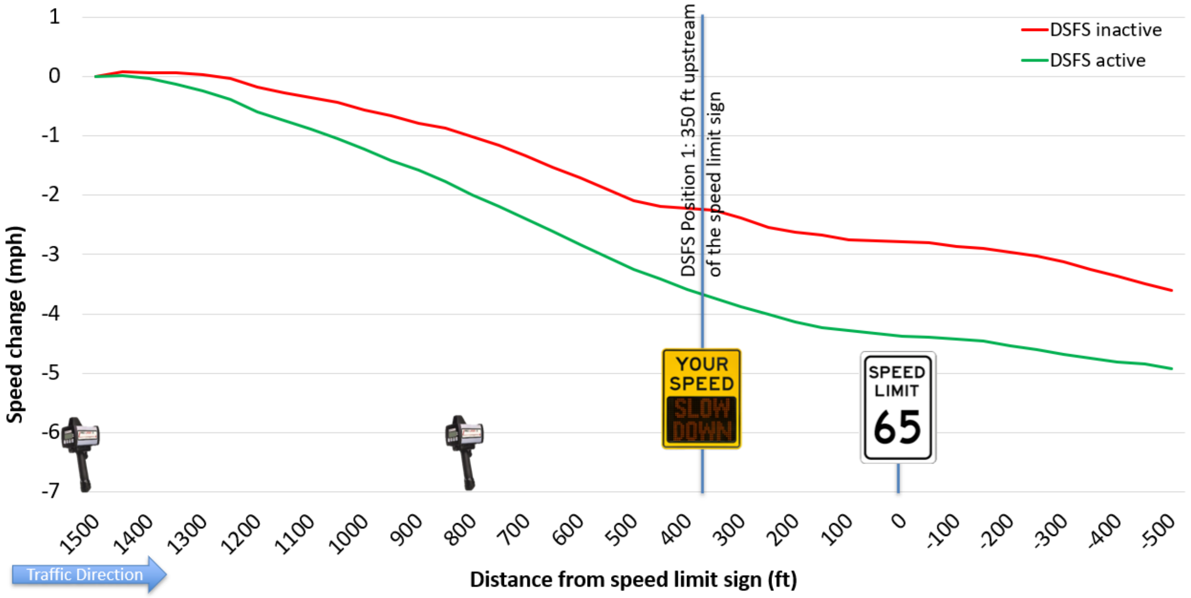


**Figure 43. Average Speed Change Trajectories for Active DSFS vs. No DSFS (DSFS 350 ft Upstream of the Speed Limit Sign)**

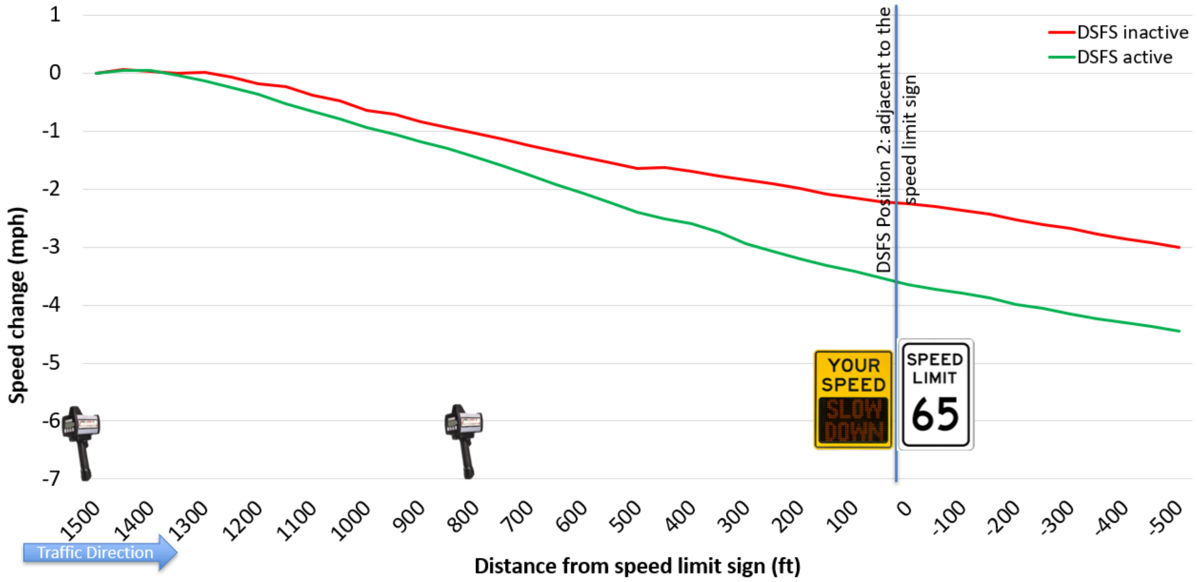


**Figure 44. Average Speed Change Trajectories for Active DSFS vs. No DSFS (DSFS Adjacent to the Speed Limit Sign)**

The preceding figures clearly demonstrate a speed reduction effect for the DSFS, with the speed reduction beginning further upstream when the DSFS was positioned upstream of the speed limit sign. After these initial comparisons, the datasets were then split by each speed threshold and message displayed to each approaching driver. The detection range for DSFS was 400 ft, so speeds at 750 ft upstream of the speed limit sign (for the first tested position of DSFS) and 400 ft upstream of the speed limit sign (for the second tested position of DSFS) were used to determine what message was displayed on the DSFS for each driver. This allowed for comparison between the two different DSFS positions for drivers approaching below or above each of the set speed thresholds. Drivers approaching below the particular speed threshold (e.g., 65, 70, or 75 mph) would only have the speed digits displayed on the DSFS, while drivers approaching above the speed threshold would have the speed digits alternating with SLOW DOWN displayed on the DSFS.

Separate regression models for speed were developed for each of the DSFS messages and each of the three speed thresholds. The primary variable of interest was the DSFS installation location. Average speed change trajectories for cases where only the speed digits were displayed on the DSFS panel are shown in **Figure 45** for vehicles approaching the DSFS below 65 mph, **Figure 46** for vehicles approaching the DSFS below 70 mph, and **Figure 47** for vehicles approaching below 75 mph. Results from linear regression models for each speed threshold with the DSFS displaying speed digits only are shown in

**Table** 30. Average speed change trajectories for cases where speed digits were alternating with a "SLOW DOWN" message on the DSFS panel are displayed in **Figure 48**, for vehicles approaching above 65 mph, in **Figure 49** for vehicles above 70 mph, and in **Figure 50** for vehicles above 75 mph. Results from linear regression models for each speed threshold with the DSFS displaying speed digits alternating with "SLOW DOWN" are provided in **Table 31**.

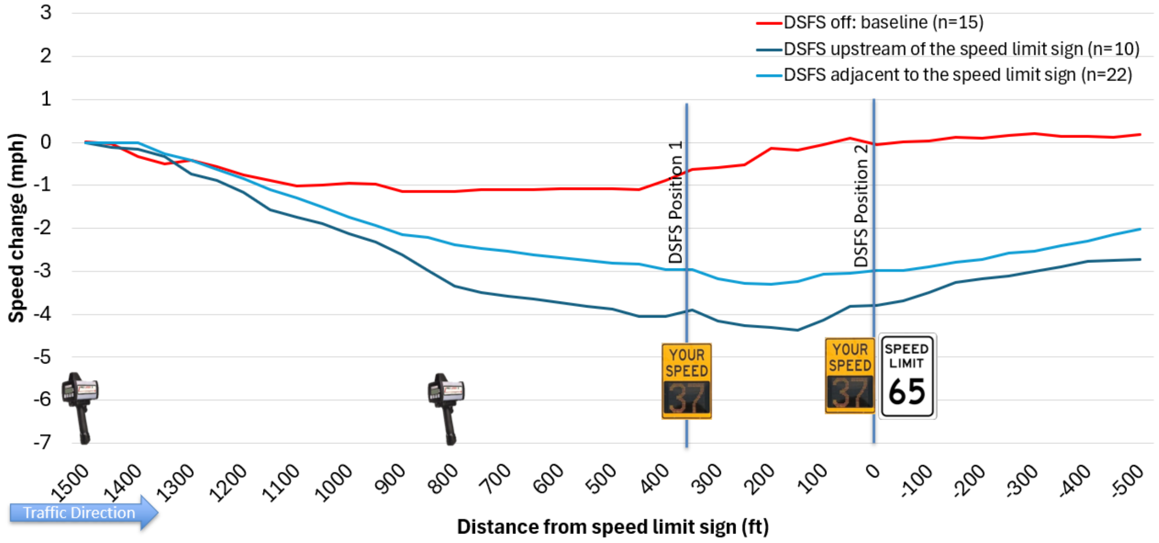


Figure 45. Average Speed Change Trajectories for Speeds < 65 mph (Speed Digits on DSFS)

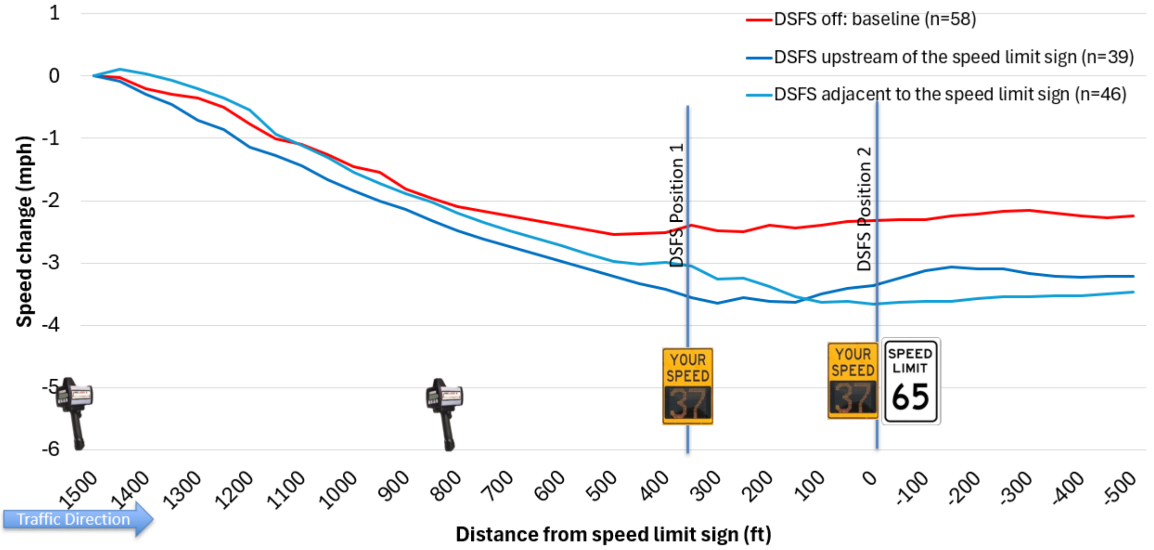


Figure 46. Average Speed Change Trajectories for Speeds < 70 mph (Speed Digits on DSFS)

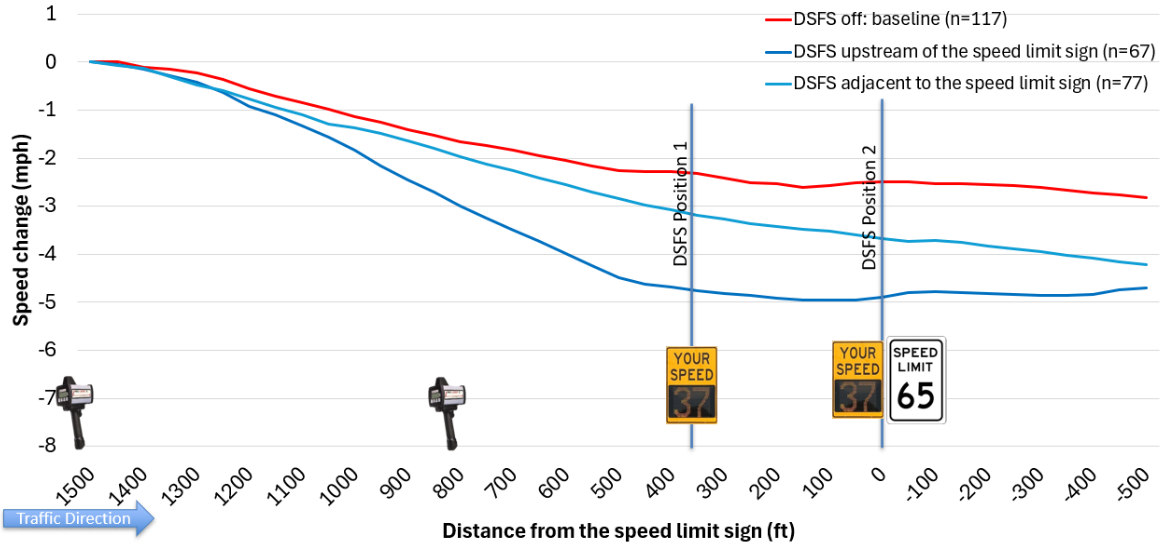


Figure 47. Average Speed Change Trajectories for Speeds < 75 mph (Speed Digits on DSFS)

## Table 30. Linear Regression Model for DSFS Displaying Speed Digits

| Speed Digits Only | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Parameters** | **Approach Speeds < 65 mph** | | | **Approach Speeds < 70 mph** | | | **Approach Speeds < 75 mph** | | |
| | **Est.** | **Std. Err** | **p-Value** | **Est.** | **Std. Err** | **p-Value** | **Est.** | **Std. Err** | **p-Value** |
| **Speed at 1,050 ft upstream of the speed limit sign** | | | | | | | | | |
| Intercept | -0.985 | 0.480 | 0.046 | -1.266 | 0.299 | <0.001 | -0.988 | 0.188 | >0.001 |
| DSFS off | *Baseline* | | | *Baseline* | | | *Baseline* | | |
| DSFS 350 ft upstream of speed limit sign | -0.913 | 0.758 | 0.235 | -0.392 | 0.471 | 0.406 | -0.582 | 0.312 | 0.063 |
| DSFS adjacent to speed limit sign | -0.523 | 0.622 | 0.405 | -0.191 | 0.461 | 0.680 | -0.310 | 0.298 | 0.300 |
| **Speed at 750 ft upstream of the speed limit sign** | | | | | | | | | |
| Intercept | -1.111 | 0.735 | 0.138 | -2.170 | 0.409 | 0.000 | -1.736 | 0.257 | >0.001 |
| DSFS off | *Baseline* | | | *Baseline* | | | *Baseline* | | |
| DSFS 350 ft upstream of speed limit sign | -2.385 | 1.162 | 0.046 | -0.450 | 0.645 | 0.486 | -1.509 | 0.426 | >0.001 |
| DSFS adjacent to speed limit sign | -1.366 | 0.953 | 0.159 | -0.425 | 0.631 | 0.502 | -0.388 | 0.408 | 0.343 |
| **Speed at 350 ft upstream of the speed limit sign** | | | | | | | | | |
| Intercept | -0.632 | 1.036 | 0.545 | -2.389 | 0.501 | >0.001 | -2.326 | 0.310 | >0.001 |
| DSFS off | *Baseline* | | | *Baseline* | | | *Baseline* | | |
| DSFS 350 ft upstream of speed limit sign | -3.271 | 1.638 | 0.052 | -1.166 | 0.789 | 0.142 | -2.436 | 0.513 | >0.001 |
| DSFS adjacent to speed limit sign | -2.331 | 1.343 | 0.090 | -0.945 | 0.772 | 0.223 | -0.862 | 0.492 | 0.081 |
| **Speed at 0 ft (speed limit sign)** | | | | | | | | | |
| Intercept | -0.049 | 1.076 | 0.964 | -2.314 | 0.540 | 0.000 | -2.488 | 0.336 | >0.001 |
| DSFS off | *Baseline* | | | *Baseline* | | | *Baseline* | | |
| DSFS 350 ft upstream of speed limit sign | -3.752 | 1.701 | 0.033 | -1.052 | 0.852 | 0.219 | -2.414 | 0.557 | >0.001 |
| DSFS adjacent to speed limit sign | -2.942 | 1.395 | 0.041 | -1.713 | 0.834 | 0.042 | -1.184 | 0.534 | 0.027 |
| **Speed at 500 ft downstream of the speed limit sign** | | | | | | | | | |
| Intercept | 0.171 | 1.200 | 0.887 | -2.247 | 0.576 | >0.001 | -2.814 | 0.378 | >0.001 |
| DSFS off | *Baseline* | | | *Baseline* | | | *Baseline* | | |
| DSFS 350 ft upstream of speed limit sign | -2.887 | 1.898 | 0.135 | -0.974 | 0.909 | 0.286 | -1.886 | 0.626 | 0.003 |
| DSFS adjacent to speed limit sign | -2.191 | 1.557 | 0.166 | -1.444 | 0.889 | 0.107 | -1.401 | 0.600 | 0.020 |

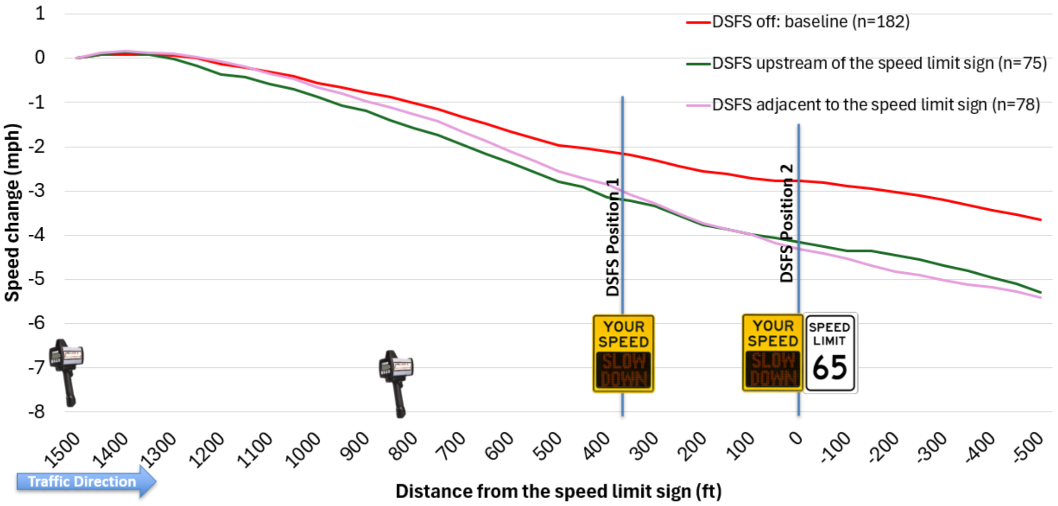


Figure 48. Average Speed Change Trajectories for Speeds >65 mph (Speed Digits Alternating with SLOW DOWN)

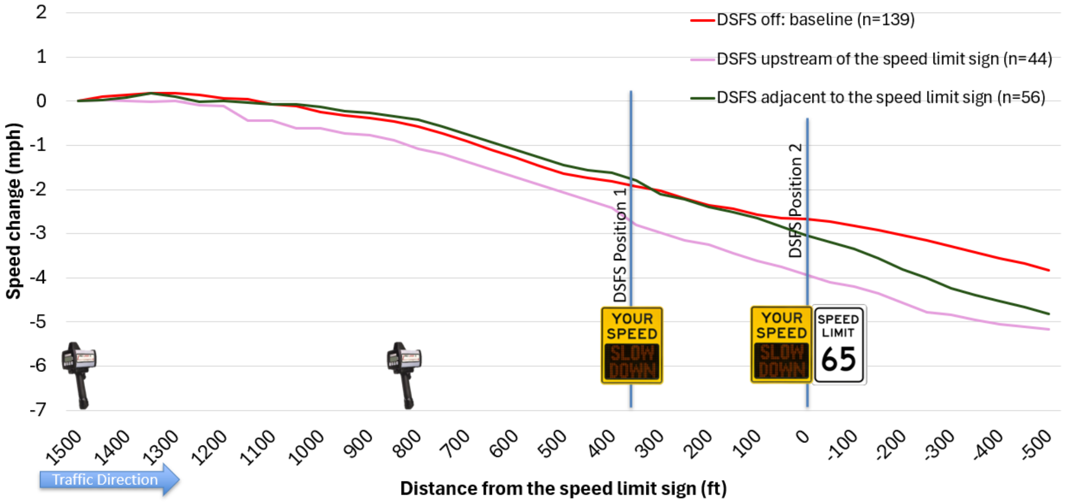


Figure 49. Average Speed Change Trajectories for Speeds >70 mph (Speed Digits Alternating with SLOW DOWN)

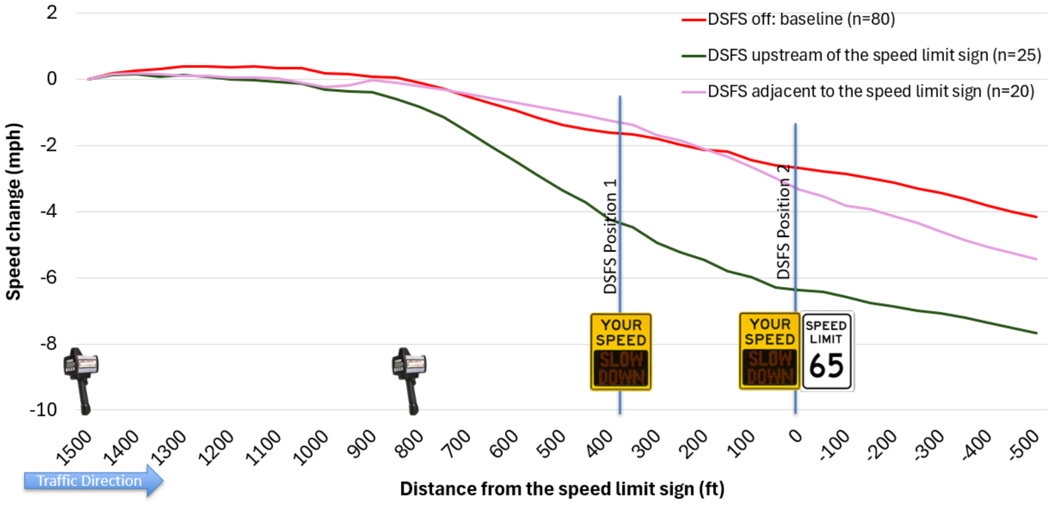


Figure 50. Average Speed Change Trajectories for Speeds >75 mph (Speed Digits Alternating with SLOW DOWN)

## Table 31. Linear Regression Model for DSFS Alternating Speed Digits with SLOW DOWN

| **Speed digits alternating with "SLOW DOWN" message** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Parameters** | **Approach Speeds > 65 mph** | | | **Approach Speeds > 70 mph** | | | **Approach Speed > 75 mph** | | |
| | **Est.** | **Std. Err** | **p-Value** | **Est.** | **Std. Err** | **p-Value** | **Est** | **Std. Err** | **p-Value** |
| **Speed at 1,050 ft upstream of the speed limit sign** | | | | | | | | | |
| Intercept | -0.407 | 0.133 | 0.002 | -0.111 | 0.142 | 0.433 | 0.318 | 0.162 | 0.053 |
| DSFS off | *Baseline* | | | *Baseline* | | | *Baseline* | | |
| DSFS 350 ft upstream of speed limit sign | -0.300 | 0.245 | 0.222 | -0.496 | 0.289 | 0.087 | -0.409 | 0.340 | 0.231 |
| DSFS adjacent to speed limit sign | -0.052 | 0.242 | 0.828 | 0.047 | 0.264 | 0.860 | -0.423 | 0.365 | 0.249 |
| **Speed at 750 ft upstream of the speed limit sign** | | | | | | | | | |
| Intercept | -1.151 | 0.188 | >0.001 | -0.722 | 0.197 | 0.000 | -0.324 | 0.230 | 0.162 |
| DSFS off | *Baseline* | | | *Baseline* | | | *Baseline* | | |
| DSFS 350 ft upstream of speed limit sign | -0.591 | 0.349 | 0.091 | -0.480 | 0.402 | 0.234 | -0.749 | 0.481 | 0.122 |
| DSFS adjacent to speed limit sign | -0.281 | 0.344 | 0.414 | 0.147 | 0.368 | 0.689 | 0.022 | 0.517 | 0.966 |
| **Speed at 350 ft upstream of the speed limit sign** | | | | | | | | | |
| Intercept | -2.177 | 0.250 | >0.001 | -1.922 | 0.281 | 0.000 | -1.747 | 0.411 | >0.001 |
| DSFS off | *Baseline* | | | *Baseline* | | | *Baseline* | | |
| DSFS 350 ft upstream of speed limit sign | -1.044 | 0.463 | 0.025 | -0.876 | 0.573 | 0.127 | -2.580 | 0.860 | 0.003 |
| DSFS adjacent to speed limit sign | -0.907 | 0.457 | 0.048 | 0.122 | 0.524 | 0.816 | 0.357 | 0.924 | 0.700 |
| **Speed at 0 ft (speed limit sign)** | | | | | | | | | |
| Intercept | -2.773 | 0.287 | >0.001 | -2.671 | 0.332 | 0.000 | -2.758 | 0.466 | >0.001 |
| DSFS off | *Baseline* | | | *Baseline* | | | *Baseline* | | |
| DSFS 350 ft upstream of speed limit sign | -1.379 | 0.530 | 0.010 | -1.253 | 0.677 | 0.065 | -3.503 | 0.975 | >0.001 |
| DSFS adjacent to speed limit sign | -1.542 | 0.523 | 0.003 | -0.354 | 0.620 | 0.569 | -0.576 | 1.047 | 0.583 |
| **Speed at 500 ft downstream of the speed limit sign** | | | | | | | | | |
| Intercept | -3.656 | 0.326 | >0.001 | -3.831 | 0.362 | 0.000 | -4.217 | 0.510 | >0.001 |
| DSFS off | *Baseline* | | | *Baseline* | | | *Baseline* | | |
| DSFS 350 ft upstream of speed limit sign | -1.644 | 0.603 | 0.007 | -1.330 | 0.738 | 0.073 | -3.435 | 1.066 | 0.002 |
| DSFS adjacent to speed limit sign | -1.759 | 0.595 | 0.003 | -0.989 | 0.675 | 0.144 | -1.225 | 1.145 | 0.287 |

Results from **Table 30** and **Table 31** suggest that DSFS was an effective speed reduction strategy in both of the tested installation positions. However, as can be observed from the preceding graphical representations of the speed reduction trajectories, the speed reductions generally began further upstream and were of a larger magnitude as vehicles passed by the speed limit sign for cases where the DSFS was positioned 350 upstream of the speed limit sign. This was particularly true for drivers approaching above 75 mph, who were the fastest group of drivers in this field study. From **Table 31** it can be observed that for drivers above 75 mph, the DSFS produced greater speed reductions when it was positioned upstream of the speed limit sign compared to adjacent to the speed limit sign. Compared to the base condition without the DSFS, speeds measured 500 ft downstream of the 65 mph speed limit sign were 3.44 mph lower when the DSFS was positioned 350 ft upstream of the speed limit sign, compared to 1.23 mph lower when the DSFS was positioned adjacent to the speed limit sign. Again, the DSFS would have been displaying speed digits alternating with SLOW DOWN as each of these drivers approached the DSFS.

**Table 30** shows that similar results were observed for drivers approaching the DSFS below 75 mph, for whom the DSFS would have displayed only the speed digits. For this group of drivers, compared to the base condition without the DSFS, speeds measured at the 65 mph speed limit sign were 1.89 mph lower when the DSFS was positioned 350 ft upstream of the speed limit sign, compared to 1.40 mph lower when the DSFS was positioned adjacent to the speed limit sign. These findings were also similar for cases where the speed threshold for the SLOW DOWN messaging was lowered to 70 mph and 65 mph.

Regardless of the additional benefits provided by positioning the DSFS upstream of the speed limit sign, the 11th Edition MUTCD states that when used for regulatory speed applications, the DSFS must be placed beneath the speed limit sign (FHWA 2023). Similarly, 11th Edition MUTCD also disallows the display of any messages other than the speed digits, including SLOW DOWN messages, even when the message alternates with the speed digits, which has been MDOT's standard application of DSFS messaging for several years. Thus, although the findings of this study, which was performed prior to publication of the 11th Edition MUTCD, would support the use of SLOW DOWN messages and positioning the DSFS upstream of the speed limit sign, neither of these applications will be recommended. Fortunately, the DSFS was found to be effective for speed reduction, albeit slightly less so, when positioned adjacent to the speed limit sign and displaying speed digits only. Thus the use of DSFS as a speed reduction countermeasure at freeway to non-freeway transitions is recommended. When used for such applications, per the 11th Edition MUTCD, the DSFS must be placed beneath the speed limit sign on the same assembly and shall only display the speed digits of approaching vehicles (FHWA 2023).

## 5.2 DSFS at Rural to Urban Transition

A DSFS was tested as a speed reduction strategy at EB M-115 entering the Village of Farwell, Michigan. This location was selected due to complaints of excessive speeds through the community by community officials. Prior to reaching the village limits, M-115 possessed a speed limit of 55 mph, which was reduced to 45 mph at the village limit.

### 5.2.1 Sign Test Conditions and Data Collection Procedures

A DSFS with a 15-inch display panel was temporarily installed adjacent to the 45 mph speed limit sign. Speed data were collected using a handheld LIDAR gun during weekday off-peak periods in September 2024. The LIDAR operator was positioned 700 ft upstream of the 45 mph speed limit sign in an unmarked vehicle parked on the roadside. The operator was positioned at the same location for all periods. The DSFS was operational for at least five days prior to data collection. The DSFS was programmed to display the following messages:

1. Baseline: No DSFS
2. Speed digits
3. Speed digits + "SLOW DOWN" for speeds > 45 mph; speed digits for speeds < 45 mph

The field evaluation layout and sign test conditions at EB M-115 entering Farwell are shown in **Figure 51**. An example of a DSFS display at this site when displaying speed digits is shown in **Figure 52**. Data were only collected for passenger vehicles due to low truck volumes.

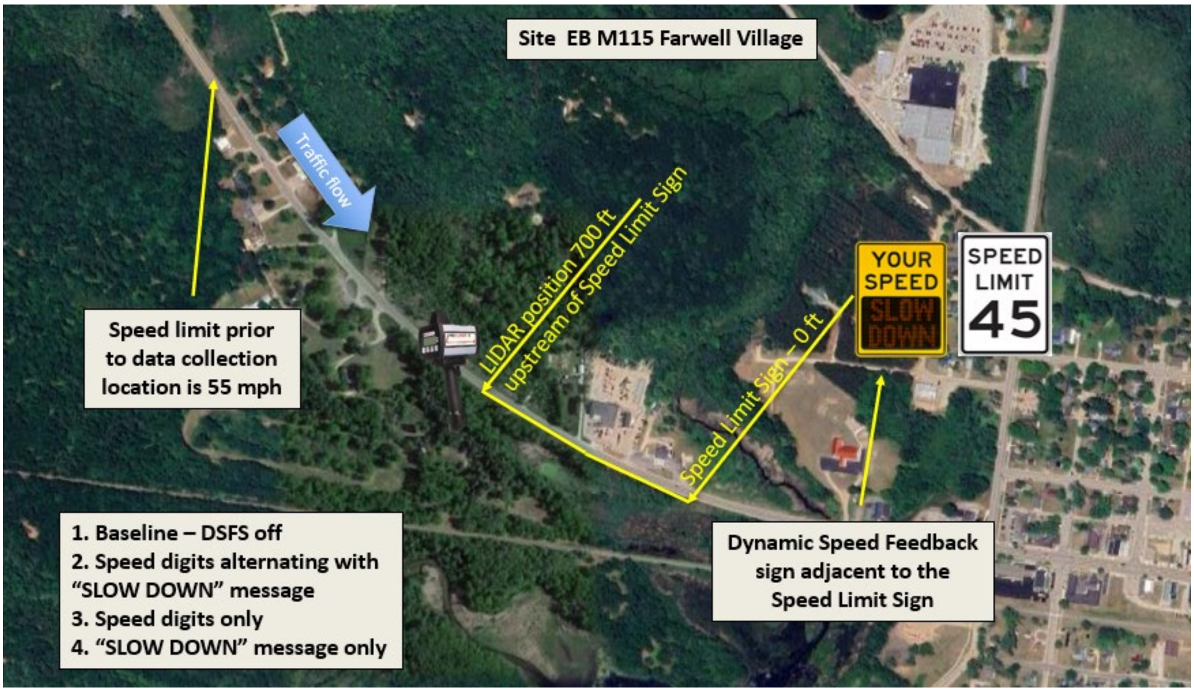


**Figure 51. Field Evaluation Layout and Sign Test Conditions at EB M-115 Entering Farwell**

Figure 52. Example of DSFS Message Display at EB M-115 Entering Farwell

### 5.2.2 Results – Speed Reduction Effect of DSFS at Transition from Rural Highway to Community based on DSFS Messaging Strategy

Prior to analysis, the speeds measured at each 50 ft increment on the approach to the speed reduction zone were subtracted from the speed measured at the furthest upstream point, which was 600 ft upstream of the 45 mph speed limit sign. Doing so converted the raw speed data into speed reduction values and controlled for the normal speeding behavior of each driver prior to encountering the DSFS. This also allowed the regression parameters to be directly interpreted as speed reduction effects (e.g., the regression parameter estimate for the particular DSFS condition would represent the speed reduction effect of the DSFS compared to the base condition without the DSFS).

After the datasets were organized into speed reductions at each 50 ft increment, to isolate the effects of the various DSFS messaging strategies, the data were further split into two separate files based on the DSFS message displayed for the approaching driver. Since the typical detection range of the DSFS radar is 400 ft, the data were separated into drivers approaching at speeds below 45 mph (for whom only speed digits were displayed on the DSFS) and vehicles approaching above 45 mph (for whom either speed digits only or speed digits alternating with SLOW DOWN were displayed, depending on the particular test condition). Descriptive statistics for drivers approaching below 45 mph are in **Table 32**, while descriptive statistics for drivers approaching above 45 mph are in **Table** 33. Speed change trajectories for drivers approaching below 45 mph and above 45 mph are displayed in **Figure 53** and **Figure 54**, respectively.

## Table 32. Descriptive Statistics for Speed on EB M-115 Approaching Farwell (< 45 mph)

| Data Collection Location | Sign Test Condition | Sample Size | Mean (mph) | 85th %tile speed (mph) | Std. Dev. (mph) |
|---|---|---|---|---|---|
| 400 ft upstream of speed limit sign | Baseline: No DSFS | 31 | 43.64 | 45.00 | 1.33 |
| | DSFS displaying speed digits | 31 | 43.46 | 45.00 | 1.62 |
| 200 ft upstream of speed limit sign | Baseline: No DSFS | 31 | 43.60 | 45.00 | 1.44 |
| | DSFS displaying speed digits | 31 | 42.46 | 44.20 | 2.00 |
| Speed at speed limit sign/DSFS | Baseline: No DSFS | 31 | 43.72 | 45.02 | 1.79 |
| | DSFS displaying speed digits | 31 | 41.98 | 44.00 | 1.80 |
| 250 ft downstream of speed limit sign | Baseline: No DSFS | 31 | 43.41 | 45.00 | 1.96 |
| | DSFS displaying speed digits | 31 | 41.81 | 44.00 | 1.99 |
| 500 ft downstream of speed limit sign | Baseline: No DSFS | 31 | 42.98 | 45.27 | 2.55 |
| | DSFS displaying speed digits | 31 | 41.40 | 44.20 | 2.14 |

## Table 33. Descriptive Statistics for Speed on EB M-115 Approaching Farwell (> 45 mph)

| Data Collection Location | Sign Test Condition | Sample Size | Mean (mph) | 85th %tile speed (mph) | Std. Dev. (mph) |
|---|---|---|---|---|---|
| 400 ft upstream of speed limit sign | Baseline: No DSFS | 135 | 52.35 | 57.00 | 3.98 |
| | DSFS displaying speed digits | 65 | 51.60 | 56.09 | 3.82 |
| | DSFS alternating speed digits / SLOW DOWN | 79 | 50.78 | 55.00 | 3.48 |
| 200 ft upstream of speed limit sign | Baseline: No DSFS | 135 | 51.55 | 56.00 | 3.98 |
| | DSFS displaying speed digits | 65 | 50.26 | 54.00 | 3.82 |
| | DSFS alternating speed digits / SLOW DOWN | 79 | 49.85 | 54.21 | 3.62 |
| Speed at speed limit sign/DSFS | Baseline: No DSFS | 135 | 50.75 | 55.31 | 4.34 |
| | DSFS displaying speed digits | 65 | 48.17 | 52.83 | 4.16 |
| | DSFS alternating speed digits / SLOW DOWN | 79 | 48.49 | 53.00 | 3.76 |
| 250 ft downstream of speed limit sign | Baseline: No DSFS | 135 | 49.76 | 55.05 | 4.46 |
| | DSFS displaying speed digits | 65 | 46.57 | 51.00 | 3.95 |
| | DSFS alternating speed digits / SLOW DOWN | 79 | 47.14 | 51.00 | 3.68 |
| 500 ft downstream of speed limit sign | Baseline: No DSFS | 135 | 48.70 | 53.94 | 4.71 |
| | DSFS displaying speed digits | 65 | 45.24 | 49.87 | 3.90 |
| | DSFS alternating speed digits / SLOW DOWN | 79 | 45.98 | 49.26 | 3.63 |

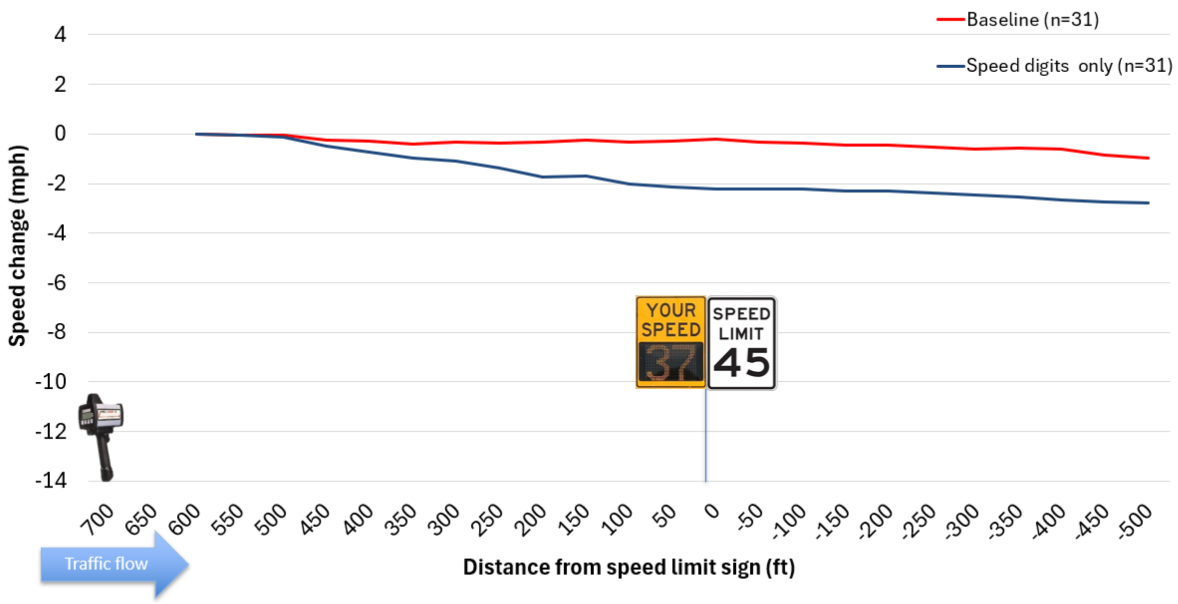


Figure 53. Average Speed Change Trajectories for speeds < 45 mph, EB M-115 at Farwell

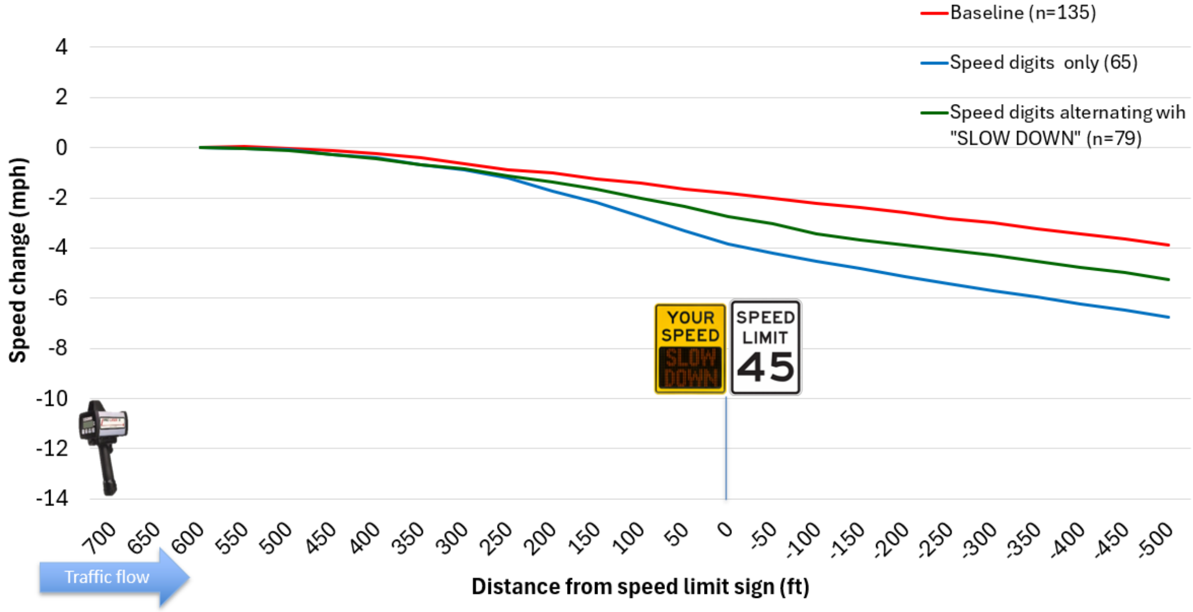


Figure 54. Average Speed Change Trajectories for speeds > 45 mph, EB M-115 at Farwell

Separate linear regression models were developed for the two driver speed groups (e.g., < 45 mph, > 45 mph), with the results displayed in **Table 34** and **Table 35**, respectively. As results in both tables suggest, the DSFS is an effective speed warning treatment for drivers approaching below or above the 45 mph speed limit. For drivers approaching below 45 mph, **Table 34** shows that compared to the base condition, the DSFS (displaying only speed digits) produced a speed reduction of 1.99 mph at the speed limit sign, which was largely sustained 500 feet beyond the speed limit sign. However, even greater speed reductions were observed for drivers approaching at speeds above 45 mph, particularly for cases where the DSFS was only displaying the speed digits. As shown in **Table 35**, for drivers approaching greater than 45 mph, the DSFS displaying only speed digits produced a speed reduction of 2.01 mph at the speed limit sign, which increased to 2.89 mph when the vehicle was 500 feet beyond the speed limit sign. Slightly lower speed reduction effects were observed for cases where the DSFS displayed SLOW DOWN alternating with the speed digest, which reached a maximum of 1.37 mph 500 feet downstream of the speed limit sign.

**Table 34. Linear Regression Model for Speed Reduction Approaching Farwell (< 45 mph)**

| Parameters | Estimate | Std. Error | p-Value |
|---|---|---|---|
| **Speed 400 ft upstream of the speed limit sign** | | | |
| Intercept | -0.295 | 0.174 | 0.096 |
| No DSFS | *Baseline* | | |
| DSFS displaying speed digits | -0.424 | 0.247 | 0.091 |
| **Speed 200 ft upstream of the speed limit sign** | | | |
| Intercept | -0.329 | 0.330 | 0.323 |
| No DSFS | *Baseline* | | |
| DSFS displaying speed digits | -1.386 | 0.467 | 0.004 |
| **Speed at Speed Limit Sign/DSFS** | | | |
| Intercept | -0.214 | 0.335 | 0.526 |
| No DSFS | *Baseline* | | |
| DSFS displaying speed digits | -1.985 | 0.474 | <0.001 |
| **Speed 250 ft downstream of the speed limit sign** | | | |
| Intercept | -0.522 | 0.380 | 0.175 |
| No DSFS | *Baseline* | | |
| DSFS displaying speed digits | -1.847 | 0.537 | 0.001 |
| **Speed 500 ft downstream of the speed limit sign** | | | |
| Intercept | -0.952 | 0.520 | 0.072 |
| No DSFS | *Baseline* | | |
| DSFS displaying speed digits | -1.831 | 0.735 | 0.015 |

Table 35. Linear Regression Model for Speed Reduction Approaching Farwell (> 45 mph)

| Parameters | Estimate | Std. Error | p-Value |
|---|---|---|---|
| **Speed 400 ft upstream of the speed limit sign** | | | |
| Intercept | -0.218 | 0.064 | 0.001 |
| No DSFS | *Baseline* | | |
| DSFS displaying speed digits | -0.182 | 0.113 | 0.107 |
| DSFS alternating speed digits / SLOW DOWN | -0.217 | 0.106 | 0.041 |
| **Speed 200 ft upstream of the speed limit sign** | | | |
| Intercept | -1.022 | 0.146 | <0.001 |
| No DSFS | *Baseline* | | |
| DSFS displaying speed digits | -0.716 | 0.257 | 0.006 |
| DSFS alternating speed digits / SLOW DOWN | -0.350 | 0.241 | 0.147 |
| **Speed at Speed Limit Sign/DSFS** | | | |
| Intercept | -1.820 | 0.237 | <0.001 |
| No DSFS | *Baseline* | | |
| DSFS displaying speed digits | -2.009 | 0.415 | <0.001 |
| DSFS alternating speed digits / SLOW DOWN | -0.905 | 0.390 | 0.021 |
| **Speed 250 ft downstream of the speed limit sign** | | | |
| Intercept | -2.807 | 0.279 | <0.001 |
| No DSFS | *Baseline* | | |
| DSFS displaying speed digits | -2.626 | 0.490 | 0.000 |
| DSFS alternating speed digits / SLOW DOWN | -1.274 | 0.460 | 0.006 |
| **Speed 500 ft downstream of the speed limit sign** | | | |
| Intercept | -3.872 | 0.310 | <0.001 |
| No DSFS | *Baseline* | | |
| DSFS displaying speed digits | -2.888 | 0.543 | <0.001 |
| DSFS alternating speed digits / SLOW DOWN | -1.368 | 0.510 | 0.008 |

For speeds above 45 mph, a series of binary logistic models were developed to determine the likelihood of drivers exceeding the speed limit and exceeding the speed limit by more than 5 mph or 10 mph at the speed limit sign. Results from **Table 36** suggest that compared to the base condition without the DSFS, drivers were 76.3 percent (1-Exp(β) = 1-0.237) less likely to exceed the 45 mph speed limit if the DSFS was displaying only speed digits, and 66.5 percent less likely to exceed the speed limit if the DSFS was displaying speed digits alternating with SLOW DOWN. Furthermore, compared to the base condition without the DSFS, drivers were 75.5 percent and 88.8 percent less likely to exceed the speed limit by 5 mph and 10 mph, respectively, when speed digits were displayed on the DSFS. For cases where the speed digits alternated with SLOW DOWN, drivers were 41.9 percent and 85.1 percent less likely to exceed the speed limit by 5 mph and 10 mph, respectively, compared to the base condition without the DSFS.

**Table 36. Binary Logistic Model for Likelihood of Exceeding Speed Limit Entering Farwell (>45 mph)**

| Condition | Parameters | Estimate | Std. Error | p-Value | Exp(B) |
|---|---|---|---|---|---|
| Exceeding speed limit at the speed limit sign | Intercept | -20.542 | 3.622 | >0.001 | 0.000 |
| | Speed 600 ft upstream of the speed limit sign | 0.454 | 0.074 | >0.001 | 1.574 |
| | No DSFS | *Baseline* | | | |
| | DSFS displaying speed digits | -1.439 | 0.473 | 0.002 | 0.237 |
| | DSFS alternating speed digits / SLOW DOWN | -1.095 | 0.442 | 0.013 | 0.335 |
| 5 mph over speed limit at the speed limit sign | Intercept | -35.143 | 4.055 | >0.001 | 0.000 |
| | Speed 600 ft upstream of the speed limit sign | 0.675 | 0.078 | >0.001 | 1.963 |
| | No DSFS | *Baseline* | | | |
| | DSFS displaying speed digits | -1.408 | 0.478 | 0.003 | 0.245 |
| | DSFS alternating speed digits / SLOW DOWN | -0.542 | 0.423 | 0.200 | 0.581 |
| 10 mph over speed limit at the speed limit sign | Intercept | -56.021 | 11.031 | >0.001 | 0.000 |
| | Speed 600 ft upstream of the speed limit sign | 0.975 | 0.194 | >0.001 | 2.652 |
| | No DSFS | *Baseline* | | | |
| | DSFS displaying speed digits | -2.187 | 1.051 | 0.037 | 0.112 |
| | DSFS alternating speed digits / SLOW DOWN | -1.905 | 1.122 | 0.089 | 0.149 |

These results support the expanded use of DSFS at transitions from rural highway into a community. These findings also support the requirements of the 11th Edition MUTCD, which states that the DSFS must be placed beneath the speed limit sign when used for regulatory speed applications and must only display speed digits (FHWA 2023).

## 5.3 DSFS at Roundabout in Rural to Urban Transition

The DSFS was also tested as a speed reduction countermeasure at four high-speed roundabout transition sites approaching a community. Two different highway contexts were included in this evaluation: 1.) roundabouts at a transition from a rural highway entering a community (two sites) and 2.) roundabouts at freeway exit ramp connectors entering a community (two sites). The sites were selected based on the following conditions:

1. Single-lane approach to the roundabout,
2. Single-circulating lane within the roundabout,
3. DSFS installation capability adjacent to the roundabout warning sign,
4. Majority of approaching vehicles are free-flowing, and
5. Suitable for LIDAR data collection (i.e., space on the roadside for a parked vehicle).

### 5.3.1 Site Descriptions and Test Conditions

#### 5.3.1.1 Site 1 - SB M-52 Chelsea

Southbound M-52 at Werkner Road approaching Chelsea possessed a 55 mph speed limit upstream of the roundabout, which was reduced to 45 mph 3,000 ft downstream of the roundabout. A total of three roundabout warning signs (W2-6) existed along the approach, with two located 1,050 ft upstream of the yield sign on both sides of the road and a third W2-6 sign positioned 500 ft upstream of the roundabout. Each of the existing W2-6 signs had flashing LED borders. Optical speed bar pavement markings existed on the approach. A DSFS was temporarily installed beneath the downstream W2-6 sign and above the 20 mph advisory speed plaque (W13-1P). Speed data were collected after one week to assess the effect of the following DSFS messaging strategies along with the effect of the flashing LED border W2-6 signs.

1. Baseline Condition: Both DSFS and flashing LEDs on roundabout warning signs were off
2. LED borders on roundabout warning signs were flashing; DSFS off
3. LED borders were off; DSFS displayed speed digits alternating with SLOW DOWN
4. LED borders were off; DSFS displayed speed digits only
5. LED borders were off; DSFS displayed SLOW DOWN only

Speed data were collected using a handheld LIDAR gun during May of 2023. The technician operating LIDAR was positioned 1,200 ft upstream of the yield sign in a vehicle parked on the roadside and remained at that location across all setups. The field evaluation layout and sign test conditions for SB M-52 Chelsea are shown in **Figure 55**.

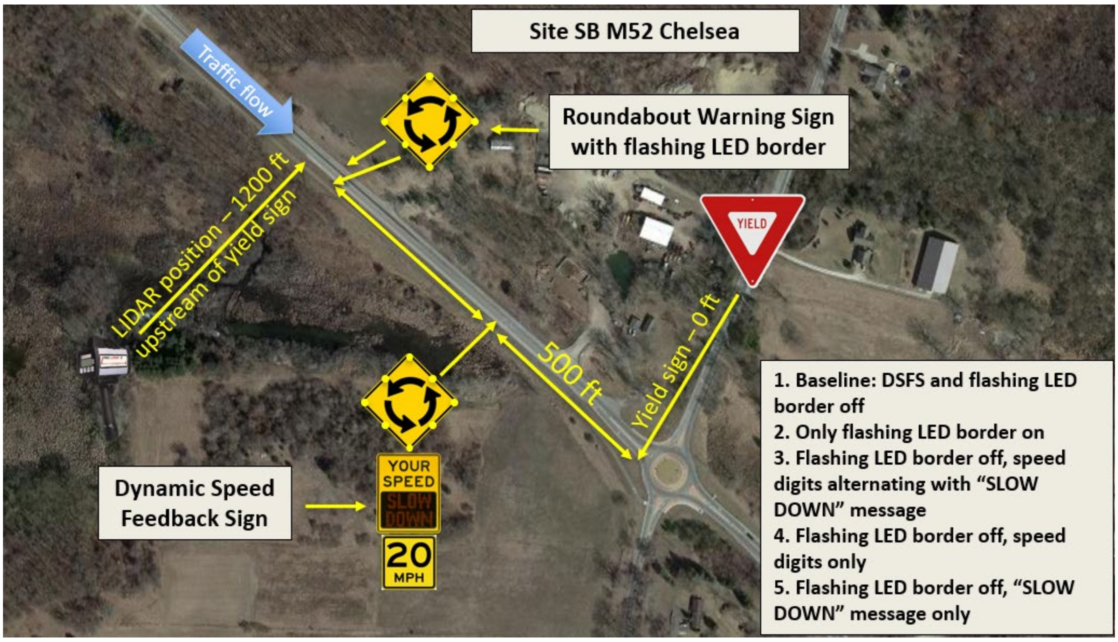


Figure 55. Field Evaluation Layout and Sign Test Conditions, SB M-52 Chelsea (Site 1)

#### 5.3.1.2 Site 2 - EB M-43 Grand Ledge

Eastbound M-43 at the Grand Ledge High School driveway possessed a 55 mph speed limit upstream of the roundabout, which was reduced to 45 mph 1,500 ft downstream of the roundabout. Two roundabout warning signs (W2-6) existed along the approach, with the first located 1,500 ft upstream of the yield sign and the second located 950 ft upstream of the yield sign. Both W2-6 signs were mounted on the right side. Optical speed bar pavement markings also existed on the approach. A DSFS was temporarily installed beneath the downstream W2-6 sign and above the 20 mph advisory speed plaque (W13-1P). Speed data were collected after one week to assess the effect of the following DSFS messaging strategies:

1. Baseline Condition: DSFS off
2. DSFS displayed speed digits alternating with SLOW DOWN
3. DSFS displayed speed digits only
4. DSFS displayed SLOW DOWN only.

Speed data were collected using a handheld LIDAR gun during May 2023. The LIDAR operator was positioned 1,450 ft upstream of the yield sign in a vehicle parked on the roadside and remained at that location across all setups. The field evaluation layout and sign test conditions for EB M-43 Grand Ledge is shown in **Figure 56**.

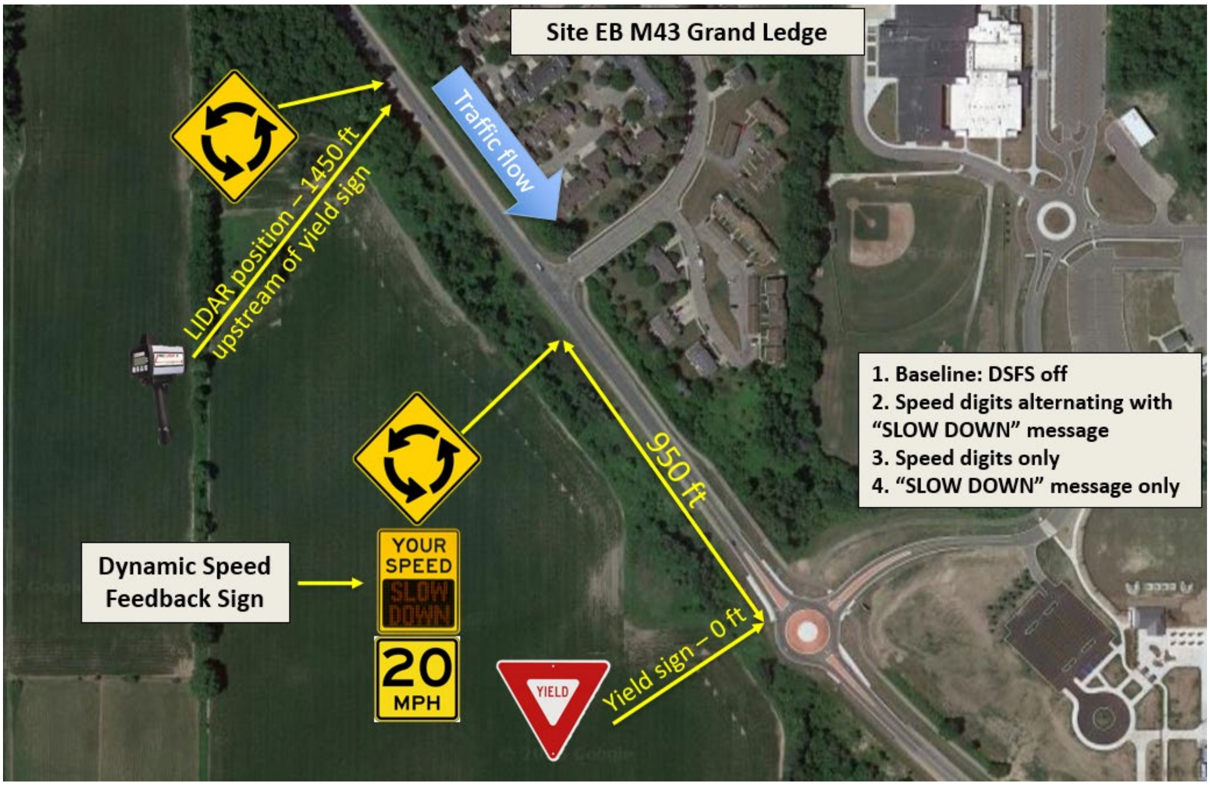


**Figure 56. Field Evaluation Layout and Sign Test Conditions, EB M-43 Grand Ledge (Site 2)**

#### 5.3.1.3 Site 3 - NB US-127 Exit 156 to Clare

Northbound US-127 is a limited access freeway with a 75 mph mainline speed limit. The exit ramp connector, which was approximately 1 mile long and did not include a posted speed limit, led into a roundabout prior to entering the Clare city limits. The speed limit was reduced to 45 mph 1,000 ft downstream of the roundabout. Two roundabout warning signs (W2-6) existed approximately 800 ft upstream of the roundabout on both sides of the road. Both warning signs had flashing amber beacons on top. A DSFS was temporarily installed beneath the right-side W2-6 sign, and above the 20 mph advisory speed plaque (W13-1P). Speed data were collected after one week to assess the effect of the following DSFS messaging strategies:

1. Baseline Condition: DSFS off; flashing amber beacons on
2. DSFS displayed speed digits alternating with SLOW DOWN; flashing amber beacons on
3. DSFS displayed speed digits only; flashing amber beacons on
4. DSFS displayed SLOW DOWN only; flashing amber beacons on

The amber beacons on top of the roundabout warning signs remained flashing during the entire study as they could not be turned off. Speed data were collected using a handheld LIDAR gun during October 2023. The LIDAR operator was positioned 1,300 ft upstream of the yield sign in a vehicle parked on the roadside and remained at that location for the study. The field evaluation layout and sign test conditions for NB US-127 Exit 156 to Clare are shown in **Figure 57**.

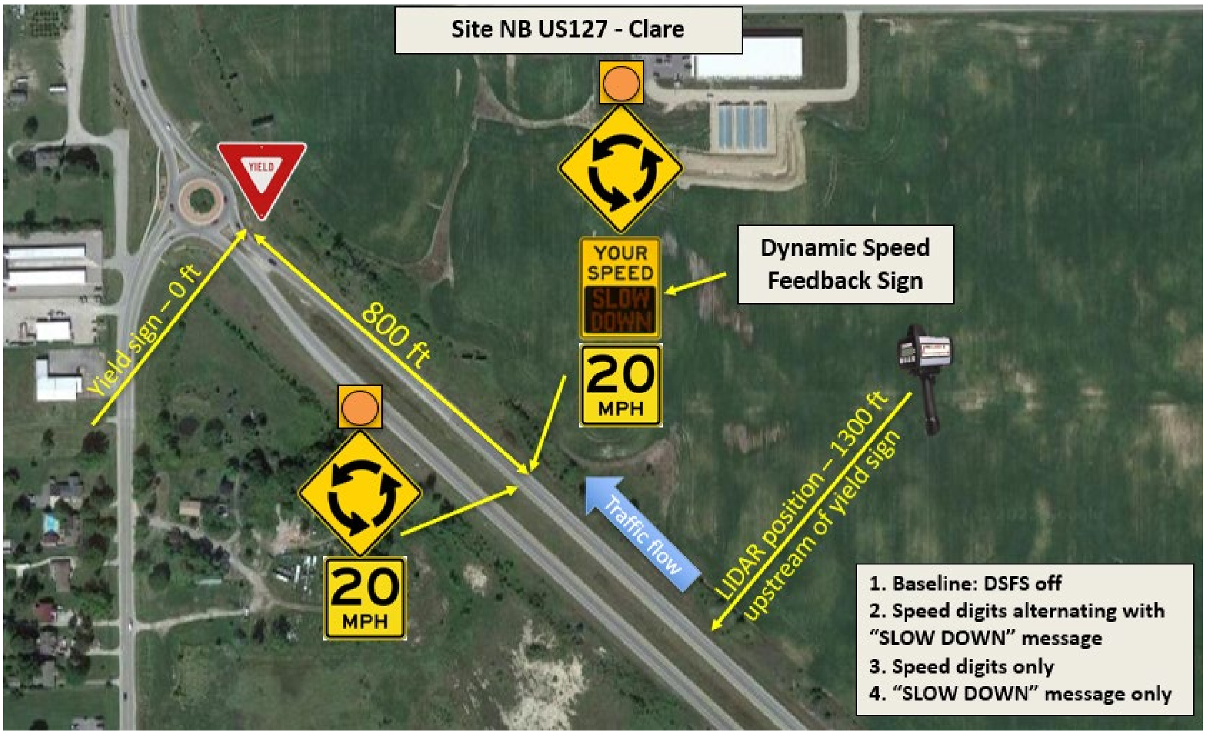


**Figure 57. Field Evaluation Layout and Sign Test Conditions, NB US-127 Exit to Clare (Site 3)**

#### 5.3.1.4 Site 4 - SB US-127 Exit 144 to Mt. Pleasant

Southbound US-127 is a limited access freeway with a 75 mph mainline speed limit. The exit ramp connector, which was approximately 0.7 miles in length and did not include a posted speed limit, led into a roundabout prior to entering the Mount Pleasant city limits. The speed limit was reduced to 45 mph immediately downstream of the roundabout. Two roundabout warning signs (W2-6) existed approximately 650 ft upstream of the roundabout on both sides of the road. A DSFS was temporarily installed beneath the right-side W2-6 sign and above the 15 mph advisory speed plaque (W13-1P). Speed data were collected after one week to assess the effect of the following DSFS messaging strategies:

1. Baseline Condition: DSFS off
2. DSFS displayed speed digits alternating with SLOW DOWN
3. DSFS displayed speed digits only
4. DSFS displayed SLOW DOWN only

Speed data were collected using a handheld LIDAR gun during November 2023. The LIDAR operator was positioned 1,400 ft upstream of the yield sign in a vehicle parked on the roadside and remained at that location during the study. The field evaluation layout and sign test conditions for SB US-127 Exit 144 to Mt Pleasant are shown in **Figure 58**. An example DSFS message is shown in **Figure 59**.

**Figure 58. Field Evaluation Layout and Sign Test Conditions at SB US-127 Exit to Mt Pleasant (Site 4)**

**Figure 59. Example DSFS Message Display (Site 2, EB M-43 Grand Ledge)**

### 5.3.2 Descriptive Statistics for Roundabout Approach Speeds

The descriptive statistics for the speed data across the various sign test conditions and speed measurement locations are shown in **Table 37** for M-52 Chelsea, **Table 38** for M-43 Grand Ledge, **Table 39** for US-127 Clare, and **Table 40** for US-127 Mt Pleasant. Graphical representations of the mean speed trajectories for each sign test condition are displayed in **Figure 60** (M-52 Chelsea), **Figure 61** (M-43 Grand Ledge), **Figure 62** (US-127 Clare), and **Figure 63** (US-127 Mt Pleasant).

### Table 37. Descriptive Statistics for Roundabout Approach Speeds, M-52 Chelsea (Site 1)

| Data Collection Location | Sign Test Condition | Sample Size | Mean (mph) | 85th %tile speed (mph) | Std. Dev. (mph) |
|---|---|---|---|---|---|
| 1,050 ft upstream of yield sign (furthest upstream measurement) | Baseline: DSFS and flashing LED sign border off | 100 | 55.04 | 60.00 | 5.32 |
| | Flashing LED sign border only | 196 | 54.60 | 59.00 | 4.60 |
| | Alternating speed digits / SLOW DOWN | 74 | 53.66 | 57.75 | 4.04 |
| | Speed digits only | 71 | 53.12 | 58.13 | 4.53 |
| | SLOW DOWN only | 61 | 52.88 | 57.00 | 4.00 |
| 950 ft upstream of yield sign | Baseline: DSFS and flashing LED sign border off | 100 | 54.88 | 60.00 | 5.31 |
| | Flashing LED sign border only | 196 | 54.51 | 59.00 | 4.60 |
| | Alternating speed digits / SLOW DOWN | 74 | 53.55 | 57.75 | 4.05 |
| | Speed digits only | 71 | 53.21 | 58.11 | 4.47 |
| | SLOW DOWN only | 61 | 52.80 | 56.90 | 3.99 |
| 750 ft upstream of yield sign | Baseline: DSFS and flashing LED sign border off | 100 | 54.59 | 59.85 | 5.11 |
| | Flashing LED sign border only | 196 | 53.95 | 58.04 | 4.61 |
| | Alternating speed digits / SLOW DOWN | 74 | 52.86 | 57.00 | 4.34 |
| | Speed digits only | 71 | 52.85 | 57.78 | 4.43 |
| | SLOW DOWN only | 61 | 52.39 | 56.70 | 3.88 |
| At test sign (500 ft upstream of yield sign) | Baseline: DSFS and flashing LED sign border off | 100 | 51.29 | 56.00 | 4.99 |
| | Flashing LED sign border only | 196 | 50.74 | 55.00 | 4.52 |
| | Alternating speed digits / SLOW DOWN | 74 | 48.58 | 53.24 | 5.24 |
| | Speed digits only | 71 | 49.70 | 54.12 | 4.52 |
| | SLOW DOWN only | 61 | 48.70 | 53.00 | 4.42 |
| 250 ft upstream of yield sign | Baseline: DSFS and flashing LED sign border off | 100 | 41.56 | 46.45 | 4.59 |
| | Flashing LED sign border only | 196 | 41.28 | 45.26 | 4.27 |
| | Alternating speed digits / SLOW DOWN | 74 | 39.54 | 44.52 | 4.36 |
| | Speed digits only | 71 | 40.28 | 44.68 | 4.40 |
| | SLOW DOWN only | 61 | 40.41 | 46.58 | 4.97 |
| 150 ft upstream of yield sign | Baseline: DSFS and flashing LED sign border off | 100 | 34.06 | 39.46 | 4.53 |
| | Flashing LED sign border only | 196 | 34.20 | 37.73 | 3.95 |
| | Alternating speed digits / SLOW DOWN | 74 | 32.93 | 36.28 | 3.78 |
| | Speed digits only | 71 | 33.45 | 37.89 | 4.46 |
| | SLOW DOWN only | 61 | 33.76 | 38.85 | 4.68 |

## Table 38. Descriptive Statistics for Roundabout Approach Speeds, M-43 Grand Ledge (Site 2)

| Data Collection Location | Sign Test Condition | Sample Size | Mean (mph) | 85th %tile speed (mph) | Std. Dev. (mph) |
|---|---|---|---|---|---|
| 1,450 ft upstream of yield sign (furthest upstream measurement) | Baseline: DSFS off | 87 | 54.95 | 59.00 | 4.16 |
| | Alternating speed digits / SLOW DOWN | 90 | 53.73 | 59.00 | 5.03 |
| | Speed digits only | 90 | 54.24 | 60.00 | 5.12 |
| | SLOW DOWN only | 92 | 54.04 | 59.00 | 4.53 |
| 1,200 ft upstream of yield sign | Baseline: DSFS off | 87 | 54.27 | 58.80 | 4.27 |
| | Alternating speed digits / SLOW DOWN | 90 | 52.98 | 58.35 | 5.11 |
| | Speed digits only | 90 | 53.45 | 60.00 | 5.21 |
| | SLOW DOWN only | 92 | 53.40 | 59.00 | 4.54 |
| At test sign (950 ft upstream of yield sign) | Baseline: DSFS off | 87 | 52.92 | 57.77 | 4.34 |
| | Alternating speed digits / SLOW DOWN | 90 | 50.95 | 57.00 | 5.50 |
| | Speed digits only | 90 | 51.28 | 57.38 | 5.64 |
| | SLOW DOWN only | 92 | 51.92 | 57.22 | 4.78 |
| 750 ft upstream of yield sign | Baseline: DSFS off | 87 | 51.34 | 55.98 | 4.24 |
| | Alternating speed digits / SLOW DOWN | 90 | 48.31 | 54.31 | 5.69 |
| | Speed digits only | 90 | 48.65 | 55.77 | 5.78 |
| | SLOW DOWN only | 92 | 49.43 | 54.41 | 5.10 |
| 500 ft upstream of yield sign | Baseline: DSFS off | 87 | 48.12 | 52.84 | 4.16 |
| | Alternating speed digits / SLOW DOWN | 90 | 44.34 | 50.22 | 5.23 |
| | Speed digits only | 90 | 44.73 | 50.16 | 5.03 |
| | SLOW DOWN only | 92 | 45.58 | 50.00 | 4.88 |
| 250 ft upstream of yield sign | Baseline: DSFS off | 87 | 41.00 | 45.20 | 3.98 |
| | Alternating speed digits / SLOW DOWN | 90 | 37.41 | 42.62 | 4.66 |
| | Speed digits only | 90 | 38.75 | 43.28 | 4.24 |
| | SLOW DOWN only | 92 | 39.02 | 43.00 | 4.25 |
| 150 ft upstream of yield sign | Baseline: DSFS off | 87 | 35.62 | 40.55 | 3.97 |
| | Alternating speed digits / SLOW DOWN | 90 | 31.85 | 37.58 | 5.02 |
| | Speed digits only | 90 | 33.82 | 38.67 | 4.09 |
| | SLOW DOWN only | 92 | 33.53 | 37.32 | 4.07 |

**Table 39. Descriptive Statistics for Roundabout Approach Speeds, US-127 Clare (Site 3)**

| Data Collection Location | Sign Test Condition | Sample Size | Mean (mph) | 85th %tile speed (mph) | Std. Dev. (mph) |
|---|---|---|---|---|---|
| 1,050 ft upstream of yield sign (furthest upstream measurement) | Baseline: DSFS off | 83 | 57.24 | 64.40 | 6.97 |
| | Alternating speed digits / SLOW DOWN | 95 | 53.95 | 60.60 | 6.36 |
| | Speed digits only | 89 | 54.06 | 59.50 | 5.33 |
| | SLOW DOWN only | 94 | 55.35 | 62.00 | 6.35 |
| 950 ft upstream of yield sign | Baseline: DSFS off | 83 | 56.93 | 63.82 | 7.07 |
| | Alternating speed digits / SLOW DOWN | 95 | 53.12 | 59.56 | 6.35 |
| | Speed digits only | 89 | 53.39 | 58.74 | 5.24 |
| | SLOW DOWN only | 94 | 54.50 | 61.37 | 6.57 |
| At test warning sign (800 ft upstream of yield sign) | Baseline: DSFS off | 83 | 55.77 | 63.26 | 7.03 |
| | Alternating speed digits / SLOW DOWN | 95 | 51.39 | 58.00 | 6.23 |
| | Speed digits only | 89 | 51.74 | 57.00 | 5.31 |
| | SLOW DOWN only | 94 | 52.77 | 58.97 | 6.78 |
| 750 ft upstream of yield sign | Baseline: DSFS off | 83 | 55.32 | 62.89 | 7.08 |
| | Alternating speed digits / SLOW DOWN | 95 | 50.70 | 57.56 | 6.22 |
| | Speed digits only | 89 | 51.15 | 56.00 | 5.41 |
| | SLOW DOWN only | 94 | 52.07 | 58.00 | 6.79 |
| 500 ft upstream of yield sign | Baseline: DSFS off | 83 | 50.97 | 57.15 | 6.35 |
| | Alternating speed digits / SLOW DOWN | 95 | 46.84 | 53.48 | 5.70 |
| | Speed digits only | 89 | 46.98 | 52.00 | 5.38 |
| | SLOW DOWN only | 94 | 47.61 | 53.87 | 6.24 |
| 250 ft upstream of yield sign | Baseline: DSFS off | 83 | 39.91 | 44.95 | 5.07 |
| | Alternating speed digits / SLOW DOWN | 95 | 39.17 | 43.73 | 4.82 |
| | Speed digits only | 89 | 37.13 | 42.63 | 5.15 |
| | SLOW DOWN only | 94 | 37.95 | 42.85 | 4.89 |
| 150 ft upstream of yield sign | Baseline: DSFS off | 83 | 31.28 | 35.96 | 4.44 |
| | Alternating speed digits / SLOW DOWN | 95 | 32.13 | 36.74 | 4.35 |
| | Speed digits only | 89 | 29.15 | 34.46 | 4.69 |
| | SLOW DOWN only | 94 | 30.27 | 34.33 | 3.84 |

Note: Flashing amber beacon was on for all sign test conditions

**Table 40. Descriptive Statistics for Roundabout Approach Speeds, US-127 Mt Pleasant (Site 4)**

| Data Collection Location | Sign Test Condition | Sample Size | Mean (mph) | 85th %tile speed (mph) | Std. Dev. (mph) |
|---|---|---|---|---|---|
| 1,200 ft upstream of yield sign (furthest upstream measurement) | Baseline: DSFS off | 83 | 53.52 | 60.00 | 6.10 |
| | Alternating speed digits / SLOW DOWN | 103 | 52.53 | 57.71 | 5.63 |
| | Speed digits only | 96 | 52.57 | 59.45 | 5.84 |
| | SLOW DOWN only | 100 | 51.50 | 57.85 | 5.63 |
| 950 ft upstream of yield sign | Baseline: DSFS off | 83 | 51.71 | 58.33 | 6.25 |
| | Alternating speed digits / SLOW DOWN | 103 | 51.07 | 56.00 | 5.73 |
| | Speed digits only | 96 | 51.23 | 58.45 | 6.05 |
| | SLOW DOWN only | 100 | 50.04 | 56.00 | 5.72 |
| 750 ft upstream of yield sign | Baseline: DSFS off | 83 | 48.56 | 53.82 | 5.57 |
| | Alternating speed digits / SLOW DOWN | 103 | 47.08 | 53.19 | 5.94 |
| | Speed digits only | 96 | 47.87 | 53.93 | 6.08 |
| | SLOW DOWN only | 100 | 45.98 | 52.00 | 5.50 |
| At test warning sign (650 ft upstream of yield sign) | Baseline: DSFS off | 83 | 46.22 | 51.41 | 5.39 |
| | Alternating speed digits / SLOW DOWN | 103 | 44.09 | 50.40 | 6.20 |
| | Speed digits only | 96 | 45.08 | 50.92 | 5.97 |
| | SLOW DOWN only | 100 | 43.11 | 48.79 | 5.49 |
| 500 ft upstream of yield sign | Baseline: DSFS off | 83 | 41.20 | 46.28 | 5.31 |
| | Alternating speed digits / SLOW DOWN | 103 | 39.31 | 45.04 | 5.59 |
| | Speed digits only | 96 | 40.11 | 45.50 | 5.66 |
| | SLOW DOWN only | 100 | 38.05 | 43.05 | 5.47 |
| 250 ft upstream of yield sign | Baseline: DSFS off | 83 | 29.53 | 35.66 | 6.12 |
| | Alternating speed digits / SLOW DOWN | 103 | 29.52 | 34.03 | 4.48 |
| | Speed digits only | 96 | 29.95 | 35.36 | 5.57 |
| | SLOW DOWN only | 100 | 28.11 | 32.85 | 4.65 |

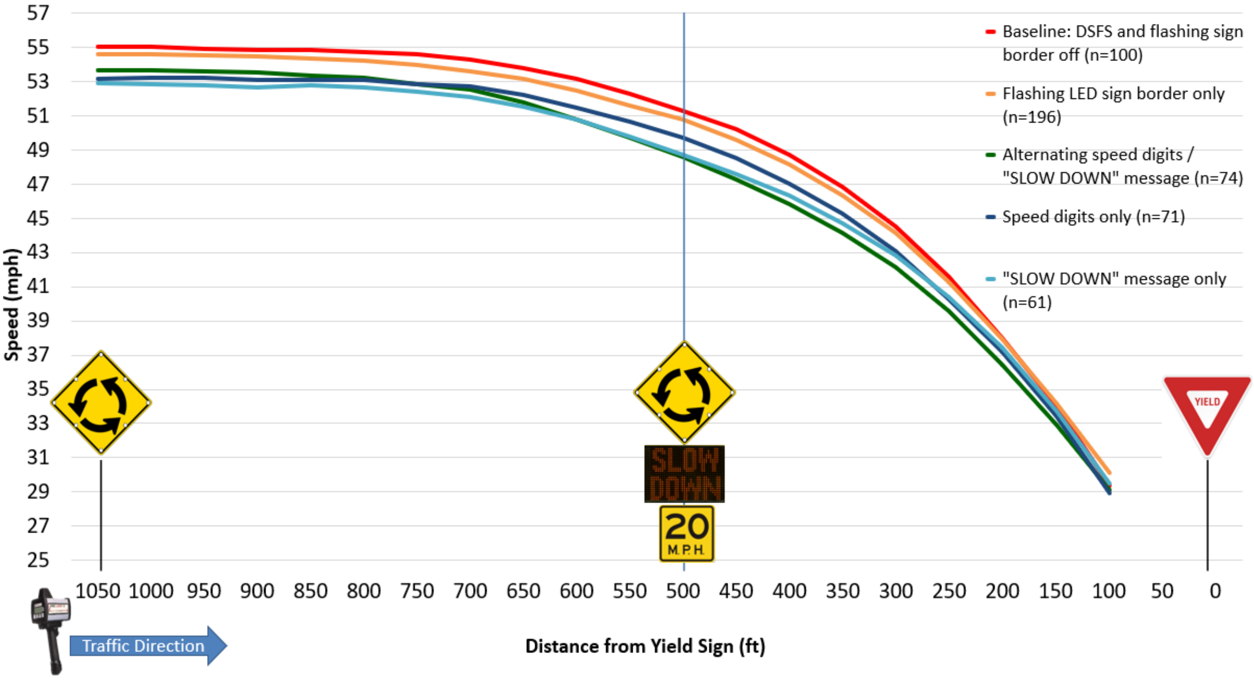


Figure 60. Average Speed Trajectories, M-52 Chelsea (Site 1)

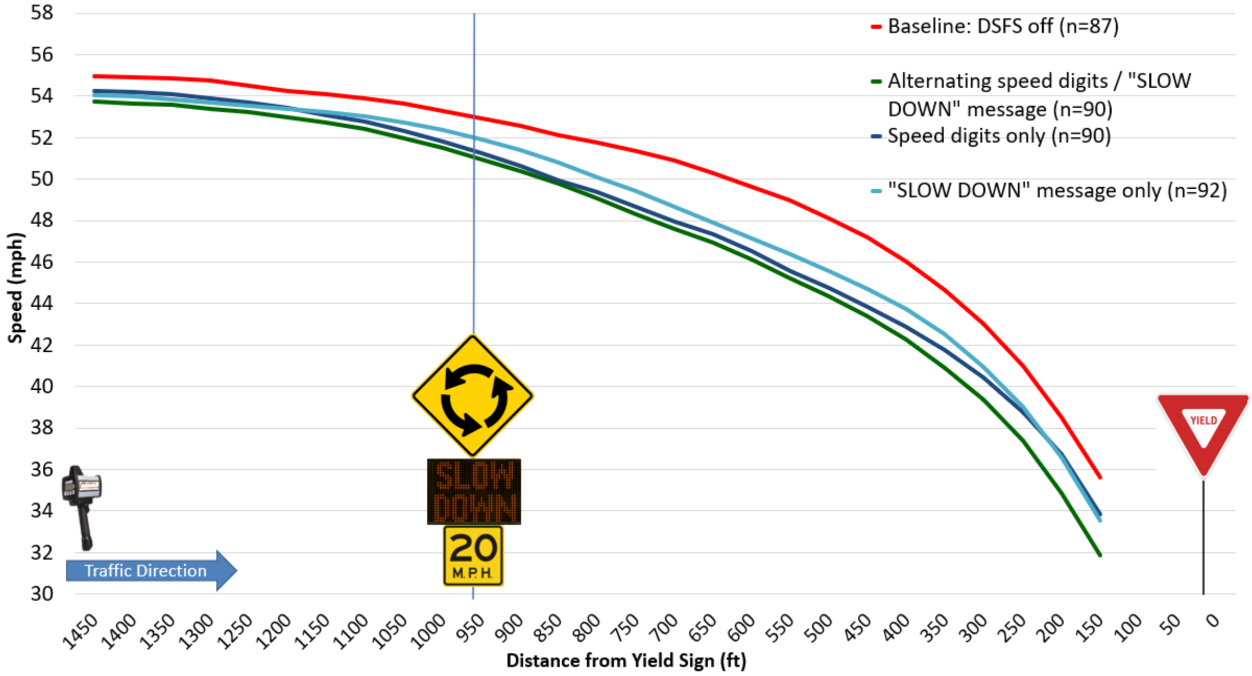


Figure 61. Average Speed Trajectories, M-43 Grand Ledge (Site 2)

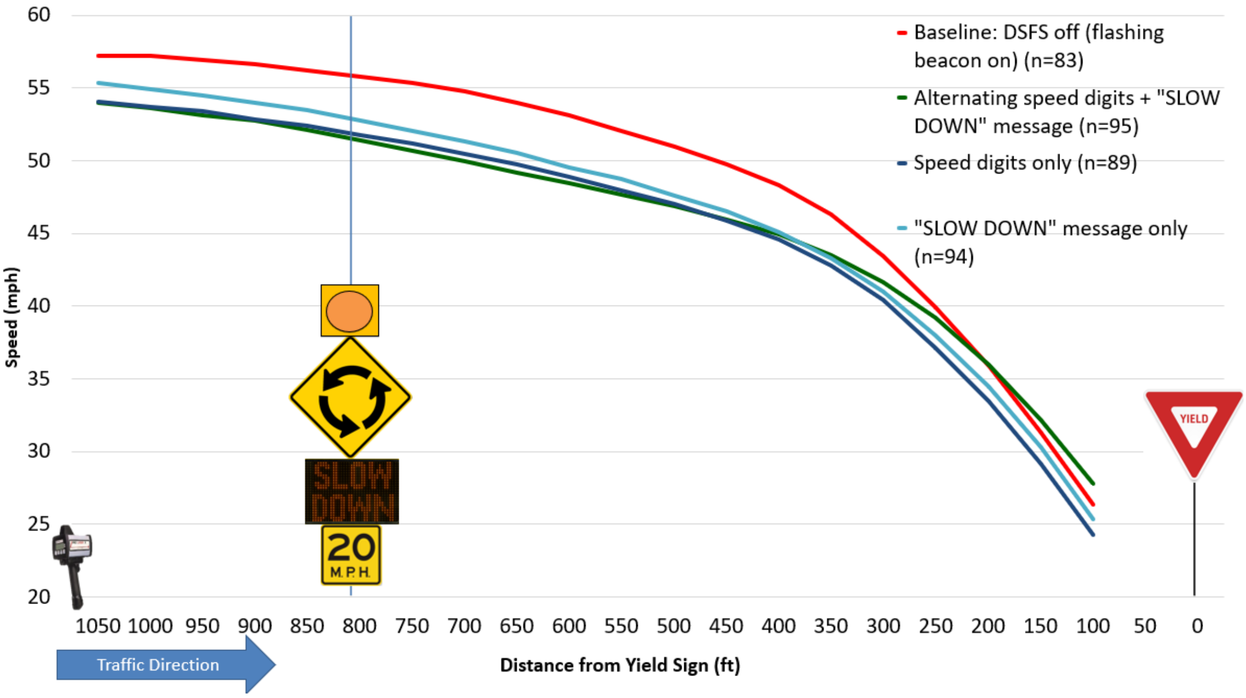


Figure 62. Average Speed Trajectories, US-127 Clare (Site 3)

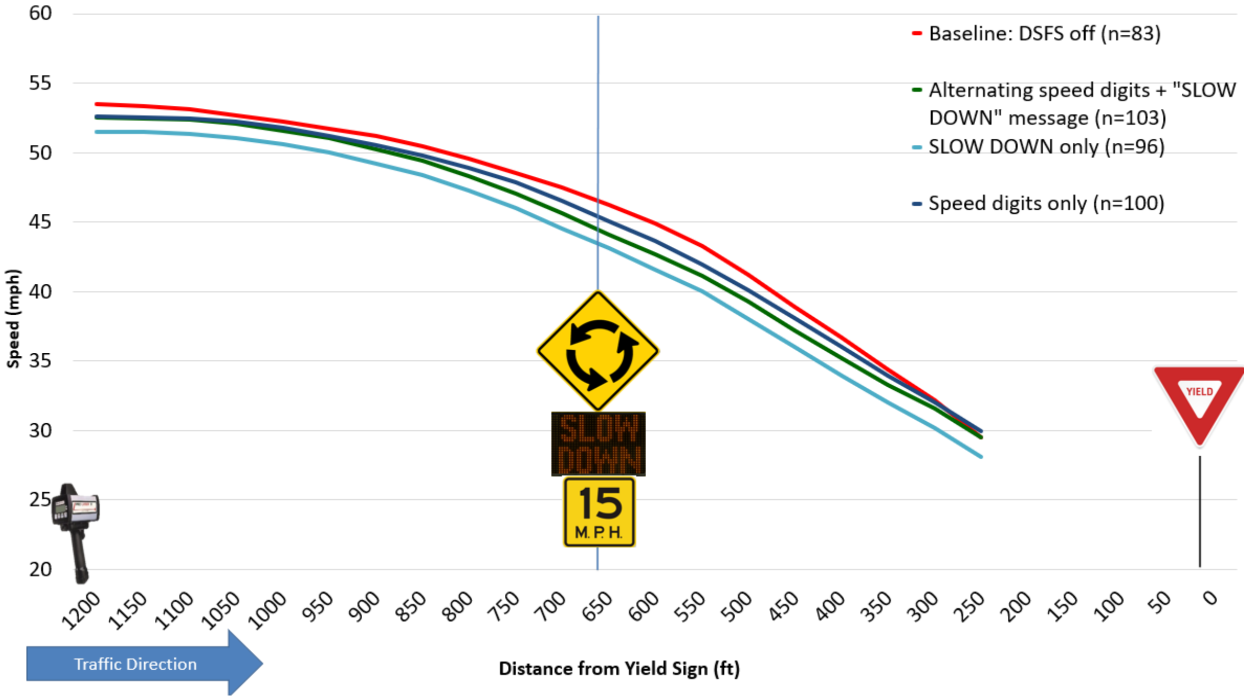


Figure 63. Average Speed Trajectories, US-127 Mt Pleasant (Site 4)

### 5.3.3 Linear Regression Results for Roundabout Approach Speeds

The speed data were analyzed separately for each site using a linear regression model. The model results are displayed in **Table 41**, **Table 42**, **Table 43**, and **Table 44** for M-52 Chelsea and M-43 Grand Ledge, US-127 Clare, and US-127 Mt Pleasant, respectively. It should be noted that the speed measured at the furthest upstream point was included as an independent variable (covariate) in the regression 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 **Figure 60**, **Figure 61**, **Figure 62**, and **Figure 63**. 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 between drivers and site conditions.

#### 5.3.3.1 Effect of DSFS

The results presented in **Table 41**, **Table 42**, **Table 43**, and **Table 44** suggest that the DSFS had a statistically significant effect on the speed of vehicles approaching the roundabout, although the magnitude of this effect differed by site and message display condition. While the active DSFS at M-43 Grand Ledge reduced speeds by up to 3.4 mph compared to the base sign condition, the speed reductions associated with the DSFS at the remaining sites were lower and did not exceed 1.8 mph. These differences are likely at least partially attributed to the more recent installation of the roundabout at M-43 Grand Ledge, which was constructed in 2021. Drivers at this location are likely less accustomed to the roundabout compared to the other three roundabouts, which were constructed more than a decade ago.

The speed reduction trajectories also differed between M-43 Grand Ledge and the other three locations. At the M-43 Grand Ledge location, with the DSFS active, speed reductions were first observed beginning at the test sign (950 ft upstream of the yield sign) and increased in magnitude as motorists approached the roundabout, with the maximum effect occurring 150 ft upstream of the yield sign. However, at the other three locations, the maximum speed reduction effect associated with the active DSFS occurred 500 ft upstream of the yield sign, which was at or slightly beyond the test sign in each case and diminished as drivers continued towards the roundabout.

## Table 41. Linear Regression Model for Roundabout Approach Speeds, M-52 Chelsea

| Parameter | Estimate | Std. Error | p-Value |
|---|---|---|---|
| **Speed 950 ft upstream of yield sign** | | | |
| Intercept | 0.565 | 0.372 | 0.129 |
| Upstream Speed | 0.987 | 0.007 | <0.001 |
| DSFS and flashing sign border off | *Baseline* | | |
| Flashing LED sign border only | 0.062 | 0.084 | 0.458 |
| Alternating speed digits / SLOW DOWN | 0.034 | 0.105 | 0.746 |
| Speed digits only | 0.221 | 0.106 | 0.038 |
| SLOW DOWN only | 0.048 | 0.112 | 0.666 |
| **Speed 750 ft upstream of yield sign** | | | |
| Intercept | 2.271 | 0.728 | 0.002 |
| Upstream Speed | 0.951 | 0.013 | <0.001 |
| DSFS and flashing sign border off | *Baseline* | | |
| Flashing LED sign border only | -0.217 | 0.164 | 0.187 |
| Alternating speed digits / SLOW DOWN | -0.417 | 0.205 | 0.042 |
| Speed digits only | 0.083 | 0.208 | 0.691 |
| SLOW DOWN only | -0.143 | 0.218 | 0.513 |
| **Speed at the test sign (500 ft upstream of yield sign)** | | | |
| Intercept | 5.133 | 1.484 | 0.001 |
| Upstream Speed | 0.839 | 0.027 | <0.001 |
| DSFS and flashing sign border off | *Baseline* | | |
| Flashing LED sign border only | -0.186 | 0.334 | 0.577 |
| Alternating speed digits / SLOW DOWN | -1.552 | 0.418 | <0.001 |
| Speed digits only | 0.017 | 0.425 | 0.969 |
| SLOW DOWN only | -0.782 | 0.445 | 0.080 |
| **Speed 250 ft upstream of yield sign** | | | |
| Intercept | 12.197 | 2.033 | <0.001 |
| Upstream Speed | 0.533 | 0.036 | <0.001 |
| DSFS and flashing sign border off | *Baseline* | | |
| Flashing LED sign border only | -0.048 | 0.458 | 0.917 |
| Alternating speed digits / SLOW DOWN | -1.284 | 0.573 | 0.025 |
| Speed digits only | -0.257 | 0.582 | 0.659 |
| SLOW DOWN only | -0.004 | 0.610 | 0.995 |
| **Speed 150 ft upstream of yield sign** | | | |
| Intercept | 13.914 | 2.112 | <0.001 |
| Upstream Speed | 0.366 | 0.038 | <0.001 |
| DSFS and flashing sign border off | *Baseline* | | |
| Flashing LED sign border only | 0.296 | 0.476 | 0.533 |
| Alternating speed digits / SLOW DOWN | -0.623 | 0.595 | 0.296 |
| Speed digits only | 0.090 | 0.604 | 0.882 |
| SLOW DOWN only | 0.493 | 0.634 | 0.437 |

### Table 42. Linear Regression Model for Roundabout Approach Speeds, M-43 Grand Ledge

| Parameter | Estimate | Std. Error | p-Value |
|---|---|---|---|
| **Speed 1,200 ft upstream of yield sign** | | | |
| Intercept | 0.036 | 0.702 | 0.959 |
| Upstream Speed | 0.987 | 0.013 | <0.001 |
| DSFS off | *Baseline* | | |
| Alternating speed digits / SLOW DOWN | -0.088 | 0.169 | 0.604 |
| Speed digits only | -0.124 | 0.169 | 0.462 |
| SLOW DOWN only | 0.020 | 0.168 | 0.907 |
| **Speed at the test sign (950 ft upstream of yield sign)** | | | |
| Intercept | 0.006 | 1.432 | 0.997 |
| Upstream Speed | 0.963 | 0.026 | <0.001 |
| DSFS off | *Baseline* | | |
| Alternating speed digits / SLOW DOWN | -0.800 | 0.345 | 0.021 |
| Speed digits only | -0.964 | 0.344 | 0.005 |
| SLOW DOWN only | -0.131 | 0.343 | 0.702 |
| **Speed 750 ft upstream of yield sign** | | | |
| Intercept | 2.227 | 1.951 | 0.254 |
| Upstream Speed | 0.894 | 0.035 | <0.001 |
| DSFS off | *Baseline* | | |
| Alternating speed digits / SLOW DOWN | -1.943 | 0.470 | <0.001 |
| Speed digits only | -2.063 | 0.469 | <0.001 |
| SLOW DOWN only | -1.102 | 0.467 | 0.019 |
| **Speed 500 ft upstream of yield sign** | | | |
| Intercept | 7.983 | 2.131 | <0.001 |
| Upstream Speed | 0.730 | 0.038 | <0.001 |
| DSFS off | *Baseline* | | |
| Alternating speed digits / SLOW DOWN | -2.887 | 0.514 | <0.001 |
| Speed digits only | -2.868 | 0.512 | <0.001 |
| SLOW DOWN only | -1.882 | 0.510 | <0.001 |
| **Speed 250 ft upstream of yield sign** | | | |
| Intercept | 15.862 | 2.323 | <0.001 |
| Upstream Speed | 0.457 | 0.042 | <0.001 |
| DSFS off | *Baseline* | | |
| Alternating speed digits / SLOW DOWN | -3.034 | 0.560 | <0.001 |
| Speed digits only | -1.926 | 0.559 | 0.001 |
| SLOW DOWN only | -1.567 | 0.556 | 0.005 |
| **Speed 150 ft upstream of yield sign** | | | |
| Intercept | 17.471 | 2.519 | <0.001 |
| Upstream Speed | 0.330 | 0.045 | <0.001 |
| DSFS off | *Baseline* | | |
| Alternating speed digits / SLOW DOWN | -3.370 | 0.608 | <0.001 |
| Speed digits only | -1.567 | 0.606 | 0.010 |
| SLOW DOWN only | -1.799 | 0.603 | 0.003 |

## Table 43. Linear Regression Model for Roundabout Approach Speeds, US-127 Clare

| Parameter | Estimate | Std. Error | p-Value |
|---|---|---|---|
| **Speed 950 ft upstream of yield sign** | | | |
| Intercept | -0.393 | 0.415 | 0.345 |
| Upstream Speed | 1.002 | 0.007 | <0.001 |
| DSFS off | *Baseline* | | |
| Alternating speed digits / SLOW DOWN | -0.516 | 0.128 | <0.001 |
| Speed digits only | -0.356 | 0.130 | 0.006 |
| SLOW DOWN only | -0.545 | 0.127 | <0.001 |
| **Speed at the test warning sign (800 ft upstream of yield sign)** | | | |
| Intercept | -0.027 | 0.887 | 0.976 |
| Upstream Speed | 0.975 | 0.015 | <0.001 |
| DSFS off | *Baseline* | | |
| Alternating speed digits / SLOW DOWN | -1.177 | 0.274 | <0.001 |
| Speed digits only | -0.929 | 0.277 | 0.001 |
| SLOW DOWN only | -1.160 | 0.271 | <0.001 |
| **Speed 750 ft upstream of yield sign** | | | |
| Intercept | 0.062 | 1.027 | 0.952 |
| Upstream Speed | 0.965 | 0.017 | <0.001 |
| DSFS off | *Baseline* | | |
| Alternating speed digits / SLOW DOWN | -1.441 | 0.317 | <0.001 |
| Speed digits only | -1.101 | 0.321 | 0.001 |
| SLOW DOWN only | -1.426 | 0.314 | <0.001 |
| **Speed 500 ft upstream of yield sign** | | | |
| Intercept | 4.497 | 1.504 | 0.003 |
| Upstream Speed | 0.812 | 0.026 | <0.001 |
| DSFS off | *Baseline* | | |
| Alternating speed digits / SLOW DOWN | -1.460 | 0.464 | 0.002 |
| Speed digits only | -1.412 | 0.470 | 0.003 |
| SLOW DOWN only | -1.834 | 0.460 | <0.001 |
| **Speed 250 ft upstream of yield sign** | | | |
| Intercept | 12.826 | 1.984 | <0.001 |
| Upstream Speed | 0.473 | 0.034 | <0.001 |
| DSFS off | *Baseline* | | |
| Alternating speed digits / SLOW DOWN | 0.824 | 0.612 | 0.179 |
| Speed digits only | -1.267 | 0.620 | 0.042 |
| SLOW DOWN only | -1.059 | 0.606 | 0.082 |
| **Speed 150 ft upstream of yield sign** | | | |
| Intercept | 13.342 | 1.917 | <0.001 |
| Upstream Speed | 0.313 | 0.033 | <0.001 |
| DSFS off | *Baseline* | | |
| Alternating speed digits / SLOW DOWN | 1.879 | 0.591 | 0.002 |
| Speed digits only | -1.129 | 0.599 | 0.060 |
| SLOW DOWN only | -0.421 | 0.586 | 0.473 |

**Table 44. Linear Regression Model for Roundabout Approach Speeds, US-127 Mt Pleasant**

| Parameter | Estimate | Std. Error | p-Value |
|---|---|---|---|
| **Speed 950 ft upstream of yield sign** | | | |
| Intercept | -1.643 | 0.652 | 0.012 |
| Upstream Speed | 0.997 | 0.012 | <0.001 |
| DSFS off | *Baseline* | | |
| Alternating speed digits / SLOW DOWN | 0.343 | 0.197 | 0.083 |
| Speed digits only | 0.461 | 0.201 | 0.022 |
| SLOW DOWN only | 0.345 | 0.200 | 0.085 |
| **Speed 750 ft upstream of yield sign** | | | |
| Intercept | 1.245 | 1.316 | 0.345 |
| Upstream Speed | 0.884 | 0.024 | <0.001 |
| DSFS off | *Baseline* | | |
| Alternating speed digits / SLOW DOWN | -0.600 | 0.399 | 0.133 |
| Speed digits only | 0.150 | 0.405 | 0.711 |
| SLOW DOWN only | -0.791 | 0.404 | 0.051 |
| **Speed at the test warning sign (650 ft upstream of yield sign)** | | | |
| Intercept | 2.915 | 1.661 | 0.080 |
| Upstream Speed | 0.809 | 0.030 | <0.001 |
| DSFS off | *Baseline* | | |
| Alternating speed digits / SLOW DOWN | -1.335 | 0.503 | 0.008 |
| Speed digits only | -0.374 | 0.511 | 0.464 |
| SLOW DOWN only | -1.474 | 0.509 | 0.004 |
| **Speed 500 ft upstream of yield sign** | | | |
| Intercept | 5.552 | 1.928 | 0.004 |
| Upstream Speed | 0.666 | 0.035 | <0.001 |
| DSFS off | *Baseline* | | |
| Alternating speed digits / SLOW DOWN | -1.234 | 0.584 | 0.035 |
| Speed digits only | -0.461 | 0.593 | 0.438 |
| SLOW DOWN only | -1.814 | 0.591 | 0.002 |
| **Speed 250 ft upstream of yield sign** | | | |
| Intercept | 5.692 | 2.205 | 0.010 |
| Upstream Speed | 0.445 | 0.040 | <0.001 |
| DSFS off | *Baseline* | | |
| Alternating speed digits / SLOW DOWN | 0.426 | 0.668 | 0.524 |
| Speed digits only | 0.834 | 0.678 | 0.220 |
| SLOW DOWN only | -0.529 | 0.676 | 0.434 |

#### 5.3.3.2 Effect of DSFS Message Type

The evaluation also afforded a comparison between the effects of three different DSFS messaging strategies, which included: speed digits only, SLOW DOWN message only, and speed digits alternating with the SLOW DOWN message. From **Table 41** and **Table 42**, it can be observed that alternating the speed digits with a SLOW DOWN message produced a considerably larger speed reduction effect at both locations compared to either of the individual DSFS messages (i.e., the speed digits or SLOW DOWN message). The speed reduction results were mixed when either of the individual messages was displayed on the DSFS. At the M-43 Grand Ledge location (**Table 42**), displaying the speed digits alone had a marginally greater effect on speeds than the SLOW DOWN message at greater distances upstream of the roundabout, while the SLOW DOWN message became equally effective closer to the roundabout. However, neither of the individual messages was found to have an effect on speeds at the M-52 Chelsea location. Comparing results from the two exit ramp locations displayed in **Table 43** and **Table 44** for US-127 Clare and US-127 Mt Pleasant, respectively, showed that the greatest speed reductions were observed with the SLOW DOWN message, although alternating the speed digits with the SLOW DOWN message had a similar effect. However, at both of the exit ramp locations, regardless of the message, the speed reduction effects had generally diminished as drivers approached within 500 ft of the roundabout yield sign.

# 6. EVALUATION OF WINTER WEATHER WARNING STRATEGIES

This chapter brings the results of field evaluations of winter weather warning strategies at horizontal curves and bridge overpasses. It includes the results of evaluations of a slippery curve flashing LED warning sign system and the evaluation of winter weather messaging on changeable message signs on the approach to bridge overpasses.

## 6.1 Slippery Curve Warning System at Rural Horizontal Curves

A field evaluation was conducted at two locations to evaluate the effectiveness of a slippery curve warning system (SCWS) as a speed reduction countermeasure for motorists approaching a horizontal curve during winter weather conditions. The following sections provide details on the study sites, sign test conditions, analysis, and results.

### 6.1.1 Site Description

The SCWS study was conducted along a 1.7-mile-long road segment of M-32 west of Gaylord, Michigan. This segment consisted of a two-lane undivided rural highway with a posted speed limit of 55 mph and an advisory speed of 45 mph at the curves. The SCWS had been installed in both the eastbound and westbound directions at this location in 2018 and was one of two such SCWS installations in Michigan at that time. The SCWS consisted of a pair of slippery-when-wet signs (W8-5) positioned on both sides of the roadway between 900 and 1,000 ft upstream of the start of the initial curve in either direction, followed 350 feet later by a curve warning sign (W1-2) positioned on the right side only. The W8-5 signs were supplemented with a “NEXT 15 MILES” plaque, while the W1-2 signs were supplemented with an advisory speed “45 MPH” plaque (W13-1P). The general signing layouts for the SCWS in each direction are shown in **Figure 64**.

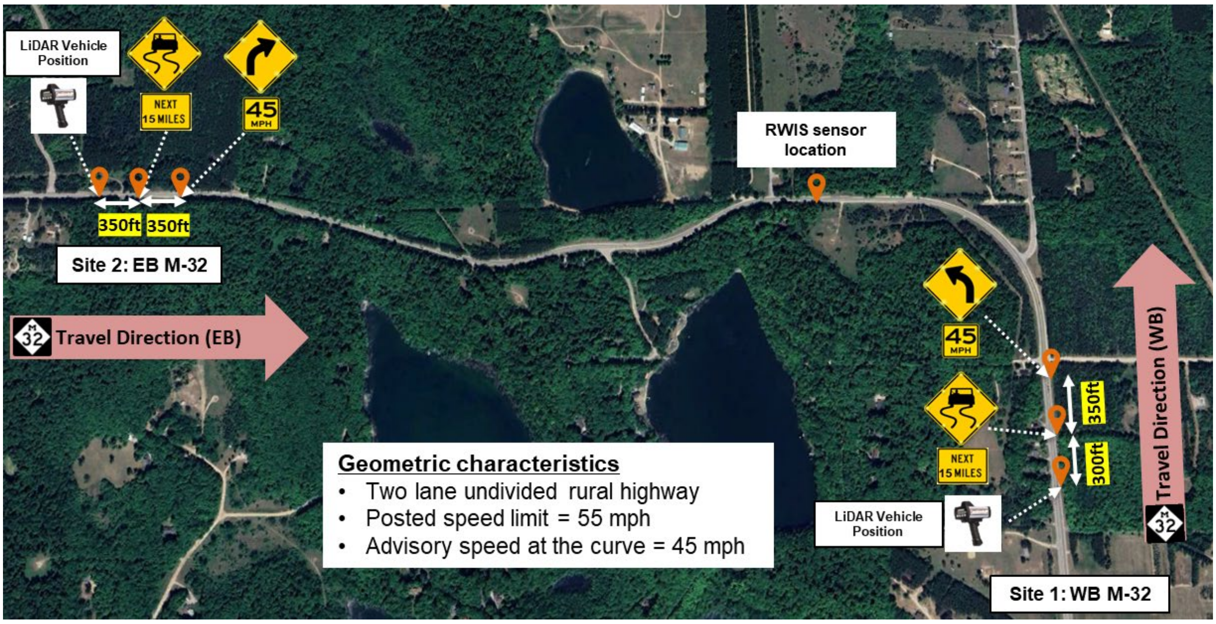


**Figure 64. Field Evaluation Layout for SCWS at M-32 Gaylord, Michigan**

Each of the W8-5 and W1-2 signs included an LED border and were connected to a road weather information system (RWIS) sensor station located along the corridor. The RWIS sensors collect real-time weather and pavement surface condition data, which are used to activate the LED sign borders upon detection of potentially slippery pavement conditions. The horizontal curves also included either chevrons (WB only) or a large arrow sign (EB only), although these signs did not include the flashing LED borders. The evaluation was performed at both the westbound and eastbound implementations of the SCWS along this roadway.

### 6.1.2 Sign Test Conditions and Data Collection Procedures

The W8-5 and W1-2 signs were 48-inch by 48-inch in size and contained eight LEDs along the sign border. When activated, the LED lights would flash at a rate of 1 hertz. During normal operation, the flashing LED border was automatically activated when the road surface temperature was below 32 degrees Fahrenheit and the road surface friction coefficient was less than 0.4, based on data collected from the RWIS sensor station. However, during the field evaluation, the flashing LED border was manually cycled between “flashing” and “off” every 30 minutes during periods of data collection, which afforded considerable control over variations in weather conditions, pavement conditions, and general driver behavior throughout the data collection period. Examples of the active SCWS at the WB and EB M-32 study sites are displayed in **Figure 65** and **Figure 66**, respectively. Two sign conditions were tested during this evaluation, which included:

1. Baseline: LED border off
2. LED border on: The LED border of the W8-5 and W1-2 were flashing at a rate of 1 hertz

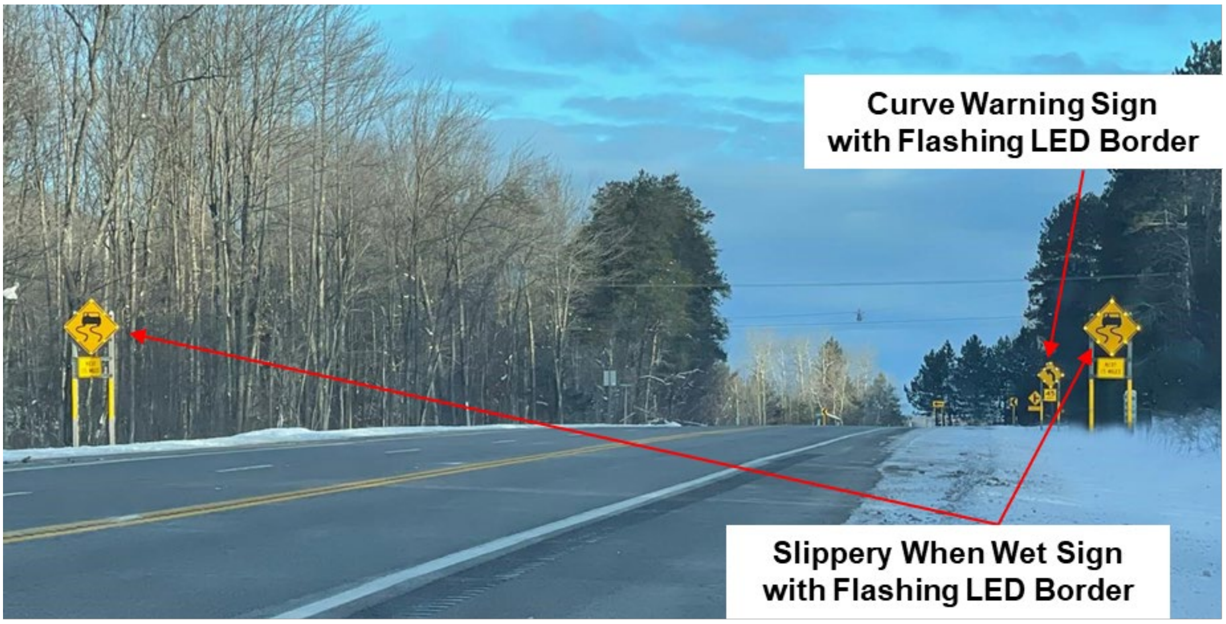


Figure 65. Example of Flashing LED SCWS Signs at WB M-32 Gaylord Site

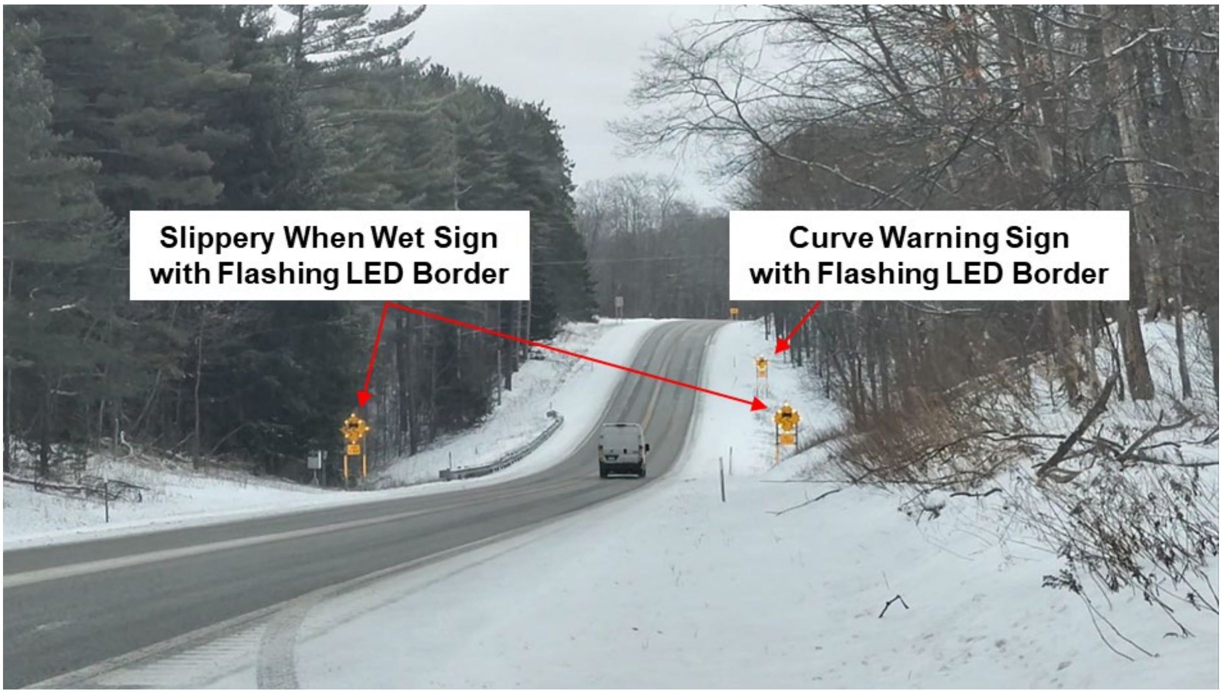


Figure 66. Example of Flashing LED SCWS Signs at EB M-32 Gaylord Site

Field data collection was conducted during February and March of 2024 using a handheld LIDAR gun. The technician operated the LIDAR gun from a vehicle parked on the roadside. At the eastbound site, the vehicle was parked at 1,250 ft upstream of the start of the curve, and on the westbound site, the vehicle was parked at 1,300 ft upstream of the start of the curve. The location of the vehicle remained the same throughout all periods of data collection. To facilitate safe and efficient data collection, the team specifically targeted days with early-morning snowfall tapering to overcast or light snow conditions by mid-morning and air temperatures in the upper 20-degree to lower 30-degree Fahrenheit range. Snow removal and de-icing were actively performed by maintenance crews during each data collection period, affording a consistently wet pavement surface throughout each period. Periods of heavy snowfall were avoided, as it was neither safe nor feasible to collect data during such conditions.

### 6.1.3 Descriptive Statistics

Datasets were prepared for analysis after completion of field data collection activities. The sign test conditions and vehicle types were coded as binary variables. Additionally, the speed collected at the furthest upstream point (i.e., 1,150 ft or 1,200 ft upstream from the curve in EB and WB, respectively) was included as an independent variable in the analysis to account for variations in the speed tendencies between drivers prior to encountering the warning sign.

The data for passenger cars were further split into three distinct driver behavior categories (e.g., faster, average, and slower) based on the speed measured for each subject driver at the furthest upstream measurement point which allowed for the assessment of whether the SCWS elicited different behaviors from faster, average, or slower drivers. Ultimately, for analytical purposes, the data were then combined across the two sites, with separate datasets created for the slower, average, and faster driver categories. Heavy vehicles were not further categorized into these driver groups due to small sample sizes.

The descriptive statistics (minimum, maximum, mean, and standard deviation) of the dependent and independent variables are presented in **Table 45** for each site and each driver behavior group. The mean values for the binary variables listed in the table represent the proportion of the total data set represented by that variable. A total of 729 completed vehicle trajectories were collected between the two directions during the evaluation periods, including 416 at eastbound and 313 at westbound sites. It should again be noted that the data were only collected during snowy weather and wet pavement conditions with air temperatures in the upper 20 to lower 30 degrees Fahrenheit. Thus, variables related to the weather and pavement conditions are not included in **Table 45**. Furthermore, because the sign test conditions were rotated throughout the data collection period every 30 minutes, it was not necessary to include the time of day as a factor in the models. Graphical representations of the mean speed trajectories of passenger cars for each sign test condition are displayed in **Figure 67** (EB), and **Figure 68** (WB), respectively, and for each driver behavior group (combined sites) in **Figure 69**.

## Table 45. Descriptive Statistics for Slippery Curve Warning System Evaluation

| **by Site** | | | | |
|---|---|---|---|---|
| **M-32 EB (n= 416)** | | | | |
| **Variables** | **Min** | **Max** | **Mean** | **Std. Dev.** |
| Upstream speed, mph | 42.000 | 67.000 | 57.222 | 4.731 |
| Speed at curve entry, mph | 34.000 | 63.000 | 50.423 | 5.329 |
| Vehicle exceeded advisory speed at curve entry (1 if yes 0 if no) | 0 | 1 | 0.827 | 0.379 |
| **Sign Test Conditions** | | | | |
| LED Border Off | 0 | 1 | 0.377 | 0.485 |
| LED Border On (Flashing) | 0 | 1 | 0.623 | 0.485 |
| **Vehicle Types** | | | | |
| Passenger Cars | 0 | 1 | 0.906 | 0.292 |
| Heavy Vehicles | 0 | 1 | 0.094 | 0.292 |
| **M-32 WB (n = 313)** | | | | |
| **Variables** | **Min** | **Max** | **Mean** | **Std. Dev.** |
| Upstream speed, mph | 42.000 | 72.000 | 56.031 | 4.228 |
| Speed at curve entry, mph | 38.000 | 66.867 | 53.877 | 4.414 |
| Vehicle exceeded advisory speed at curve entry (1 if yes 0 if no) | 0 | 1 | 0.965 | 0.184 |
| **Sign Test Conditions** | | | | |
| LED Border Off | 0 | 1 | 0.339 | 0.474 |
| LED Border On (Flashing) | 0 | 1 | 0.661 | 0.474 |
| **Vehicle Types** | | | | |
| Passenger Cars | 0 | 1 | 0.824 | 0.381 |
| Heavy Vehicles | 0 | 1 | 0.176 | 0.381 |
| **by Driver Group (Passenger Cars Only)** | | | | |
| **Faster Drivers (n = 211)** | | | | |
| **Variables** | **Min** | **Max** | **Mean** | **Std. Dev.** |
| Upstream speed, mph | 49.000 | 72.000 | 61.053 | 2.919 |
| Speed at curve entry, mph | 40.000 | 67.000 | 55.541 | 4.186 |
| **Sign Test Conditions** | | | | |
| LED Border Off | 0 | 1 | 0.502 | 0.501 |
| LED Border On (Flashing) | 0 | 1 | 0.498 | 0.501 |
| **Average Drivers (n = 211)** | | | | |
| **Variables** | **Min** | **Max** | **Mean** | **Std. Dev.** |
| Upstream speed, mph | 42.000 | 63.000 | 57.082 | 1.908 |
| Speed at curve entry, mph | 40.000 | 60.000 | 52.268 | 3.914 |
| **Sign Test Conditions** | | | | |
| LED Border Off | 0 | 1 | 0.508 | 0.501 |
| LED Border On (Flashing) | 0 | 1 | 0.492 | 0.501 |
| **Slower Drivers (n = 211)** | | | | |
| **Variables** | **Min** | **Max** | **Mean** | **Std. Dev.** |
| Upstream speed, mph | 42.000 | 61.000 | 51.977 | 2.976 |
| Speed at curve entry, mph | 34.000 | 59.000 | 47.890 | 4.503 |
| **Sign Test Conditions** | | | | |
| LED Border Off | 0 | 1 | 0.488 | 0.501 |
| LED Border On (Flashing) | 0 | 1 | 0.512 | 0.501 |

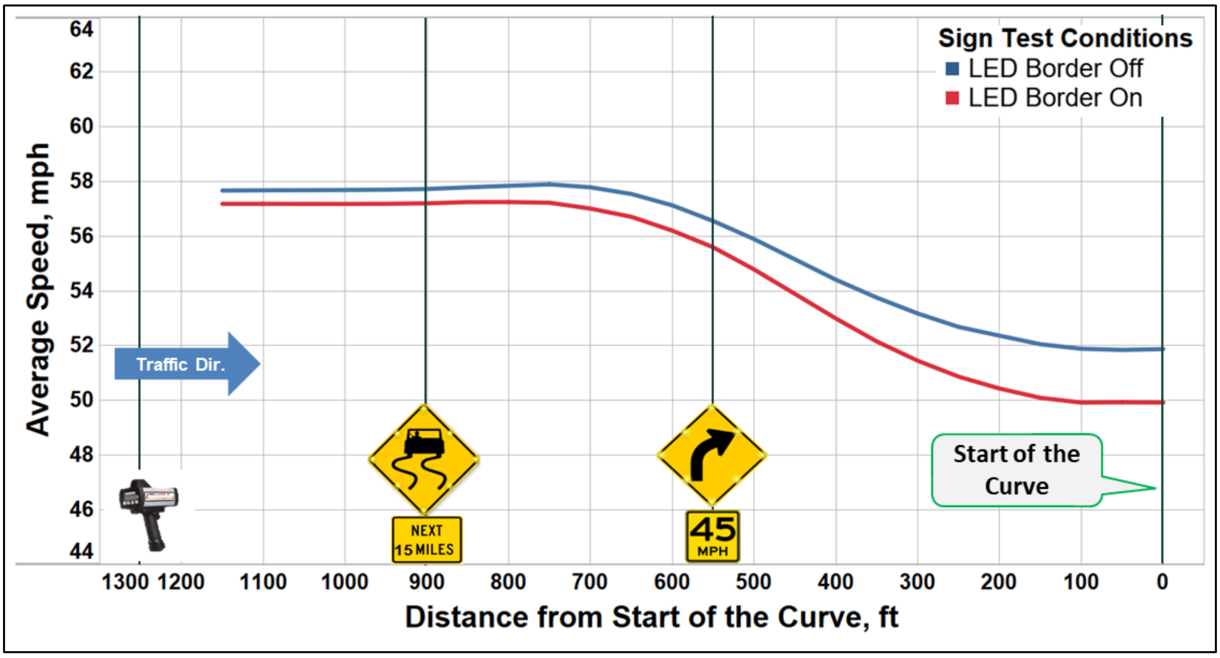


Figure 67. Mean Speed Trajectories by Sign Test Condition, EB M-32

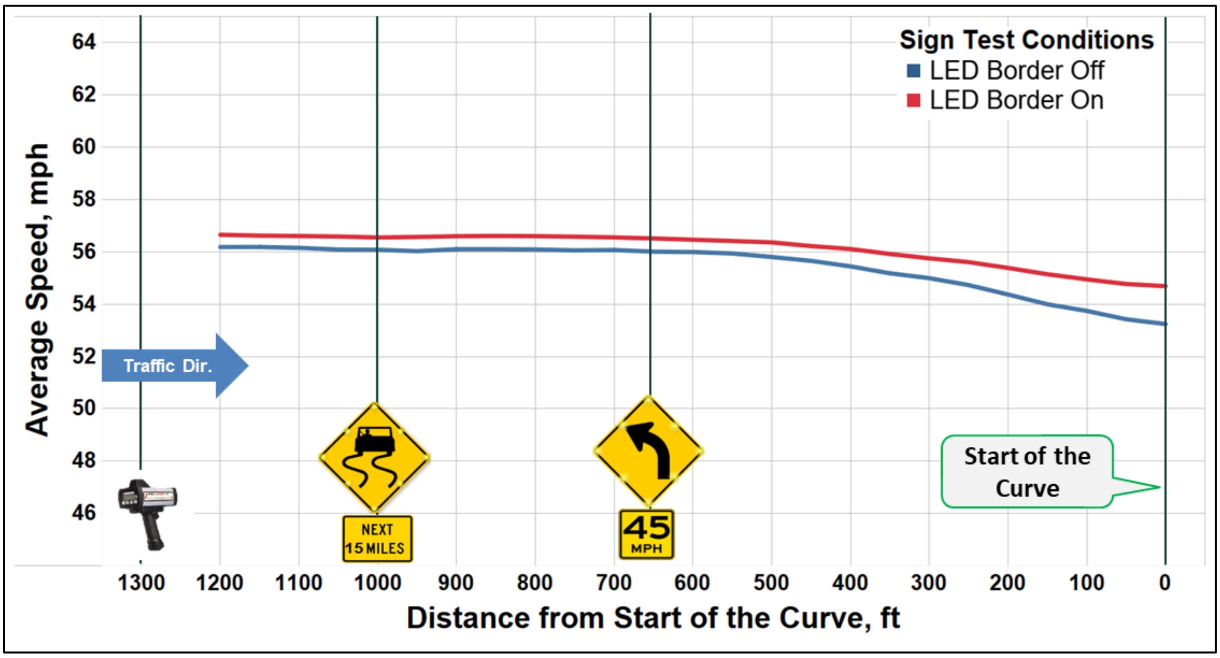


Figure 68. Mean Speed Trajectories by Sign Test Condition, WB M-32

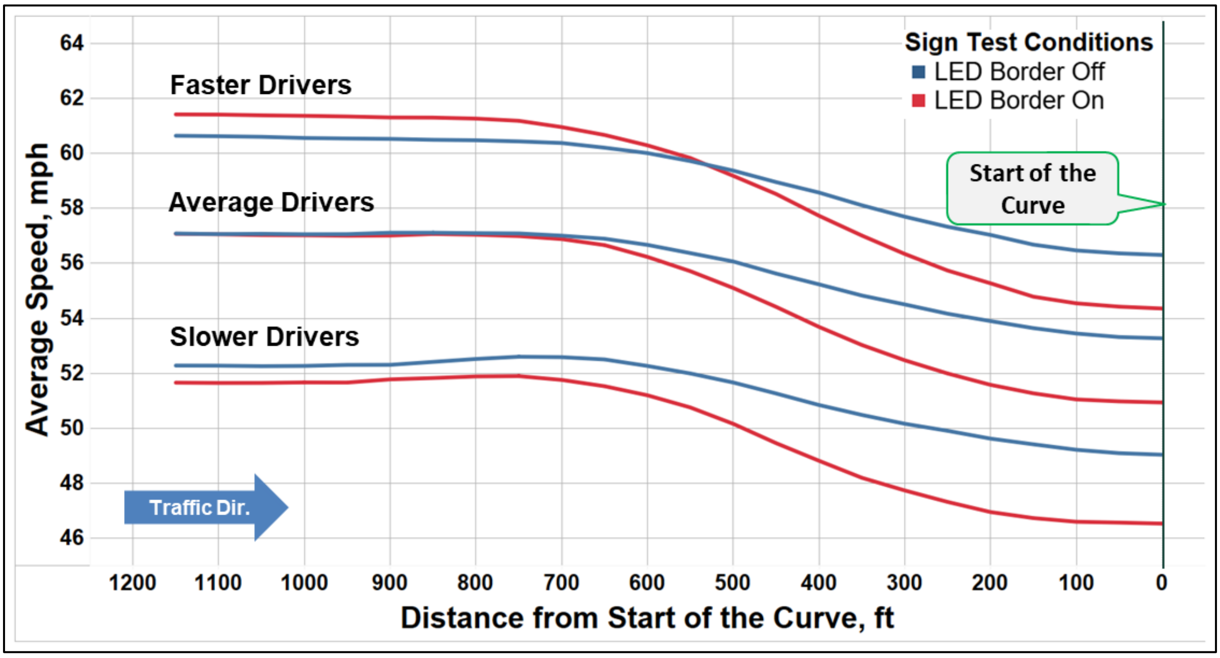


**Figure 69. Mean Speed Trajectories by Sign Condition and Driver Type**

### 6.1.4 Results – Effect of Slippery Curve Warning System on Curve Entry Speed

The data were analyzed to determine both the magnitude of the speed reduction and the likelihood of drivers exceeding the advisory speed at the curve entry point associated with the flashing LED border compared to the base condition with the LED borders off. Separate models were developed for each site along with separate analyses for the slower, average, and faster driver groups using data combined across the two sites. The inclusion of 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 **Figure 67** through **Figure 69**. 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 pavement conditions, weather conditions, and the general behavior of drivers. The final linear regression model results are presented for each site in **Table 46** and for each for each driver behavior group in **Table 47**.

**Figure 70**, **Figure 71**, and **Figure 72** display the mean speed reduction trajectories, which were developed by setting the speed measured at the furthest upstream measurement point to zero. Displaying the speed data in this manner allows for the 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 curve. Thus, these graphics are generally reflective of the regression model parameter estimates for speeds at the curve across each of the test conditions.

## Table 46. Linear Regression Results for Curve Entry Speed, by Site

| **M-32 EB (n = 416)** | | | |
|---|---|---|---|
| **Parameters** | **Estimate, mph** | **Std. Error** | **p-value** |
| Intercept | 2.868 | 2.006 | 0.154 |
| Upstream Speed | 0.850 | 0.034 | <0.001 |
| **Sign Test Conditions** | | | |
| LED Border Off | *Baseline* | | |
| LED Border On (Flashing) | -1.548 | 0.335 | <0.001 |
| **Vehicle Types** | | | |
| Passenger Cars | *Baseline* | | |
| Heavy Vehicles | -1.246 | 0.559 | <0.001 |
| **M-32 WB (n = 313)** | | | |
| **Parameters** | **Estimate, mph** | **Std. Error** | **p-value** |
| Intercept | 12.450 | 2.298 | <0.001 |
| Upstream Speed | 0.744 | 0.040 | <0.001 |
| **Sign Test Conditions** | | | |
| LED Border Off | *Baseline* | | |
| LED Border On (Flashing) | -0.868 | 0.350 | 0.014 |
| **Vehicle Types** | | | |
| Passenger Cars | *Baseline* | | |
| Heavy Vehicles | -1.895 | 0.448 | <0.001 |

## Table 47. Linear Regression Results for Curve Entry Speed, by Driver Behavior Group

| **Passenger Cars, Faster Drivers (n = 211)** | | | |
|---|---|---|---|
| **Parameters** | **Estimate, mph** | **Std. Error** | **p-value** |
| Intercept | 19.642 | 6.399 | 0.017 |
| Upstream Speed | 0.640 | 0.105 | <0.001 |
| **Sites** | | | |
| M-32 WB | *Baseline* | | |
| M-32 EB | -3.567 | 0.485 | <0.001 |
| **Sign Test Conditions** | | | |
| LED Border Off | *Baseline* | | |
| LED Border On (Flashing) | -1.669 | 0.449 | <0.001 |
| **Passenger Cars, Average Drivers (n = 211)** | | | |
| **Parameters** | **Estimate, mph** | **Std. Error** | **p-value** |
| Intercept | 15.689 | 10.247 | 0.127 |
| Upstream Speed | 0.700 | 0.180 | <0.001 |
| **Sites** | | | |
| M-32 WB | *Baseline* | | |
| M-32 EB | -4.094 | 0.512 | <0.001 |
| **Sign Test Conditions** | | | |
| LED Border Off | *Baseline* | | |
| LED Border On (Flashing) | -1.297 | 0.451 | 0.004 |
| **Passenger Cars, Slower Drivers (n = 211)** | | | |
| **Parameters** | **Estimate, mph** | **Std. Error** | **p-value** |
| Intercept | 5.558 | 3.215 | 0.085 |
| Upstream Speed | 0.874 | 0.061 | <0.001 |
| **Sites** | | | |
| M-32 WB | *Baseline* | | |
| M-32 EB | -4.616 | 0.369 | <0.001 |
| **Sign Test Conditions** | | | |
| LED Border Off | *Baseline* | | |
| LED Border On (Flashing) | -0.852 | 0.365 | 0.021 |

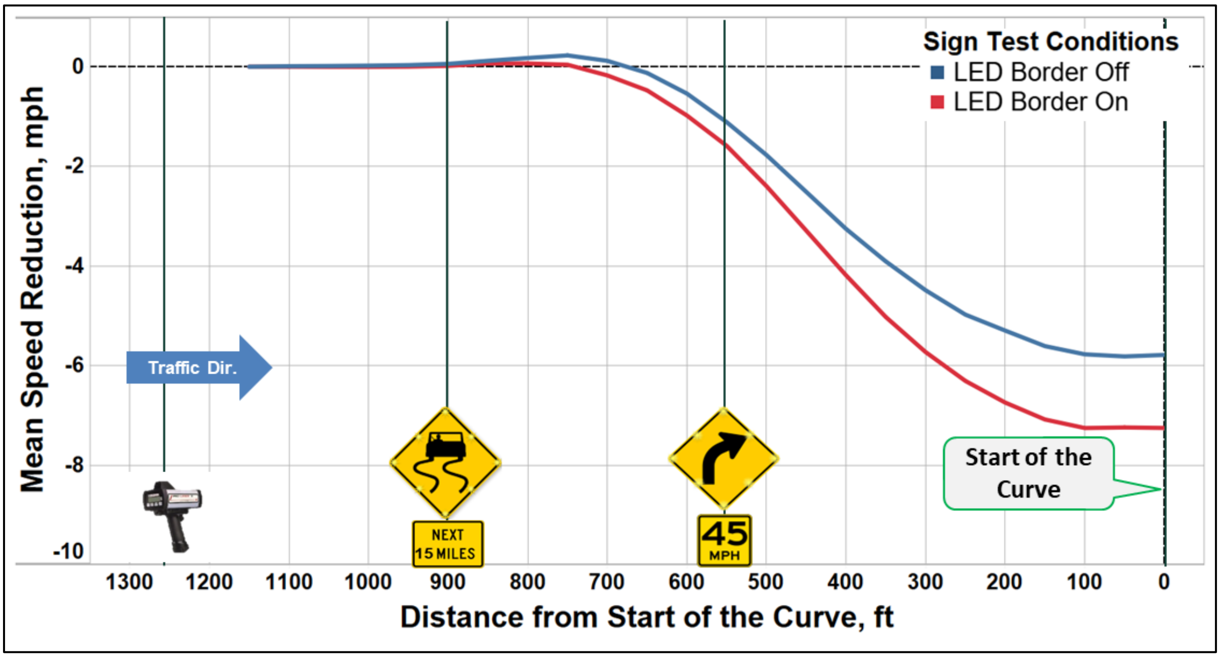


Figure 70. Mean Speed Reduction Trajectories by Sign Test Condition, EB M-32

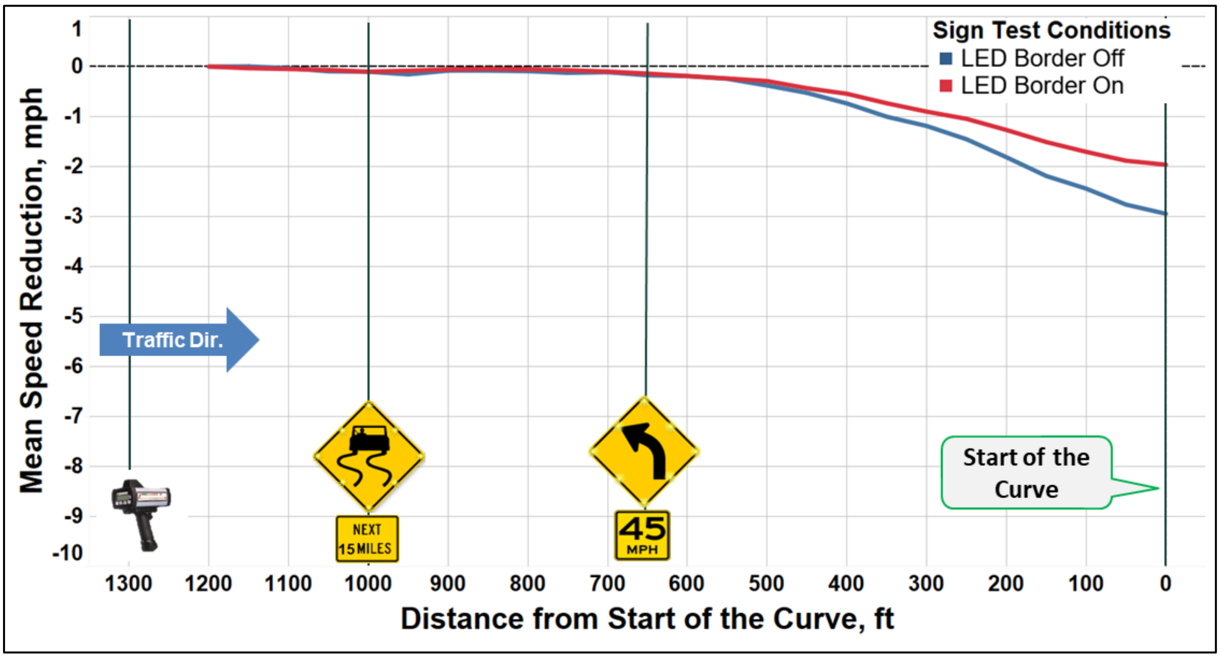


Figure 71. Mean Speed Reduction Trajectories by Sign Test Condition, WB M-32

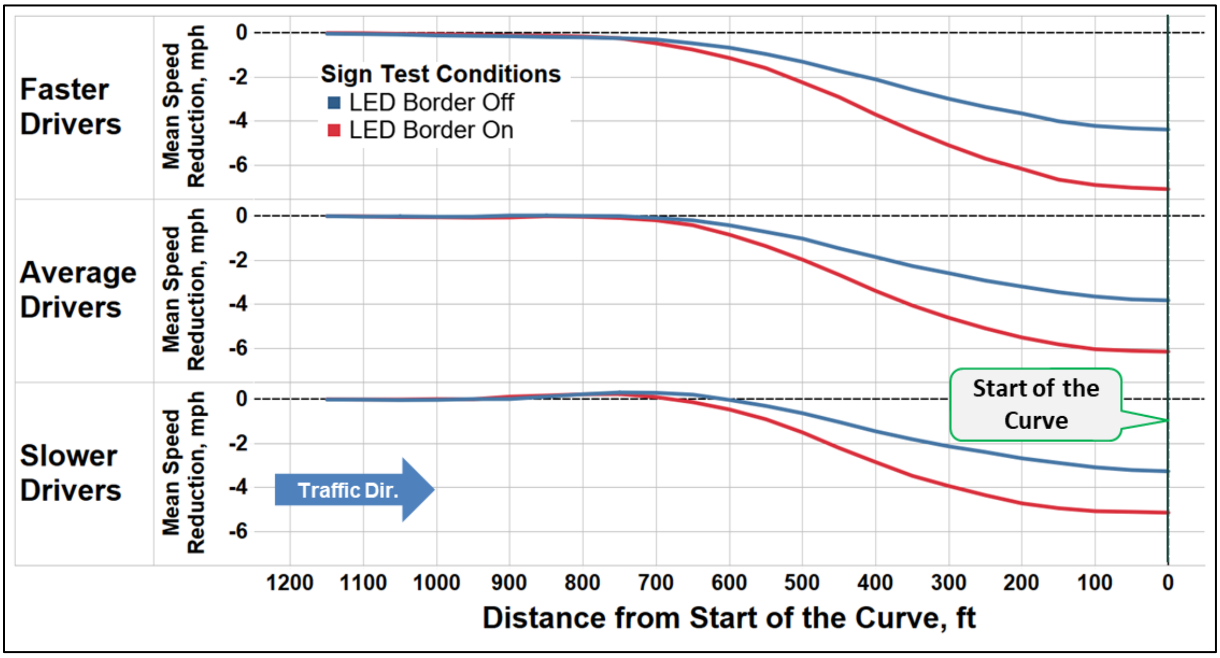


**Figure 72. Mean Speed Reduction Trajectories by Sign Test Condition and Driver Type**

The linear regression results presented in **Table 46** suggest that the slippery curve warning system (SCWS) had a significant speed reduction effect for drivers approaching the curve during winter weather conditions. At the eastbound M-32 site, with LED borders on, the vehicle speeds at the curve were 1.5 mph lower, on average, compared to the base condition (LED borders off). Similarly, at the westbound M-32 site, when the LED borders were on, the speed at the curve was 0.9 mph lower, on average, compared to when the LED borders were off. It can be observed from **Table 46** that the speeds of heavy vehicles were 1.2 mph and 1.9 mph lower at the eastbound and westbound sites, respectively, compared to passenger cars.

**Table 47** shows that each of the three driver groups showed significantly greater speed reductions while the LED borders were flashing compared to when the LED borders were off. However, the speed reduction effect associated with the flashing LED borders was strongest among faster drivers, as the speeds at the curve entry point were 1.7 mph lower compared to when the LED borders were off. This is contrasted with a 0.9 mph speed reduction for the slower driver group. This result is encouraging from a highway safety standpoint, as the fastest drivers are most in need of speed reduction to safely traverse the curve during slippery conditions.

While the aforementioned results demonstrated the magnitude of the speed reduction associated with sign test conditions, logistic regression was utilized to assess whether sign conditions impacted the likelihood of drivers exceeding the advisory speed at the curve entry point. This additional analysis was important to assess the level of driver response to the SCWS without regard to the magnitude of the speed reduction. The dependent variable for this analysis was coded based on whether the subject vehicle exceeded the advisory speed of 45 mph at the curve entry point. Similar to the linear regression model, the upstream speed of each vehicle was included as a covariate in the binary logistic regression models to control for differences in the general driving behavior between individual drivers. **Table 48** presents the results of the binary logistic regression models for the likelihood of exceeding the curve advisory speed at each site.

**Table 48. Logistic Regression Results for Likelihood of Exceeding Advisory Speed at Curve**

| **M-32 EB (n = 416)** | | | | |
|---|---|---|---|---|
| **Parameters** | **β** | **Std. Error** | **p-value** | **Odds Ratio** |
| Intercept | -23.054 | 2.900 | <0.001 | |
| Upstream Speed | 0.464 | 0.055 | <0.001 | 1.591 |
| **Sign Test Conditions** | | | | |
| LED Border Off | *Baseline* | | | |
| LED Border On (Flashing) | -0.972 | 0.401 | 0.015 | 0.378 |
| **Vehicle Type** | | | | |
| Passenger Cars | *Baseline* | | | |
| Heavy Vehicles | -1.357 | 0.486 | 0.005 | 0.257 |
| **M-32 WB (n = 313)** | | | | |
| **Parameters** | **β** | **Std. Error** | **p-value** | **Odds Ratio** |
| Intercept | -16.041 | 4.594 | <0.001 | |
| Upstream Speed | 0.386 | 0.092 | <0.001 | 1.471 |
| **Sign Test Conditions** | | | | |
| LED Border Off | *Baseline* | | | |
| LED Border On (Flashing) | -1.274 | 0.728 | 0.080 | 0.280 |
| **Vehicle Type** | | | | |
| Passenger Cars | *Baseline* | | | |
| Heavy Vehicles | -1.413 | 0.713 | 0.048 | 0.243 |

The logistic regression model results presented in **Table 48** show that drivers were less likely to exceed the advisory speed while the LED borders were flashing compared to when the LED borders were off. At the EB M-32 site, when the LED borders were flashing, drivers were 62 percent less likely to exceed the advisory speed at the curve as compared to the base (i.e., LED borders off) condition. Similarly, at the WB M-32 site, the likelihood of exceeding the advisory speed at the curve was reduced by 72 percent with the LED borders flashing compared to off. **Table 48** also indicates that heavy vehicle drivers were approximately 75 percent less likely to exceed the advisory speed at the curve compared to passenger cars.

## 6.2 Winter Weather Warning Messages on Changeable Message Signs at Freeway Bridge Overpasses

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. A series of field evaluations were performed during the winters of 2023 and 2024 to assess the effectiveness of weather-related warning messages displayed on changeable message signs on driver speed-selection while approaching a bridge overpass during winter weather conditions. The following sections provide details on the study sites, test messages, analysis, and results.

### 6.2.1 Site Descriptions

Three freeway bridge overpasses were selected for the field evaluation, including:

- Site 1: Northbound (NB) US-127 over Willoughby Road, Lansing
- Site 2: Westbound (WB) I-196 over abandoned railbed at mile marker 72.5, Grand Rapids
- Site 3: Eastbound (EB) I-196 over 32nd Ave, Grand Rapids

The field evaluation layout of sites 1, 2, and 3 are shown in **Figure 73**, **Figure 74**, and **Figure 75**, respectively. All three sites were located on a limited-access freeway with two lanes in each direction and a speed limit of 70 mph for passenger cars and 65 mph for heavy vehicles (trucks and buses). Each site included a standard BRIDGE ICES BEFORE ROAD (W8-13) warning sign on the bridge approach. The sites were primarily selected due to the presence of a permanent CMS on the approach to the bridge. Additionally, each site was on a relatively straight segment with broad shoulders and a flat roadside to facilitate data collection. At sites 1 and 2, the CMS was located near (e.g., 100 to 150 feet upstream) the start of the bridge deck, while at site 3, the CMS was located 900 feet upstream. This variation in CMS positioning made it possible to analyze the spatial characteristics of the CMS on driver response.

### 6.2.2 Sign Test Conditions and Data Collection Procedures

Each CMS was a full matrix amber rectangular LED panel that was 29.33 feet wide by 8 feet tall and capable of displaying 25 alphanumeric characters 13 inches wide by 18.2 inches tall in each of the three rows. 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 research advisory panel, and MDOT statewide operations center personnel. The CMS test messages were pre-programmed by MDOT TOC staff to change every 20 minutes during data collection, meaning that each of the three messages was displayed during each hour of data collection. These messaging cycles were repeated during each day of data collection. The periodic change in CMS test messages every 20 minutes afforded considerable control over any variations in weather conditions, pavement conditions, and general driver behavior throughout the data collection periods. Three CMS messages were tested at each site (**Figure 76**), including:

1. Baseline: Travel Times (e.g. Time to downtown via / I-196 15 MIN / M-6/US-131 17 MIN)
2. BRIDGES ICE / BEFORE ROAD / REDUCE SPEEDS (Reinforces W8-13 sign message "BRIDGE ICES BEFORE ROAD" while adding desired action "REDUCE SPEEDS")
3. SLIPPERY / ROAD CONDITIONS / REDUCE SPEEDS (MDOT's standard CMS message used during winter weather advisories)

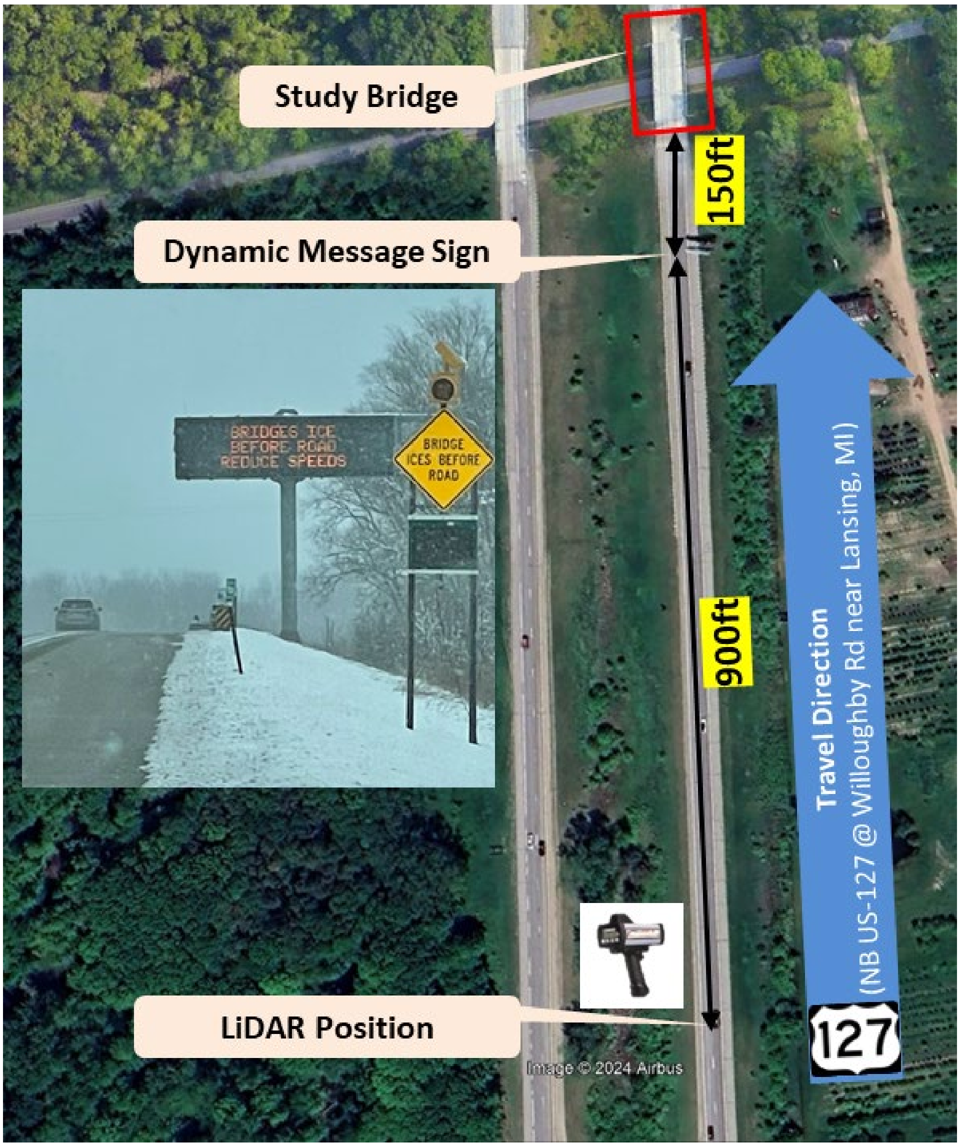


**Figure 73. Field Evaluation Layout at NB US-127 over Willoughby Road, Lansing, Michigan (Site 1)**

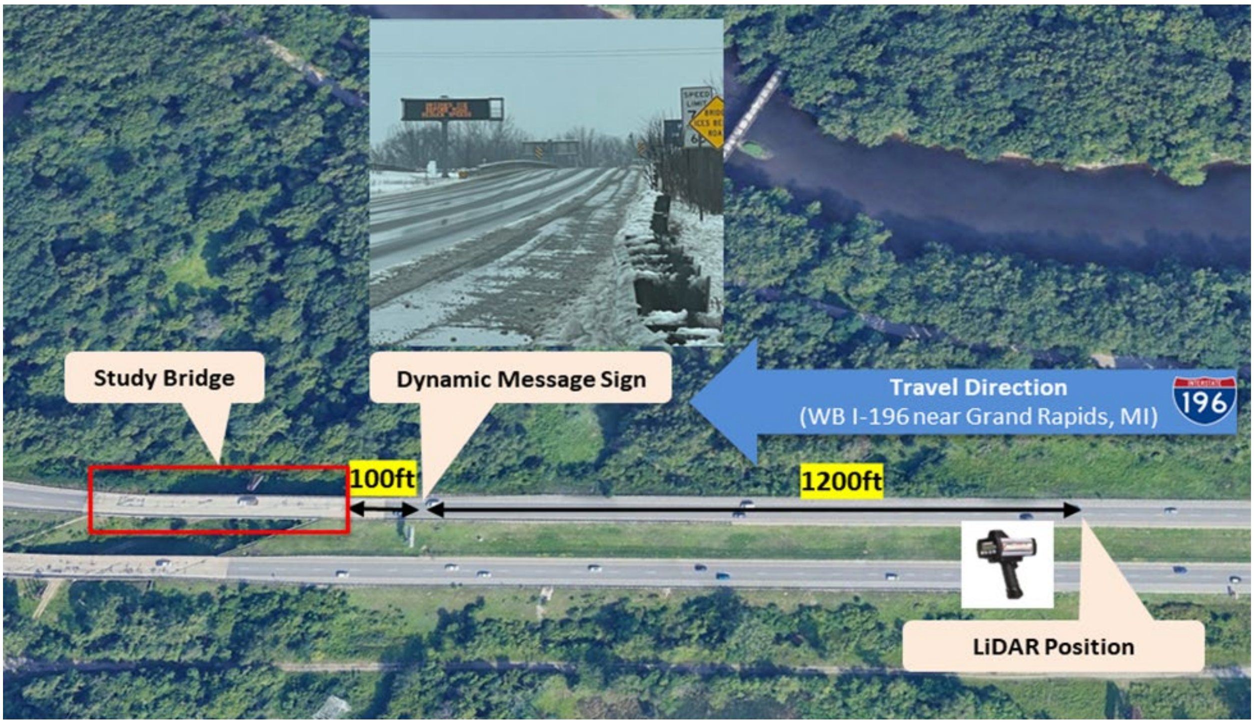


Figure 74. Field Evaluation Layout at WB I-96 over Abandoned Railbed at Mile Marker 72.5, Grand Rapids, Michigan (Site 2)

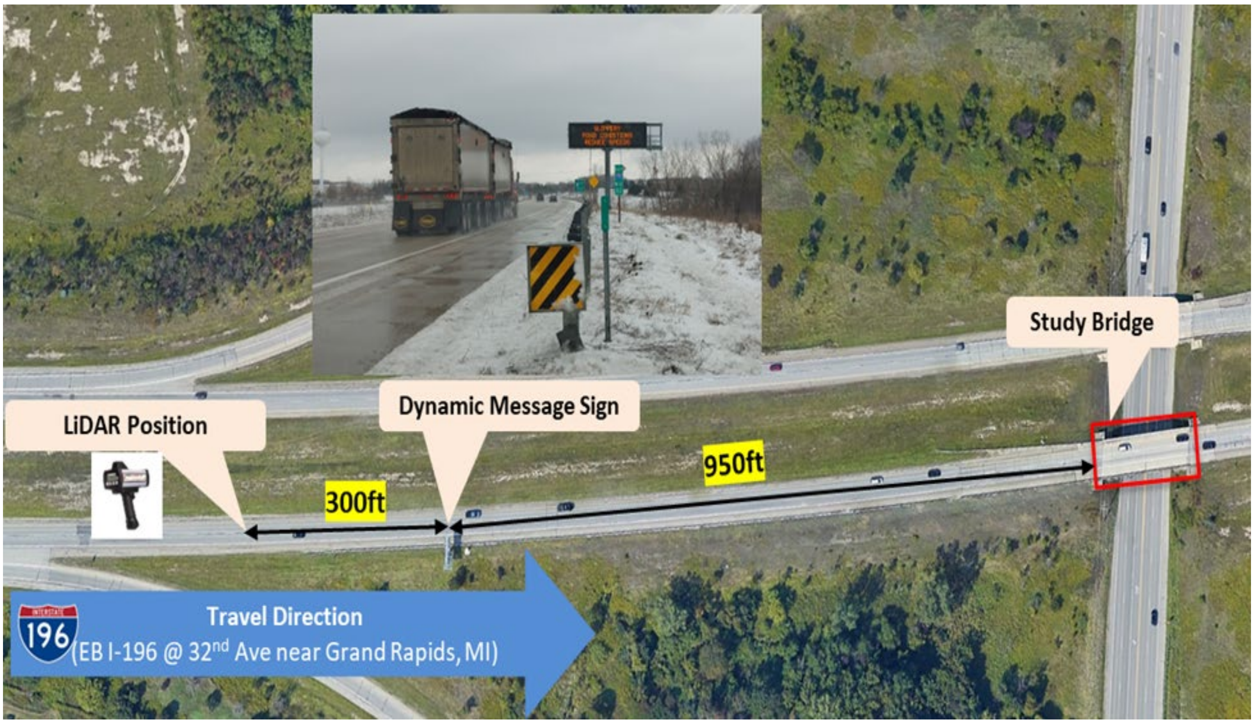


Figure 75. Field Evaluation Layout at EB I-96 over 32nd Ave, Grand Rapids, Michigan (Site 3)

Figure 76. Example of CMS Test Messages Displayed During Data Collection at Site 3

Field data collection was performed in March 2023 for Site 1 and February 2024 for Sites 2 and 3. Speed data were collected using a handheld LIDAR gun that was operated by a technician positioned in a vehicle parked on the roadside. The technician was positioned 1,050 ft upstream of the start of the bridge at Site 2, 1,300 ft upstream of the start of the bridge at Site 2, and 1,250 ft upstream of the start of the bridge at Site 3. The technician remained in the same position for all data collection performed at the site. To facilitate safe and efficient data collection, the team specifically targeted days with early-morning snowfall tapering to overcast or light snow conditions by mid-morning and high temperatures in the upper 20-degree to lower 30-degree Fahrenheit range. Snow removal and de-icing were actively performed by maintenance crews during each data collection period, affording a consistently wet pavement surface throughout each period. Periods of heavy snowfall were avoided, as it was neither safe nor feasible to collect LIDAR data during such conditions.

### 6.2.3 Descriptive Statistics

After the completion of data collection in February 2024, all datasets were prepared for analysis. The vehicle speed data collected at the three sites were compiled into a single file for further analysis. The datasets were structured such that each row in the file represented the complete record for a single vehicle traversing the site during the specified CMS test message. The CMS test messages were coded as a series of binary variables, which allowed for the speed-related effects of each warning message to be analyzed against the base messaging condition (travel time). The remaining categorical factors were also incorporated as a series of binary variables. These variables included: vehicle type (passenger car, heavy vehicle), and CMS location (near the bridge, far upstream from the bridge). The furthest upstream speed measurement for each subject vehicle was also included as an independent variable in the analysis accounting for driver general speed behavior prior to encountering the CMS message. As the LIDAR vehicle position varied between the sites, it was necessary to utilize the furthest upstream speed measurement point that was common between the three sites, which was 950 feet upstream from the start of the bridge deck.

A total of 1,270 vehicles were included in the dataset across the three sites, including 1,032 passenger cars and 238 heavy vehicles. The data were subdivided based on vehicle type (passenger cars vs. heavy vehicles) and analyzed separately due to differences in the general driver speed behavior between these two vehicle classes. The descriptive statistics (minimum, maximum, mean, and standard deviation) of the dependent and independent variables are presented in **Table 49**. The mean values for the binary variables listed in the table represent the proportion of the total data set represented by that variable. It should again be noted that the data were collected during relatively consistent weather and pavement surface conditions (e.g., wet and overcast with temperatures in the upper 20s to lower 30s), both within each site and between the three sites. Thus, additional variables related to the specific weather and pavement conditions were not created. Further, it was not necessary to include time-of-day as a factor in the model, as each message was displayed for 20 minutes during each hour of data collection. **Figure 77** displays the mean speed trajectories across the three CMS message conditions by vehicle type for all three sites combined.

**Table 49. Descriptive Statistics for CMS Weather Messaging Evaluation, by Vehicle Type**

| **Passenger Cars (n = 1032)** | | | | |
|---|---|---|---|---|
| **Variable** | **Min** | **Max** | **Mean** | **Std. Dev.** |
| Upstream Speed (950 ft from the start of the bridge), mph | 50 | 88 | 70.678 | 5.361 |
| Speed at the Bridge, mph | 47 | 86 | 69.979 | 5.638 |
| Speed Reduction Prior to the Bridge (0 = no, 1 = yes) | 0 | 1 | 0.459 | 0.499 |
| **CMS Test Message** | | | | |
| Travel Times | 0 | 1 | 0.284 | 0.451 |
| BRIDGES ICE BEFORE ROAD / REDUCE SPEEDS | 0 | 1 | 0.379 | 0.485 |
| SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS | 0 | 1 | 0.337 | 0.473 |
| **CMS Location (distance upstream from start of bridge)** | | | | |
| Upstream of Bridge (900 ft) | 0 | 1 | 0.236 | 0.425 |
| Near Bridge (100-150ft) | 0 | 1 | 0.764 | 0.425 |
| **Heavy Vehicles (n = 238)** | | | | |
| **Variable** | **Min** | **Max** | **Mean** | **Std. Dev.** |
| Upstream Speed (950 ft from the start of the bridge), mph | 49 | 75 | 63.893 | 4.325 |
| Speed at the Bridge, mph | 48 | 75 | 62.918 | 5.087 |
| Speed Reduction Prior to the Bridge (0 = no, 1 = yes) | 0 | 1 | 0.517 | 0.501 |
| **CMS Test Message** | | | | |
| Travel Times | 0 | 1 | 0.239 | 0.428 |
| BRIDGES ICE BEFORE ROAD / REDUCE SPEEDS | 0 | 1 | 0.429 | 0.496 |
| SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS | 0 | 1 | 0.332 | 0.472 |
| **CMS Location (distance upstream from start of bridge)** | | | | |
| Upstream of Bridge (900 ft) | 0 | 1 | 0.550 | 0.498 |
| Near Bridge (100-150ft) | 0 | 1 | 0.450 | 0.498 |

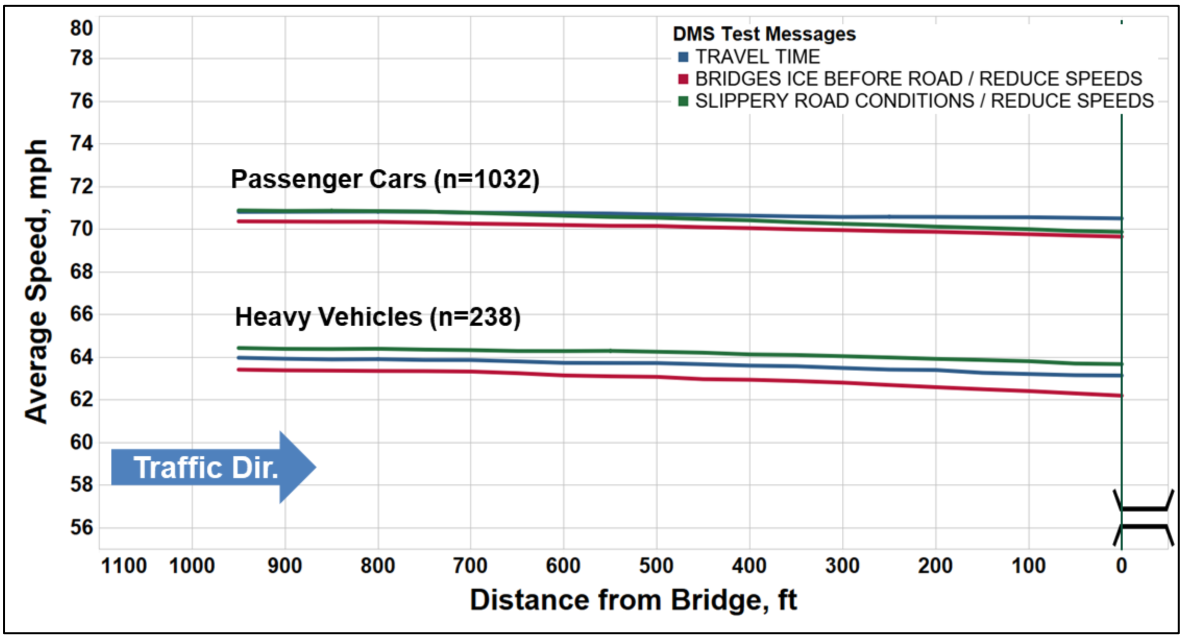


**Figure 77. Mean Speed Trajectories by CMS Test Message and Vehicle Type**

The data for passenger cars were further split into three distinct driver behavior categories (e.g., faster, average, and slower) based on the speed measured for each subject driver at the furthest upstream measurement point. This allowed for the assessment of whether the CMS messages elicited different behaviors from faster, average, or slower drivers. Ultimately, for analytical purposes, the data were then combined across the three sites, with separate datasets created and analyzed for the slower, average, and faster driver categories. The descriptive statistics (minimum, maximum, mean, and standard deviation) of the dependent and independent variables are presented in **Table 50**. **Figure 78** displays the mean speed trajectories for each CMS test message separated by driver type.

**Table 50. Descriptive Statistics for CMS Weather Messaging Evaluation, by Driver Type**

| **Passenger Cars, Faster Drivers (n = 343)** | | | | |
|---|---|---|---|---|
| **Variable** | **Min** | **Max** | **Mean** | **Std. Dev.** |
| Upstream Speed (950 ft from the start of the bridge), mph | 71 | 88 | 76.153 | 3.018 |
| Speed at the Bridge, mph | 64 | 86 | 75.192 | 3.678 |
| Speed Reduction Prior to the Bridge (0 = no, 1 = yes) | 0 | 1 | 0.487 | 0.501 |
| **CMS Test Message** | | | | |
| Travel Times | 0 | 1 | 0.283 | 0.451 |
| BRIDGES ICE BEFORE ROAD / REDUCE SPEEDS | 0 | 1 | 0.379 | 0.486 |
| SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS | 0 | 1 | 0.338 | 0.474 |
| **CMS Location (distance upstream from start of bridge)** | | | | |
| Upstream of Bridge (900 ft) | 0 | 1 | 0.236 | 0.425 |
| Near Bridge (100-150ft) | 0 | 1 | 0.764 | 0.425 |
| **Passenger Cars, Average Drivers (n = 344)** | | | | |
| **Variable** | **Min** | **Max** | **Mean** | **Std. Dev.** |
| Upstream Speed (950 ft from the start of the bridge), mph | 67 | 76 | 70.718 | 2.148 |
| Speed at the Bridge, mph | 62 | 78 | 70.130 | 3.019 |
| Speed Reduction Prior to the Bridge (0 = no, 1 = yes) | 0 | 1 | 0.451 | 0.498 |
| **CMS Test Message** | | | | |
| Travel Times | 0 | 1 | 0.282 | 0.451 |
| BRIDGES ICE BEFORE ROAD / REDUCE SPEEDS | 0 | 1 | 0.381 | 0.486 |
| SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS | 0 | 1 | 0.337 | 0.473 |
| **CMS Location (distance upstream from start of bridge)** | | | | |
| Upstream of Bridge (900 ft) | 0 | 1 | 0.235 | 0.425 |
| Near Bridge (100-150ft) | 0 | 1 | 0.765 | 0.425 |
| **Passenger Cars, Slower Drivers (n = 345)** | | | | |
| **Variable** | **Min** | **Max** | **Mean** | **Std. Dev.** |
| Upstream Speed (950 ft from the start of the bridge), mph | 50 | 72 | 65.194 | 3.527 |
| Speed at the Bridge, mph | 47 | 75 | 64.646 | 4.131 |
| Speed Reduction Prior to the Bridge (0 = no, 1 = yes) | 0 | 1 | 0.441 | 0.497 |
| **CMS Test Message** | | | | |
| Travel Times | 0 | 1 | 0.287 | 0.453 |
| BRIDGES ICE BEFORE ROAD / REDUCE SPEEDS | 0 | 1 | 0.377 | 0.485 |
| SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS | 0 | 1 | 0.336 | 0.473 |
| **CMS Location (distance upstream from start of bridge)** | | | | |
| Upstream of Bridge (900 ft) | 0 | 1 | 0.238 | 0.426 |
| Near Bridge (100-150ft) | 0 | 1 | 0.762 | 0.426 |

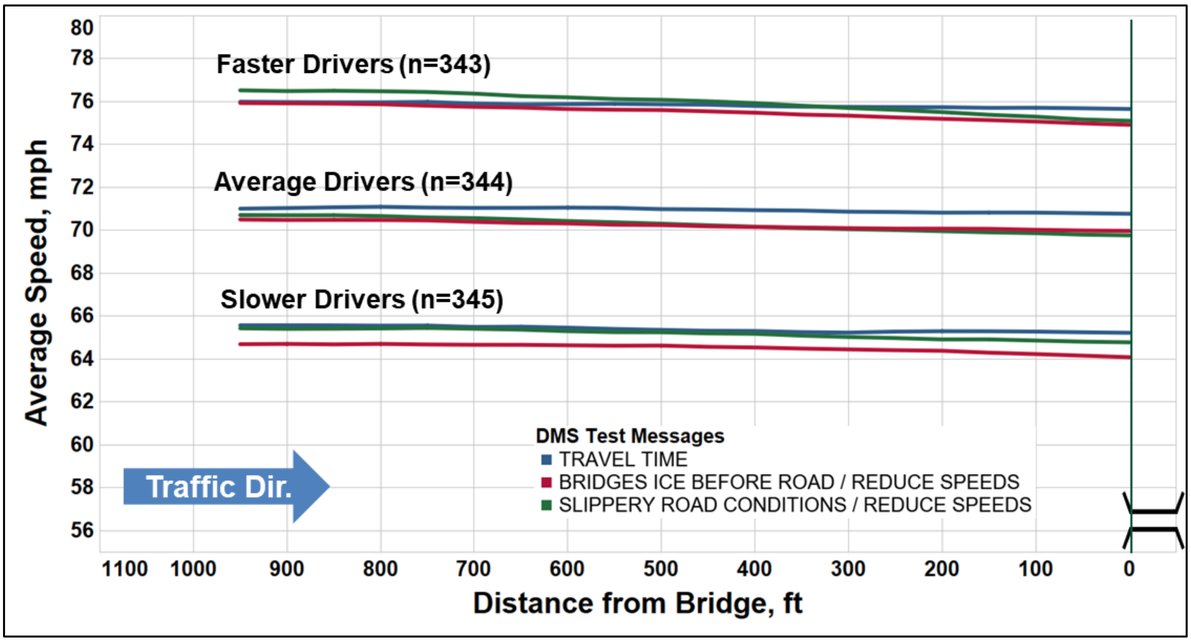


Figure 78. Mean Speed Trajectories by CMS Test Message and Driver Type

### 6.2.4 Results – Effect of CMS Winter Weather Warning Messages on Speed at the Bridge

The data were analyzed to determine the effect of each CMS messaging strategy during winter weather conditions on both the magnitude of the speed reduction and the likelihood of drivers reducing their speed prior to reaching the bridge. The data were analyzed using linear and binary logistic regression models. In the linear regression models, the speed of vehicles at the start of the bridge was the dependent variable. While the linear regression model afforded an assessment of the magnitude of the speed reduction effect, it was also of interest to assess whether each CMS messaging strategy impacted the likelihood of drivers reducing their speed by any measurable amount between the furthest upstream measurement point and the bridge. As this assessment was binary in nature (i.e., driver reduced speed vs. driver did not reduce speed), the data were modeled using binary logistic regression.

Separate models were developed for passenger vehicles and heavy vehicles and for the slower, average, and faster driver groups. The inclusion of 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 **Figure 77** and **Figure 78**. 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 pavement conditions, weather conditions, and the general behavior of drivers. The linear regression model results are presented in **Table 51**.

## Table 51. Linear Regression Model Results for Speed at the Bridge

| **Model 1: All Passenger Cars (n = 1032)** | | | |
|---|---|---|---|
| **Parameter** | **Estimate, mph** | **Std. Error** | **p-value** |
| Intercept | 3.525 | 0.778 | <0.001 |
| Upstream Speed | 0.962 | 0.010 | <0.001 |
| **CMS Test Message** | | | |
| Travel Times | *Baseline* | | |
| BRIDGES ICE BEFORE ROAD / REDUCE SPEEDS | -0.484 | 0.131 | <0.001 |
| SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS | -0.763 | 0.134 | <0.001 |
| **CMS Location (distance upstream from start of bridge)** | | | |
| Upstream of Bridge (900 ft) | *Baseline* | | |
| Near Bridge (100-150ft) | -1.406 | 0.131 | <0.001 |
| **Model 2: Passenger Cars, Faster Drivers (n = 343)** | | | |
| **Parameter** | **Estimate, mph** | **Std. Error** | **p-value** |
| Intercept | 7.598 | 3.173 | 0.017 |
| Upstream Speed | 0.912 | 0.040 | <0.001 |
| **CMS Test Message** | | | |
| Travel Times | *Baseline* | | |
| BRIDGES ICE BEFORE ROAD / REDUCE SPEEDS | -0.749 | 0.247 | 0.003 |
| SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS | -1.108 | 0.254 | <0.001 |
| **CMS Location (distance upstream from start of bridge)** | | | |
| Upstream of Bridge (900 ft) | *Baseline* | | |
| Near Bridge (100-150ft) | -1.609 | 0.283 | <0.001 |
| **Model 3: Passenger Cars, Average Drivers (n = 344)** | | | |
| **Parameter** | **Estimate, mph** | **Std. Error** | **p-value** |
| Intercept | 0.208 | 4.510 | 0.963 |
| Upstream Speed | 1.007 | 0.061 | <0.001 |
| **CMS Test Message** | | | |
| Travel Times | *Baseline* | | |
| BRIDGES ICE BEFORE ROAD / REDUCE SPEEDS | -0.337 | 0.209 | 0.107 |
| SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS | -0.760 | 0.212 | <0.001 |
| **CMS Location (distance upstream from start of bridge)** | | | |
| Upstream of Bridge (900 ft) | *Baseline* | | |
| Near Bridge (100-150ft) | -1.223 | 0.306 | <0.001 |
| **Model 4: Passenger Cars, Slower Drivers (n = 345)** | | | |
| **Parameter** | **Estimate, mph** | **Std. Error** | **p-value** |
| Intercept | 1.994 | 2.066 | 0.335 |
| Upstream Speed | 0.980 | 0.030 | <0.001 |
| **CMS Test Message** | | | |
| Travel Times | *Baseline* | | |
| BRIDGES ICE BEFORE ROAD / REDUCE SPEEDS | -0.334 | 0.227 | 0.143 |
| SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS | -0.380 | 0.231 | 0.101 |
| **CMS Location (distance upstream from start of bridge)** | | | |
| Upstream of Bridge (900 ft) | *Baseline* | | |
| Near Bridge (100-150ft) | -1.324 | 0.246 | <0.001 |
| **Model 5: All Heavy Vehicles (n = 238)** | | | |
| **Parameter** | **Estimate, mph** | **Std. Error** | **p-value** |
| Intercept | -1.233 | 1.431 | 0.390 |
| Upstream Speed | 1.017 | 0.022 | <0.001 |
| **CMS Test Message** | | | |
| Travel Times | *Baseline* | | |
| BRIDGES ICE BEFORE ROAD / REDUCE SPEEDS | -0.068 | 0.215 | 0.753 |
| SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS | 0.137 | 0.224 | 0.540 |
| **CMS Location (distance upstream from start of bridge)** | | | |
| Upstream of Bridge (900 ft) | *Baseline* | | |
| Near Bridge (100-150ft) | -1.942 | 0.189 | <0.001 |

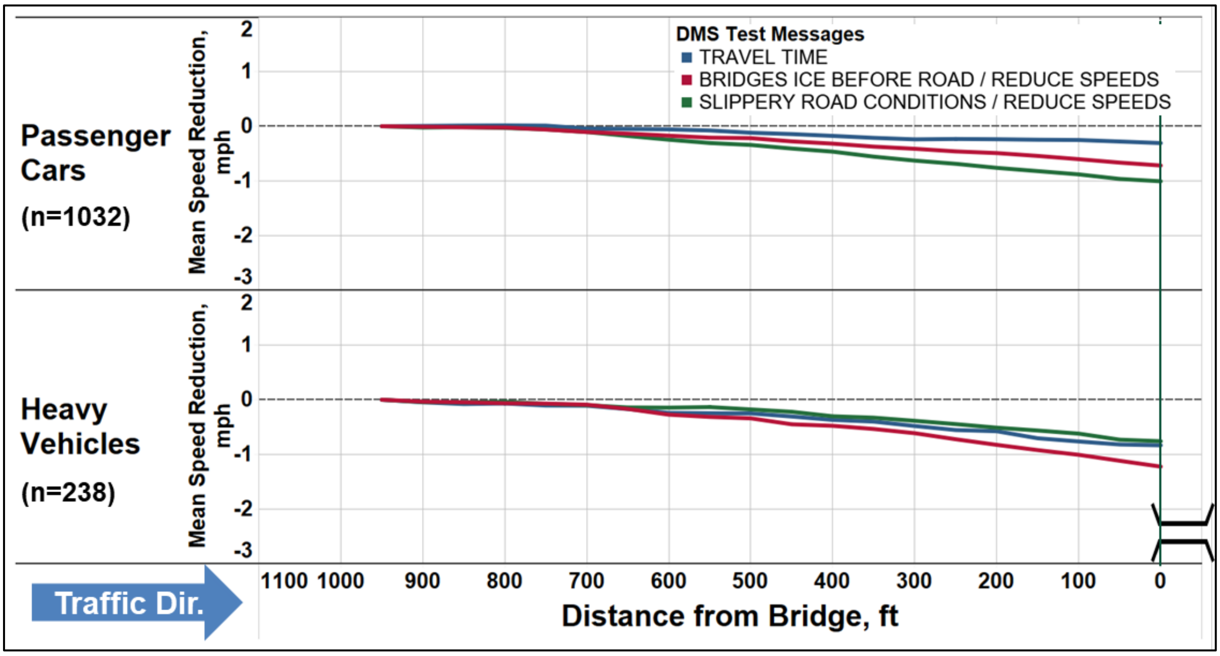


Figure 79. Mean Speed Reduction Trajectories by CMS Test Message and Vehicle Type

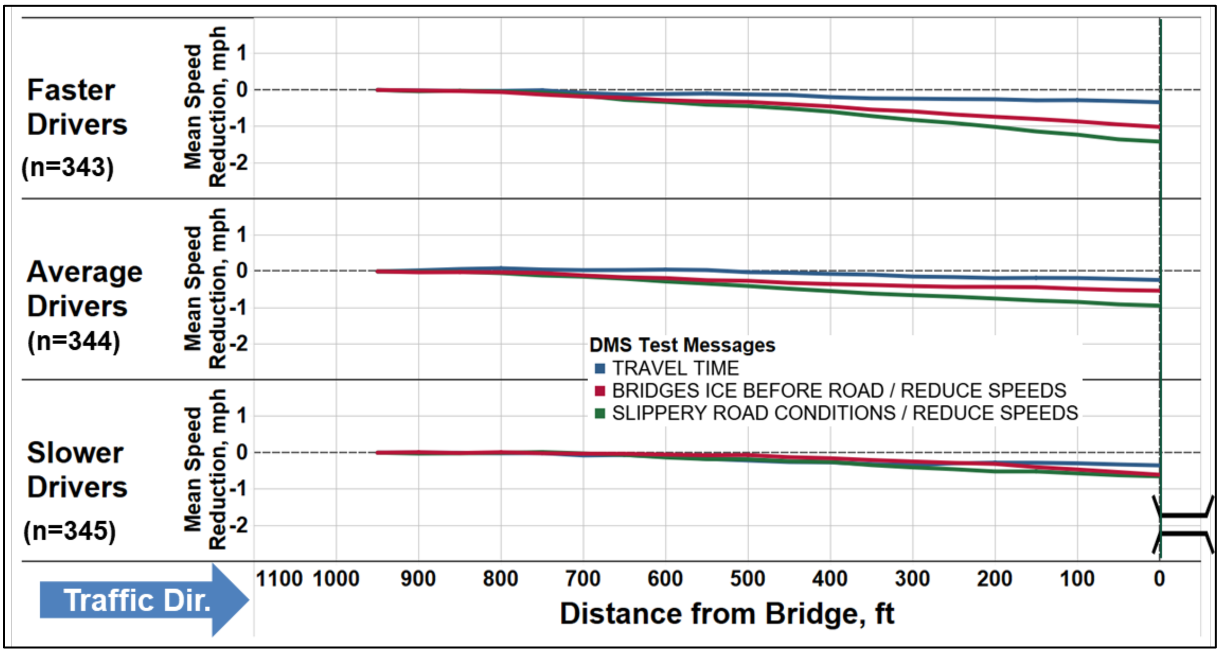


Figure 80. Mean Speed Reduction Trajectories by CMS Test Message and Driver Type

**Figure 79** and **Figure 80** display the speed reduction trajectories, which were developed by setting the speed measured at the furthest upstream point (950 ft from the start of the bridge) to zero. Displaying the speed data in this manner allows for the visual comparison of the speed reduction effects associated with each of the CMS message test conditions while adjusting for the travel speeds observed upstream of the CMS. Thus, these graphics are generally reflective of the regression model results displayed in **Table 51** for speeds at the bridge across each of the CMS test message conditions.

The linear regression results presented **Table 51** in suggest that both of the winter weather warning messages had a significant effect on passenger vehicles' speeds upon reaching the bridge. The strongest speed reduction effect was observed when the "SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS" message was displayed on the CMS. With this message displayed, the speed measured at the bridge was approximately 0.8 mph lower, on average, for passenger cars compared to when travel time messages were displayed on the CMS (base condition). Similarly, when CMS displayed "BRIDGE ICES BEFORE ROAD / REDUCE SPEEDS" the speed at the bridge was approximately 0.5 mph lower, on average, compared to the baseline condition. From **Table 51** it can also be observed that the winter weather warning messages did not affect speed selection for drivers of heavy vehicles.

Similar results were observed across the three driver behavior categories. Each of the three driver groups showed the greatest speed reductions when the "SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS" message was displayed on CMS. The strongest effects associated with this message were observed among faster drivers, as speeds at the bridge were 1.1 mph lower compared to when the standard travel time message was displayed, while speed reductions of 0.8 mph and 0.4 mph were observed for average and slower drivers, respectively. Similarly, when the "BRIDGE ICES BEFORE ROAD / REDUCE SPEEDS" message was displayed, the speeds of faster drivers were 0.7 mph lower at the bridge, although no significant speed effects were observed for average or slower drivers.

Whereas the aforementioned results demonstrated the *magnitude* of the speed reduction associated with each winter weather message, logistic regression was utilized to assess whether each CMS message impacted the likelihood of drivers reducing speed *by any measurable amount* between the furthest upstream measurement point and the start of the bridge. This additional analysis was important to assess the level of driver response to the winter weather CMS messages without regard to the magnitude of the speed reduction. Similar to the linear regression model, separate models were developed for passenger cars and heavy vehicles and also for each driver behavior group. The results of the binary logistic regression model for the likelihood of a speed reduction are presented in **Table 52**. The logistic regression model results can be directly interpreted from the odds ratio (Exp(β)) compared to the baseline condition.

## Table 52. Logistic Regression Model for Likelihood of Speed Reduction at the Bridge

| **Model 6: All Passenger Cars (n = 1032)** | | | | |
|---|---|---|---|---|
| **Parameters** | **β** | **Std. Err** | **p-value** | **Odds Ratio** |
| Intercept | -1.564 | 0.190 | <0.001 | |
| **CMS Test Message** | | | | |
| Travel Times | *Baseline* | | | |
| BRIDGES ICE BEFORE ROAD / REDUCE SPEEDS | 0.430 | 0.162 | 0.008 | 1.537 |
| SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS | 0.709 | 0.167 | <0.001 | 2.032 |
| **CMS Location (distance upstream from start of bridge)** | | | | |
| Upstream of Bridge (900 ft) | *Baseline* | | | |
| Near Bridge (100-150ft) | 1.272 | 0.167 | <0.001 | 3.569 |
| **Model 7: Passenger Cars, Faster Drivers (n = 343)** | | | | |
| **Parameters** | **β** | **Std. Err** | **p-value** | **Odds Ratio** |
| Intercept | -1.442 | 0.320 | <0.001 | |
| **CMS Test Message** | | | | |
| Travel Times | *Baseline* | | | |
| BRIDGES ICE BEFORE ROAD / REDUCE SPEEDS | 0.627 | 0.281 | 0.026 | 1.872 |
| SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS | 0.855 | 0.289 | 0.003 | 2.352 |
| **CMS Location (distance upstream from start of bridge)** | | | | |
| Upstream of Bridge (900 ft) | *Baseline* | | | |
| Near Bridge (100-150ft) | 1.111 | 0.278 | <0.001 | 3.037 |
| **Model 8: Passenger Cars, Average Drivers (n = 344)** | | | | |
| **Parameters** | **β** | **Std. Err** | **p-value** | **Odds Ratio** |
| Intercept | -2.006 | 0.361 | <0.001 | |
| **CMS Test Message** | | | | |
| Travel Times | *Baseline* | | | |
| BRIDGES ICE BEFORE ROAD / REDUCE SPEEDS | 0.326 | 0.287 | 0.256 | 1.386 |
| SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS | 0.970 | 0.299 | 0.001 | 2.638 |
| **CMS Location (distance upstream from start of bridge)** | | | | |
| Upstream of Bridge (900 ft) | *Baseline* | | | |
| Near Bridge (100-150ft) | 1.698 | 0.319 | <0.001 | 5.464 |
| **Model-9: Passenger Cars, Slower Drivers (n = 345)** | | | | |
| **Parameters** | **β** | **Std. Err** | **p-value** | **Odds Ratio** |
| Intercept | -1.322 | 0.320 | <0.001 | |
| **CMS Test Message** | | | | |
| Travel Times | *Baseline* | | | |
| BRIDGES ICE BEFORE ROAD / REDUCE SPEEDS | 0.334 | 0.277 | 0.227 | 1.397 |
| SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS | 0.328 | 0.284 | 0.249 | 1.388 |
| **CMS Location (distance upstream from start of bridge)** | | | | |
| Upstream of Bridge (900 ft) | *Baseline* | | | |
| Near Bridge (100-150ft) | 1.082 | 0.283 | <0.001 | 2.951 |
| **Model 10: All Heavy Vehicles (n = 238)** | | | | |
| **Parameters** | **β** | **Std. Err** | **p-value** | **Odds Ratio** |
| Intercept | -1.523 | 0.364 | <0.001 | |
| **CMS Test Message** | | | | |
| Travel Times | *Baseline* | | | |
| BRIDGES ICE BEFORE ROAD / REDUCE SPEEDS | 0.745 | 0.421 | 0.077 | 2.106 |
| SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS | 0.270 | 0.439 | 0.539 | 1.310 |
| **CMS Location (distance upstream from start of bridge)** | | | | |
| Upstream of Bridge (900 ft) | *Baseline* | | | |
| Near Bridge (100-150ft) | 2.837 | 0.342 | <0.001 | 17.068 |

As indicated by the odds ratios displayed in **Table 52**, compared to the travel time message, drivers of passenger cars were twice as likely to reduce their speed on the approach to the bridge when the "SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS" message was displayed and 1.5 times more likely when "BRIDGE ICES BEFORE ROAD / REDUCE SPEEDS" was displayed. The strongest effects for the weather-related warning messages were observed for faster drivers, who were 2.4 times more likely to reduce speed with the "SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS" message displayed and 1.9 times more likely with the "BRIDGE ICES BEFORE ROAD / REDUCE SPEEDS" message displayed compared to the travel time message. Again, speed reductions among drivers of heavy vehicles were not significantly impacted by message type.

### 6.2.5 Results – Effect of CMS Location on Speed at the Bridge

As mentioned previously, the site-to-site variation in CMS location with respect to the bridge afforded analysis whether receiving the message earlier (i.e., when the CMS was 900 ft of the bridge) or later (i.e., when CMS was within 150 ft of the bridge) impacted driver speeds at the bridge. From **Table 51** it can be observed that greater speed reductions were observed when the CMS was located closer to the bridge (sites 1 and 2). This finding was consistent across all vehicle types (passenger cars and heavy vehicles) and driver behavior categories (faster, average, and slower). The strongest speed reduction effects were observed for heavy vehicles and faster drivers. Similar results were obtained from the logistic regression analysis for speed reduction likelihood presented in **Table 52**, which shows that drivers across all subcategories were more likely to reduce speeds when the CMS was located near the bridge.

# 7. PRIORITIZATION OF HORIZONTAL CURVES FOR FUTURE SPEED WARNING TREATMENT INSTALLATION

This section provides details on a network screening crash analysis conducted to identify and prioritize potential horizontal curve sites on freeways (mainlines) and two-lane rural trunklines in Michigan for future speed warning treatment installation. The screening process for freeway exit ramps was recently performed in MDOT research project OR17-204 (Gates et al, 2022) and, as a result, is not included in this report. However, the process implemented here generally follows that which was utilized for the exit ramp analysis. The steps to the network screening prioritization analysis are described in the sections that follow.

## 7.1 Identification of Freeway and Non-Freeway Horizontal Curves

The research team developed a statewide curve shapefile containing PR numbers, beginning mile points (BMP), end mile points (EMP), curve radii, and geographic coordinates (latitude and longitude) of all rural horizontal trunkline curves across Michigan. This dataset served as the base file for the analysis. Using the roadway type information, the curves were categorized as either freeways or two-lane rural trunkline highways. The final curve dataset included 1,180 freeway curves and 3,080 two-lane trunkline curves. Each curve was manually reviewed using Google Maps to collect information on the posted speed limit and curve advisory speed. The curves were filtered based on the following eligibility criteria:

1. Posted speed limit of at least 65 mph for freeways and 50 mph for two-lane highways and
2. Presence of a curve advisory speed plaque (W13-1p) with an advisory speed at least 5 mph below the posted speed limit

## 7.2 Target Crash Data Collection

The statewide annual crash databases for the period of 2019 to 2023 were obtained from the Michigan State Police (MSP). Lane departure crashes were identified based on the corresponding field in the MSP crash report form. For the purpose of this study, only single-vehicle lane departure crashes that did not involve animals were considered as target crashes. The crash dataset included the PR number and mile point for each crash, which were used to associate crashes with individual curves and to obtain the total crash and lane departure crash frequencies. To improve spatial accuracy, a 200 ft buffer was added to both the BMP and EMP of each curve, extending the effective curve length by 400 ft.

## 7.3 Traffic Volume Data Collection

Annual traffic volume data for each curve was obtained from the MDOT's Traffic Data Management System (TMDS). The Average Annual Daily Traffic (AADT) dataset included PR numbers, beginning mile points (BMP), and end mile points (EMP) for each road segment, which were used to assign AADT values to the corresponding curves.

## 7.4 Ranking of Horizontal Curve Sites by Crash Frequency and Crash Rate

The curves were then ranked based on two safety performance metrics over the five-year study period:

1. Single-vehicle lane departure crash frequency and
2. Single-vehicle lane departure crash rate, per million vehicle miles traveled (MVMT)

The crash rate for each curve was calculated using **Equation 3:**

$$R_{Curves} = \frac{C\times 10^{6}}{AADT\times T\times L\times 365} \qquad \textbf{(Eq. 3)}$$

Where,

$R_{Curves}$= Curve lane departure crash rate (per million vehicle miles traveled)
C = Lane departure crashes occurring during the 5-year analysis period,
AADT = Average annual daily traffic volume (vehicle/day)
T = Study period (5 years)
L = Curve length (miles)

**Figure 81** and **Figure 82** present a map of the top 50 two-lane rural highway curves with the highest lane departure crash frequency and crash rate, respectively. **Figure 83** and **Figure 84** present a map of the top 25 freeway curves with the highest lane departure crash frequency and crash rate, respectively. Additionally, tables containing the lists of freeway and non-freeway horizontal curve sites ranked by five-year lane departure crash frequency and five-year lane departure crash rate are provided in **Appendix C**, **Appendix D**, **Appendix E**, and **Appendix F**. These tables contain the rank, PR number, BMP, EMP, geographical coordinates, speed limit, advisory speed, total crashes, lane departure crashes, and lane departure crash rates for each curve. It is important to note that while this analysis provides a quantitative basis for prioritization, an engineering study is necessary to determine the actual suitability of each site for speed warning treatment installation.

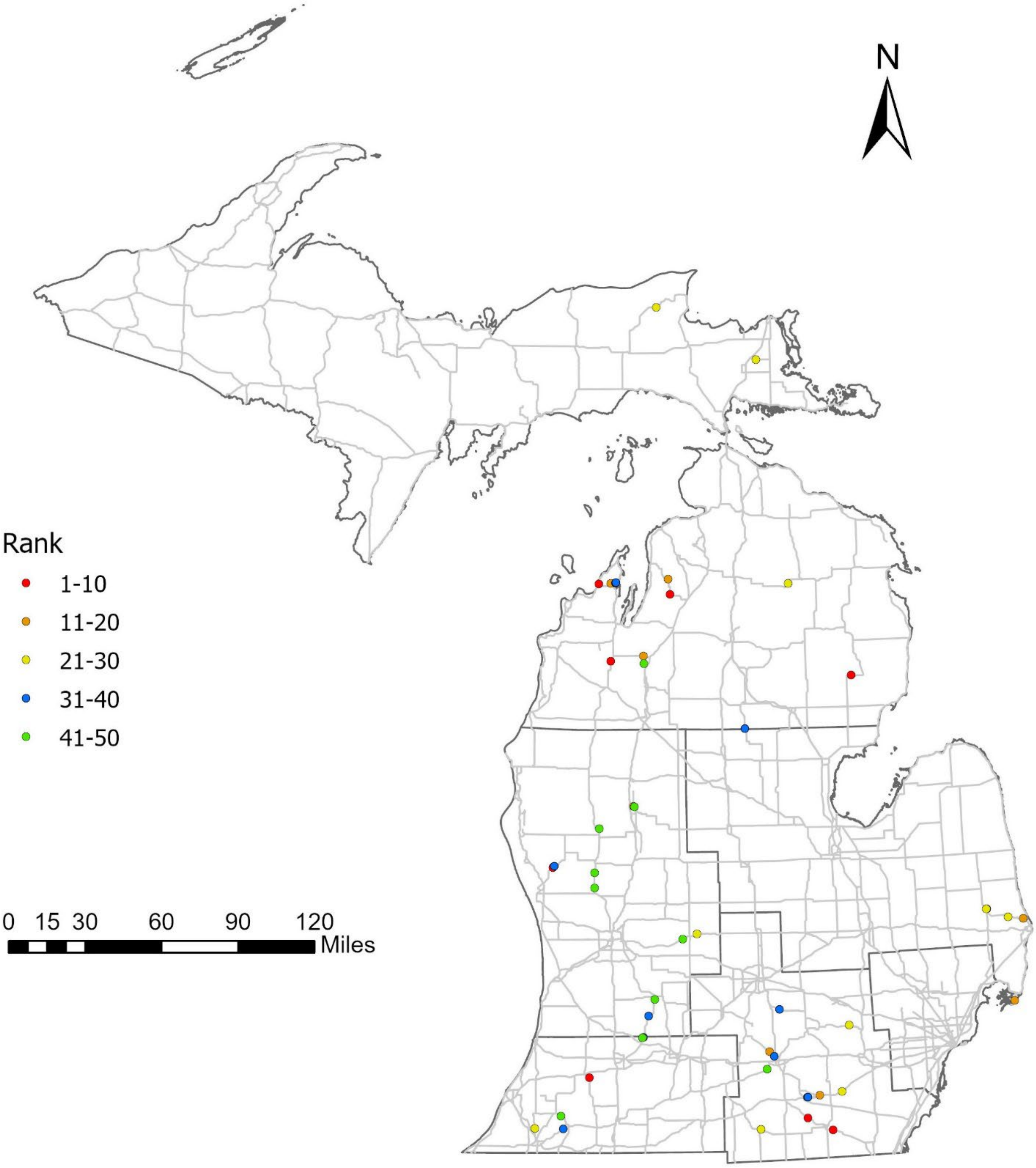


Figure 81. Top 50 Horizontal Curves with Highest Lane Departure Crash Frequency on Two-Lane Rural Trunkline Highways in Michigan

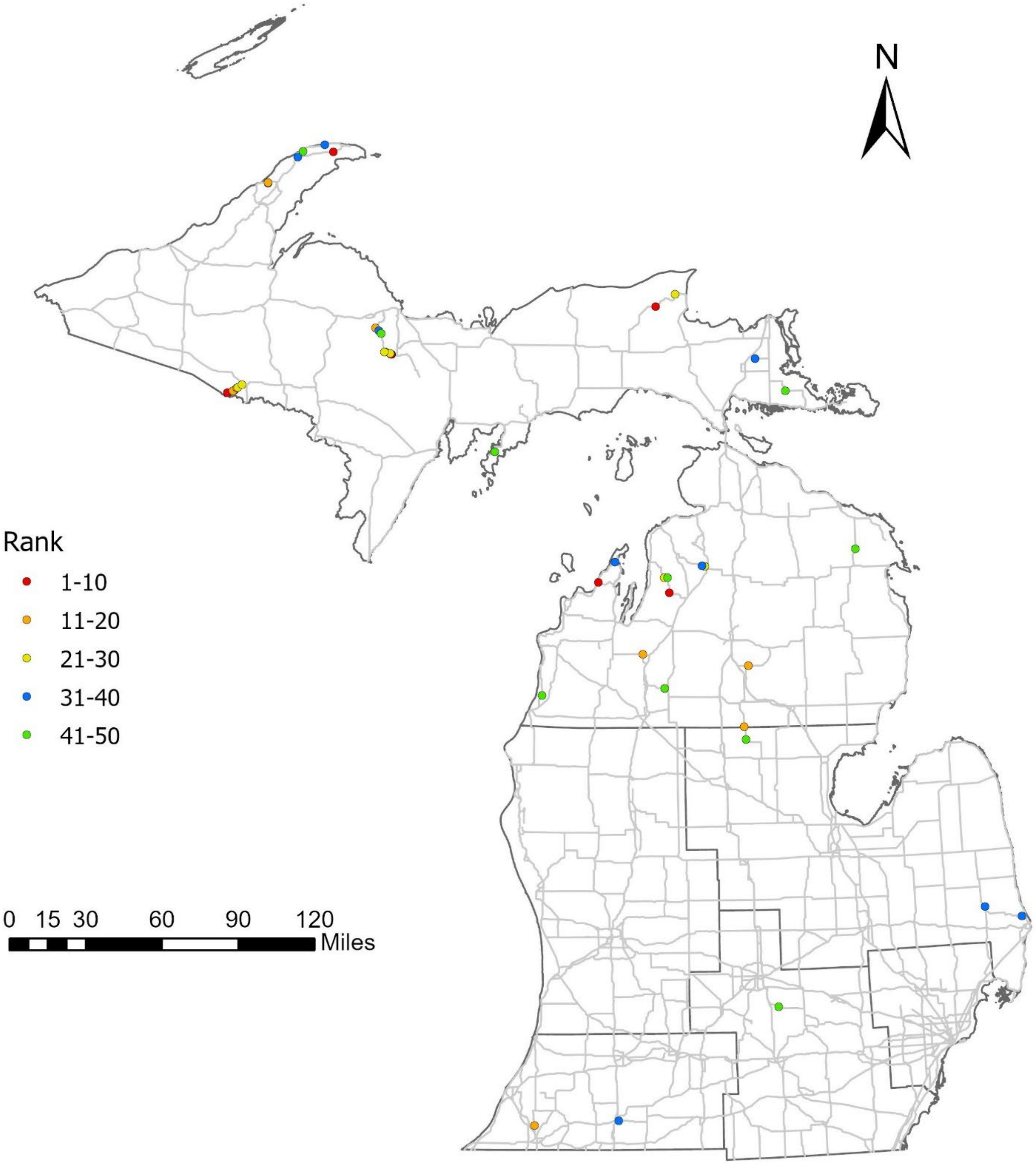


Figure 82. Top 50 Horizontal Curves with Highest Lane Departure Crash Rate on Two-Lane Rural Trunkline Highways in Michigan

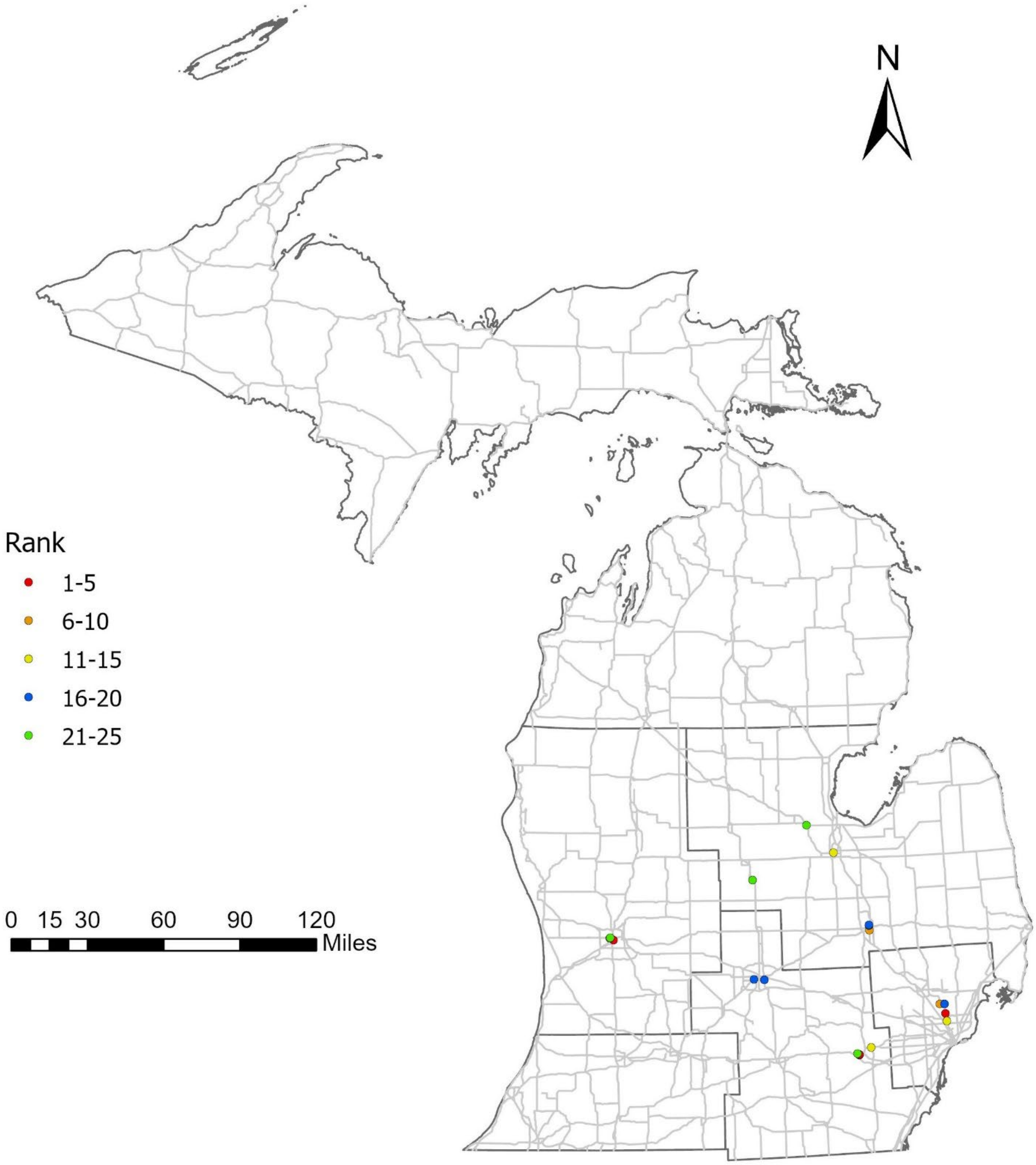


**Figure 83. Top 25 Horizontal Curves with Highest Lane Departure Crash Frequency on Freeways in Michigan**

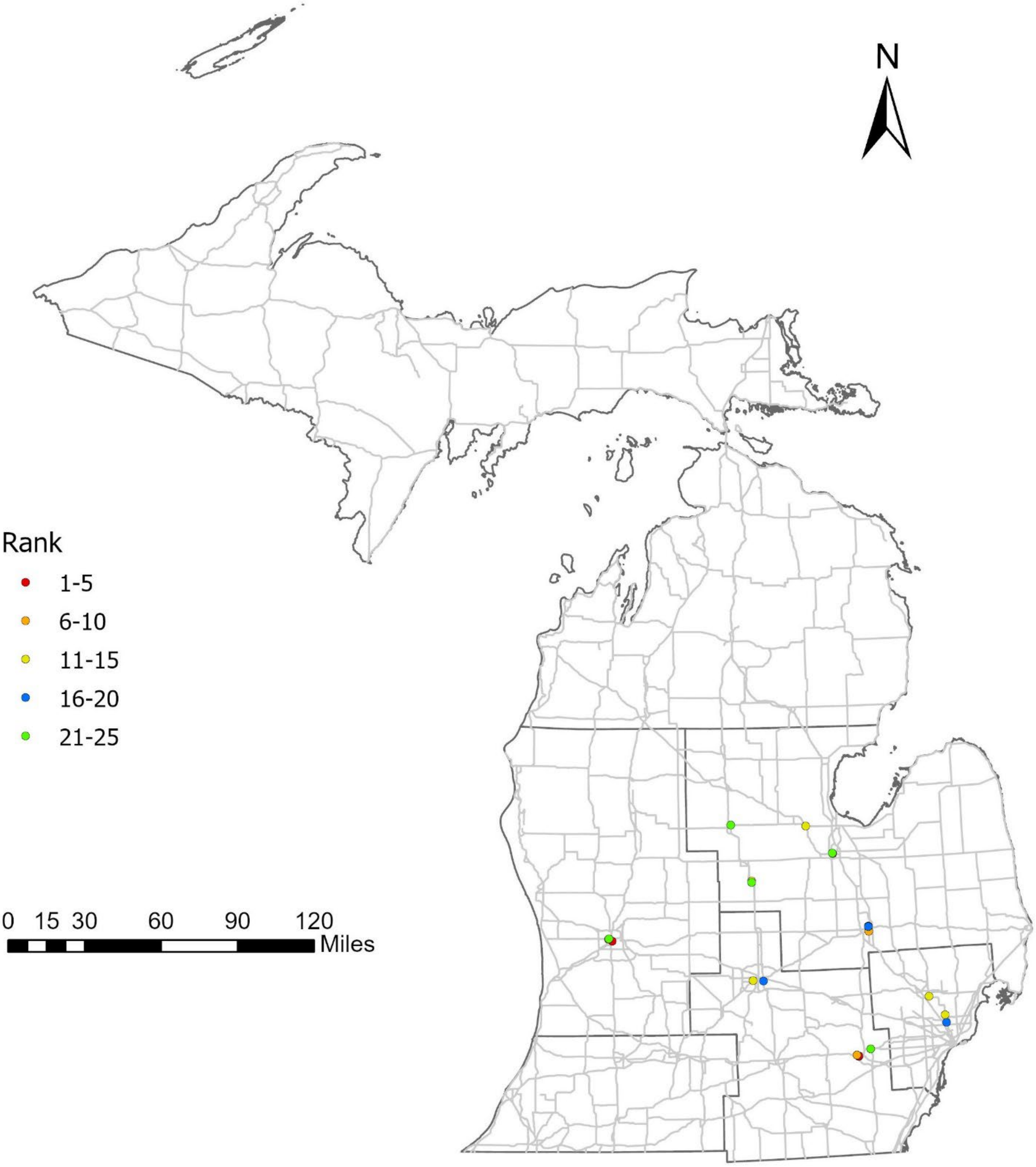


Figure 84. Top 25 Horizontal Curves with Highest Lane Departure Crash Rate on Freeways in Michigan

# 8. CONCLUSIONS AND RECOMMENDATIONS

Research was undertaken to determine the effectiveness of various speed warning technologies across a variety of critical speed-change contexts in order to provide guidance to support future installation and operation of such treatments in Michigan. The speed warning technologies evaluated in this research included dynamic speed feedback signs, a flashing LED chevron system for horizontal curves, a weather-activated slippery curve warning system, and targeted winter weather messages on changeable message signs. The speed reduction effectiveness of the selected speed warning technologies was assessed through a series of field evaluations performed at critical highway speed-change contexts, which included:

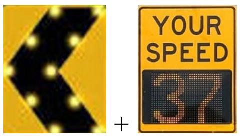
- Horizontal curve
    - Freeway ramp (DSFS)
    - Freeway mainline (DSFS)
    - Rural highway (flashing LED chevrons with and without DSFS)
- Speed limit transition
    - Freeway to non-freeway (DSFS)
    - Roundabout approaching a community (DSFS)
    - Rural highway entering a community (DSFS)
- Winter weather warning
    - Rural highway curve (slippery curve warning system)
    - Freeway bridge overpass (CMS weather warning messages)

The messaging strategies, warning alerts, and installation positions for each evaluation were selected based on the highway context and warning technology being evaluated. Speeds of free-flowing vehicles were measured at multiple locations while traversing the speed-change area during each of the specified test conditions. The primary measure of effectiveness across all contexts was the speed reduction for each test sign condition compared to the existing signing.

## 8.1 Summary of Findings

Overall, it was concluded that enhanced speed warning signing technologies can contribute to meaningful speed reductions in critical areas. However, the benefits depend heavily on site-specific factors, including roadway context, along with the type, installation, and operation of the signing treatment. A summary of the primary findings from each of the signing treatments and roadway contexts included in the field evaluations is provided in **Table 53**.

**Table 53. Primary Findings from Field Evaluations of Enhanced Warning Sign Treatments**

| Sign Treatment | Roadway Context | No. of Sites | Primary Findings Related to the Sign Treatment |
|---|---|---|---|
|  <br>Dynamic Speed Feedback Sign | Horizontal Curve on Freeway Exit Ramp | 5 | ● Speed reductions at the ramp curve were observed at 3 of 5 sites after DSFS installed. The magnitude of the speed reductions were:<br>o 1.5 to 2.0 mph during daytime<br>o 0.6 to 1.8 mph during nighttime<br>● DSFS was considerably more effective at interchanges where the freeway passed over the crossroad due to greater sight distance. |
| | Horizontal Curve on Freeway Mainline | 2 | ● After installation of the DSFS:<br>o Speed reductions at the curve were up to 1.2 mph greater.<br>o Drivers were 65% to 71% less likely to exceed curve advisory speed by > 10 mph. |
| | Freeway to Non-Freeway Speed Limit Transition | 1 | ● Speed reductions were up to 3.4 mph greater after installation of the DSFS.<br>● Greater speed reductions were observed:<br>o with the DSFS 350 ft upstream of the speed limit sign vs. next to the sign and<br>o for drivers exceeding 75 mph |
| | Roundabout Approaching Community | 4 | ● Greater speed reductions were observed at all four roundabout approaches after installation of the DSFS, ranging from 1.8 to 3.4 mph |
| | Rural Highway Entering Community | 1 | ● After installation of the DSFS:<br>o Speed reductions entering the community were up to 2.9 mph greater.<br>o Drivers were 67% to 76% less likely to exceed the reduced speed limit. |
| <br>Flashing LED Chevrons | Horizontal Curve on Rural Highway | 3 | ● After installation of the LED chevrons:<br>o Speed reductions at the curve were 1.4 to 2.3 mph greater across all sites<br>o Drivers were 50% to 60% less likely to exceed curve advisory speed by > 10 mph<br>● Simultaneous flash mode was generally more effective than sequential mode. |
|  <br>Flashing LED Chevrons + DSFS | Horizontal Curve on Rural Highway | 1 | ● Speed reductions were 0.8 to 1.2 mph greater when the DSFS was paired with the flashing LED chevrons vs. the LED chevrons alone.<br>● DSFS had the greatest effect when adjacent to the curve warning sign. |
| <br>Slippery Curve Warning System | Horizontal Curve on Rural Highway During Winter Weather | 2 | ● During winter weather conditions, the flashing LED borders:<br>o Reduced curve speeds by 0.9 to 1.5 mph<br>o Reduced occurrence of drivers exceeding the curve advisory speed by 62% to 72%<br>o Had strongest effect on the fastest drivers |
|  <br>CMS Weather Warning Message | Freeway Bridge During Winter Weather | 3 | ● During winter weather conditions, the CMS weather warning messages:<br>o Reduced bridge speeds by 0.5 to 0.8 mph<br>o Increased the number of drivers reducing their speed by 54% to 103%<br>o Had strongest effect on the fastest drivers<br>● "SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS" had the greatest effect |

To collectively summarize the results displayed in **Table 53**, generally speaking, the dynamic speed feedback signs and flashing LED warning signs (including chevrons) were found to have a statistically significant speed reduction effect on drivers traversing the critical speed change areas investigated in this study. The magnitude of the speed reductions varied based on the site context, although speed reductions of up to 3.5 mph were observed at both horizontal curves and speed limit transition areas after installation of the selected sign treatment. Similarly, drivers were 50 to 75% less likely to exceed the curve advisory speed or posted speed limit (or some increment above those speeds) after treatment installation. Typically, the treatments were found to have the strongest speed reduction effects on drivers approaching the speed-change area at speeds that were higher-than-average, which is typically the driver behavior group most targeted by the installation of such treatments.

## 8.2 Recommendations for Implementation and Operation of Speed Warning Technologies

Based on the study findings, the continued use of the tested speed warning technologies is recommended for the highway contexts evaluated in this study. A series of specific recommendations related to sign characteristics, operational performance, and installation details for each road context are provided in the following subsections. These recommendations were developed on the basis of providing optimal performance toward reducing high speeds and associated crashes in contexts where speed adjustments are necessary. Further, the recommendations comply with the requirements of the 11th Edition MUTCD, which provides considerably greater restrictions towards the utilization of DSFS compared to prior editions. Finally, these recommendations may be utilized by MDOT towards the development of implementable guidelines, standards, and/or provisions for the use of speed warning technologies at freeway and non-freeway horizontal curve applications, speed limit transition areas, and CMS messaging during winter weather conditions.

### 8.2.1 Speed Warning Technologies at Horizontal Curves

This section provides details on the recommended application of speed warning technologies at horizontal curves on freeway ramps, freeway mainlines, and rural non-freeways. In addition to the field speed evaluations, this research also developed a series of rankings for the freeway and non-freeway curve locations with the highest lane departure crash frequency or rate. The sites appearing in these rankings, which are provided in **Appendices C, D, E,** and **F**, serve as potential candidate locations for future implementation of speed warning technologies on MDOT freeways and two-lane highways.

#### 8.2.1.1 Freeway Ramps

The recommended guidance for speed warning technologies at freeway ramps remains largely unchanged from that provided in the final report for MDOT research project OR17-204, which specifically focused on the use of DSFS at freeway exit ramps (Gates et al. 2022). Deviations from the prior guidance are noted below in italics wherever applicable.

- **Site Selection:** Potential freeway exit ramp sites may be appropriate for the installation of a DSFS based on the following conditions:
    - Evidence of frequent vehicle lane-departures, including run-off and rollover (consider crash reports and/or on-site evidence)
    - Posted ramp advisory speed (or ramp design speed) does not exceed 35 mph
    - Average vehicular curve entry speed exceeds the ramp advisory speed (or design speed) by more than 10 mph
    - Ramp AADT of 1,000 or higher
    - Site can accommodate DSFS sign installation considering:
        - Roadside adjacent to the ramp can accommodate installation of the DSFS
        - Clear visibility of the roadside within 20 feet of the traveled way for at least 600 ft in advance of the ramp curve
        - *If both conditions cannot be met, consider the use of flashing LED chevrons as an alternative to a DSFS. Placement of the DSFS in the ramp gore area is no longer recommended due to potential lane departure collision.*
    - Note that a prioritized list of potential exit ramps for future DSFS installation is provided in Chapter 9 of the final report for project OR17-204 (Gates et al. 2022).
- **DSFS Installation Position Relative to the Curve:** Install the DSFS as close to the point of curvature as practical, but not more than 250 ft upstream of the curve.
- **Lateral DSFS Installation Position:** Install the DSFS on the right roadside. *If a right-side mount for the DSFS cannot be accommodated, consider the use of flashing LED chevrons as an alternative. Placement of the DSFS in the ramp gore area is no longer recommended.*
- **DSFS Characteristics:** The DSFS shall include a full matrix amber LED feedback display capable of displaying characters that are a minimum of 15 inches in height (*18-inch displays are preferred for freeway applications*). The "YOUR SPEED" legend shall be black on a yellow retroreflective background. *If no automatic dimming sensor is included, the LED brightness should be set to achieve optimal visibility during daylight conditions*.

- **DSFS Messaging Strategy:** *For speeds at or below the curve advisory speed, the display should remain blank. For speeds exceeding the advisory speed, display the speed number. Following the requirements of the 11th Edition MUTCD (Section 2C.13), no other messages, symbols, or animated features, including flashing or strobing effects, may be utilized.*
    - No maximum cap for the speed feedback message is recommended.
    - A minimum speed threshold of 15 mph is recommended for activation of the feedback panel to prevent activation from rain and small objects.
- **DSFS Activation Range:** Ensure that the feedback panel activates for approaching vehicles a minimum of 250 ft in advance of the point of curvature.
- **Additional Warning Sign Enhancements:** *For locations with exceptionally high rates of lane departures, consider the combined use of flashing LED chevrons and DSFS. For locations that experience a high rate of lane departure crashes during wet, icy, or snowy conditions, consider the installation of an RWIS-activated slippery curve warning system.*

#### 8.2.1.2 Freeway Mainlines

The recommended guidance for the implementation of speed warning technologies at horizontal curves on mainline freeways is provided as follows.

- **Site Selection:** Potential freeway mainline curve locations may be appropriate for the installation of a DSFS based on the following conditions:
    - Evidence of frequent vehicle lane-departure events or crashes. Note: the top 25 curves ranked by lane departure crashes are provided in **Appendices E** and **F.**
    - Curve design speed or advisory speed is at least 5 mph below the speed limit.
    - Average vehicular curve entry speed exceeds the curve advisory speed (or design speed) by more than 10 mph
    - Site can accommodate DSFS installation considering:
        - Roadside adjacent to the curve can accommodate installation of DSFS
        - Clear visibility of the roadside within 20 feet of the traveled way for at least 600 ft in advance of the curve
        - If both conditions cannot be met, consider the use of flashing LED chevrons as an alternative to a DSFS.
- **DSFS Installation Position Relative to the Curve:** The DSFS shall be installed on an independent assembly between the point of curvature and the curve warning sign, but no more than 500 ft upstream of the point of curvature.

- **DSFS Characteristics:** The DSFS shall include a full matrix amber LED feedback display capable of displaying characters that are a minimum of 15 inches in height (18-inch displays are preferred for freeway applications). The “YOUR SPEED” legend shall be black on a yellow retroreflective background. If no automatic dimming sensor is included, the LED brightness should be set to achieve optimal visibility during daylight conditions.
- **DSFS Messaging Strategy:** For speeds at or below the curve advisory speed, the display should remain blank. For speeds exceeding the advisory speed, display the speed number. Following requirements of the 11th Edition MUTCD (Section 2C.13), no other messages, symbols, or animated features, including flashing or strobing effects, may be utilized.
    - No maximum cap for the speed feedback message is recommended.
    - A minimum speed threshold of 15 mph is recommended for activation of the feedback panel to prevent activation from rain and small objects.
- **DSFS Activation Range:** Ensure that the feedback panel activates for approaching vehicles a minimum of 250 ft in advance of the point of curvature.
- **Additional Warning Sign Enhancements:** For locations with exceptionally high rates of lane departures, consider the combined use of flashing LED chevrons and DSFS. For locations that experience a high rate of lane departure crashes during wet, icy, or snowy conditions, consider the installation of an RWIS-activated slippery curve warning system.

#### 8.2.1.3 Rural Non-Freeway Trunkline Highways

The recommended guidance for the implementation of speed warning technologies at horizontal curves on non-freeway trunkline highways is provided as follows.

- **Site Selection:** Potential curve locations on non-freeway trunklines may be appropriate for the installation of a DSFS, flashing LED chevrons, or slippery curve warning system based on the following conditions:
    - Evidence of frequent vehicle lane-departure events or crashes. Note: the top 50 curves on two-lane trunklines ranked by lane departure crashes are provided in **Appendices C** and **D**.
    - Curve design speed or advisory speed is at least 5 mph below the speed limit.
    - Average vehicular curve entry speed exceeds the curve advisory speed (or design speed) by more than 10 mph
    - Site can accommodate the installation of DSFS or flashing LED chevrons considering:

        - Roadside adjacent to the curve (LED chevrons) or approach to the curve (DSFS) can accommodate installation of the signs
        - For DSFS, clear visibility of the roadside within 20 feet of the traveled way for at least 600 ft in advance of the curve. Any DSFS installation shall be installed between the point of curvature and the curve warning sign, but no more than 500 ft upstream of the point of curvature.
        - If a site can accommodate both DSFS and flashing LED chevrons, the deciding factor can be cost, which is provided in **Appendix G**.
- **Operation:**
    - For flashing LED chevrons:
        - LED chevrons should flash only when the curve advisory speed is exceeded.
        - All LED chevrons should flash simultaneously at a frequency of 1 Hz.
        - LED chevrons must be aimed to provide optimal LED visibility for drivers approaching the curve.
    - For DSFS:
        - The DSFS must include a full matrix amber LED panel capable of displaying characters that are a minimum of 15 inches in height. The panel must be encased within a yellow retroreflective background with a black "YOUR SPEED" legend.
        - For speeds at or below the curve advisory speed, the display should remain blank.
        - For speeds exceeding the advisory speed, display the speed number. Following the requirements of the 11th Edition MUTCD (Section 2C.13), no other messages, symbols, or animated features, including flashing or strobing effects, may be utilized.
    - For either treatment:
        - If no auto-dimming sensor is included, the LED brightness should be set to achieve optimal visibility during daylight conditions.
        - A minimum speed threshold of 15 mph is recommended for activation to prevent activation from rain and small objects.
        - No maximum speed cap for activation is recommended.
        - Ensure that activation occurs for approaching vehicles a minimum of 250 ft in advance of the point of curvature.

- **Additional Considerations:** For locations with exceptionally high rates of lane departures, consider the combined use of flashing LED chevrons and DSFS. For locations that experience a high rate of lane departure crashes during wet, icy, or snowy conditions, consider the installation of an RWIS-activated slippery curve warning system.

### 8.2.2 Speed Warning Technologies at Speed Limit Transition Areas

This section provides details on the recommended application of speed warning technologies at speed limit transition areas. Note that the 11th Edition of the MUTCD disallows the use of DSFS as a speed reduction countermeasure at roundabouts. Thus, although the findings of this study suggest that DSFS provide speed reductions on the approach to roundabouts, no guidance for the use of DSFS at roundabouts will be provided herein.

The recommended guidance for implementation of a DSFS at freeway to non-freeway speed limit reduction areas, including freeways to non-freeways and rural highways entering a community, is provided as follows. Note that a specific ranking of candidate sites for speed warning treatments in these contexts was not performed.

- **Site Selection:** A DSFS may be used as a speed reduction strategy at speed limit transitions when the speed limit difference is at least 10 mph.
- **DSFS Installation Location:** Following the requirements of Section 2C.13 of the 11th Edition MUTCD (FHWA 2023) for posted speed limit applications, the DSFS shall consist of a W13-20aP plaque that is mounted beneath the speed limit sign. An example of a W13-20aP DSFS plaque mounted for speed limit application is displayed in **Figure 85**.

**Figure 85. Example DSFS Installation for Posted Speed Limit Application**

- **DSFS Sign Design:** Following the requirements of Section 2C.13 of the 11th Edition MUTCD (FHWA 2023) for posted speed limit applications, the W13-20aP must be utilized.

The feedback display characters should be approximately the same height, width, and stroke as those on the speed limit sign it is mounted below. The entire W13-20aP plaque should be approximately the same width as the speed limit sign it is mounted below.

- **DSFS Activation:** Ensure that the feedback panel activates for approaching vehicles a minimum of 250 ft in advance of the sign.
- **DSFS Messaging Strategy:** For speeds at or below the speed limit posted on the sign above the DSFS, the display should remain blank. For speeds exceeding the speed limit, display the speed number. Following the requirements of the 11th Edition MUTCD (Section 2C.13), no other messages, symbols, or animated features, including flashing or strobing effects, may be utilized.
    - No maximum cap for the speed feedback message is recommended.
    - A minimum speed threshold of 15 mph is recommended for activation of the feedback panel to prevent activation from rain and small objects.
    - If no auto-dimming sensor is included, the LED brightness should be set to achieve optimal visibility during daylight conditions.

### 8.2.3 Speed Warning Technologies for Winter Road Conditions

This section provides details on the recommended application of speed warning technologies for winter road conditions at freeway bridges or horizontal curves. Note that a specific ranking of candidate sites for speed warning treatments in these contexts was not performed.

#### 8.2.3.1 Rural Horizontal Curves

In areas that are prone to frequent severe winter weather conditions, it is recommended that MDOT continues to expand the use of the slippery curve warning system, which includes a MUTCD W8-5 (slippery when wet) sign and a W1-2 (curve warning) sign, each with a flashing LED border that is activated when warranted based on road surface conditions as determined by a pavement sensor at the site. The installation location for the signs with respect to the start of the curve should be determined according to the placement guidelines specified by MDOT. The LEDs should include an auto-dimming sensor to ensure that optimal visibility is achieved during both day and night. If such a sensor is not available, then the LED brightness should be set to achieve optimal visibility during daylight conditions. Further, in areas that regularly experience heavy snowfall, it is recommended to use durable LEDs that are designed to withstand snow from passing plows.

#### 8.2.3.2 Freeway Bridge Overpasses

Based on the findings from this study, the “SLIPPERY ROAD CONDITIONS / REDUCE SPEEDS” message is recommended to be displayed on CMS located on the approach to bridge overpasses during adverse winter driving conditions. This CMS message is most commonly utilized by MDOT for alerting motorists of winter travel advisories and should continue to be used as such. The message should be displayed on a single frame, as displayed in **Figure 86**, and splitting this message between two frames is not recommended.

**Figure 86. Recommended CMS Message for Winter Weather Warning at Bridge Overpasses**

Bridge overpasses that may be most susceptible to unexpected icing and may subsequently benefit the most from winter weather warning messages and/or other alerts include bridges on superelevated curves, locations with snow removal or deicing challenges, long bridge decks, and bridges with a pattern of winter weather-related crashes. To that end, consideration should be given to such locations when determining locations for new CMS and other bridge deck weather warning systems. Note that a list of candidate bridges for winter weather warning treatments was provided in the final report for MDOT project OR21-016 entitled *Evaluation of Bridge Deck Winter Weather Warning Systems* (Gates et al. 2023). Wherever possible, it is highly recommended to connect the CMS to sensors capable of detecting icy bridge surface conditions (e.g., RWIS) to automatically enable the warning messages.

### 8.3 Limitations and Direction for Future Research

While this research provided substantial evidence of the effectiveness of various speed warning signing technologies as a speed reduction countermeasure across a variety of contexts, future evaluation should assess the effectiveness of implemented treatments towards reducing the frequency and/or severity of the crashes that the signs are intended to target. Furthermore, additional long-term evaluations should be performed to further confirm whether the speed reduction effects of the treatments remain consistent or diminish with time.

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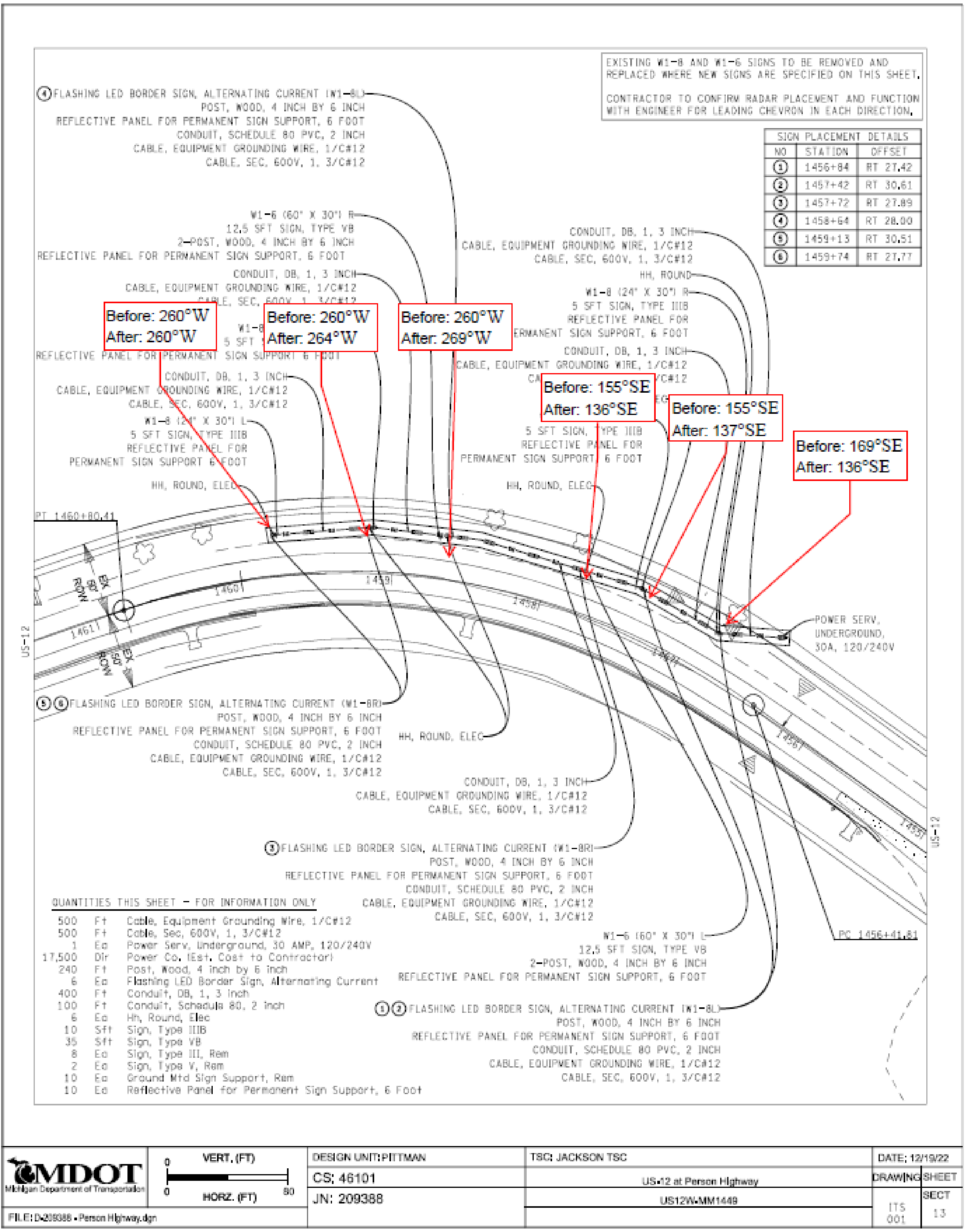
# Appendix A - Placement and Angles of Chevron Signs at US-12, Person Highway



EXISTING W1-8 AND W1-6 SIGNS TO BE REMOVED AND REPLACED WHERE NEW SIGNS ARE SPECIFIED ON THIS SHEET.

CONTRACTOR TO CONFIRM RADAR PLACEMENT AND FUNCTION WITH ENGINEER FOR LEADING CHEVRON IN EACH DIRECTION.

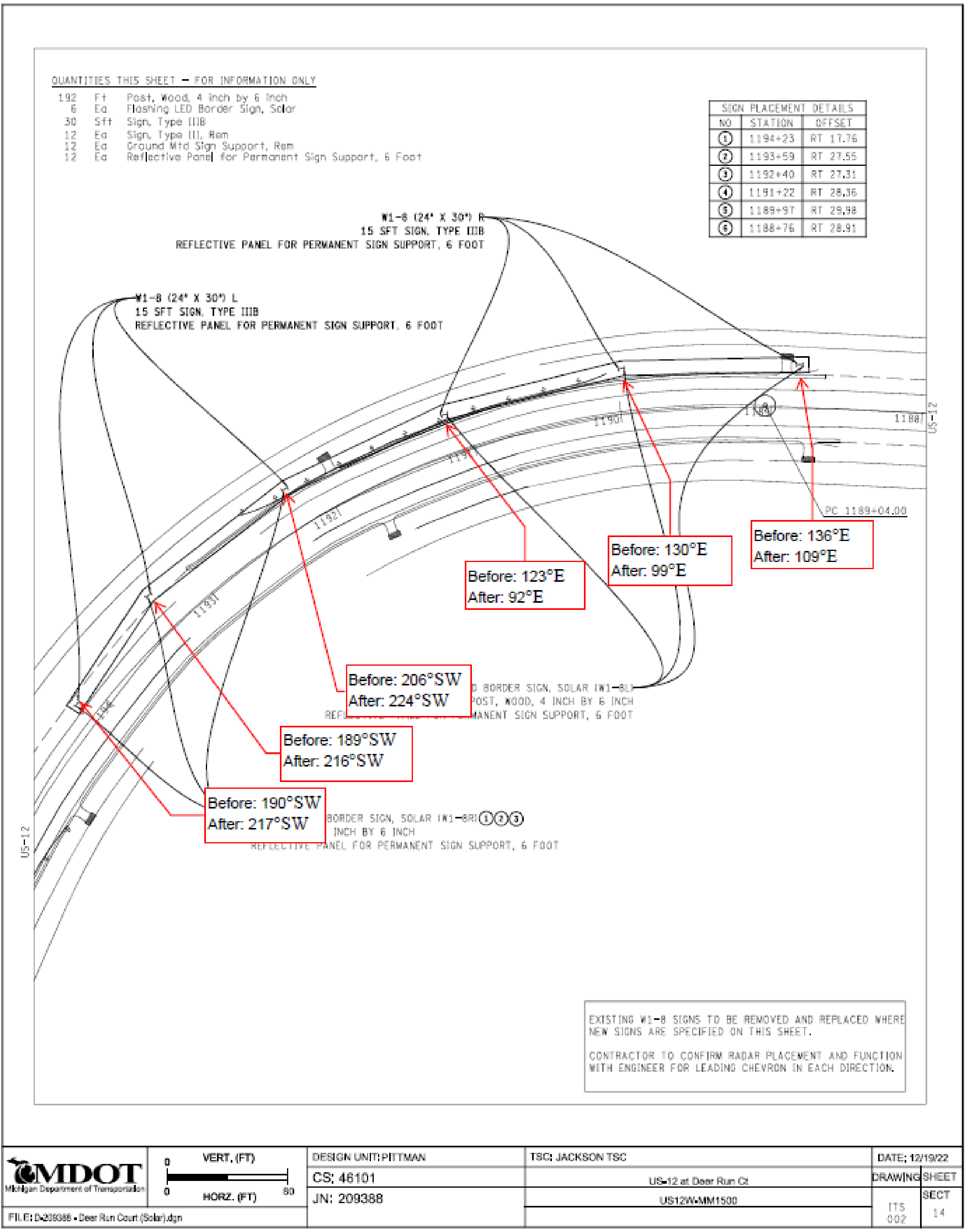
| SIGN PLACEMENT DETAILS | | |
|---|---|---|
| NO | STATION | OFFSET |
| ① | 1456+84 | RT 27.42 |
| ② | 1457+42 | RT 30.61 |
| ③ | 1457+72 | RT 27.89 |
| ④ | 1458+64 | RT 28.00 |
| ⑤ | 1459+13 | RT 30.51 |
| ⑥ | 1459+74 | RT 27.77 |

QUANTITIES THIS SHEET - FOR INFORMATION ONLY

| | | |
|---|---|---|
| 500 | Ft | Cable, Equipment Grounding Wire, 1/C#12 |
| 500 | Ft | Cable, Sec, 600V, 1, 3/C#12 |
| 1 | Ea | Power Serv, Underground, 30 AMP, 120/240V |
| 17,500 | Dlr | Power Co. (Est. Cost to Contractor) |
| 240 | Ft | Post, Wood, 4 inch by 6 inch |
| 6 | Ea | Flashing LED Border Sign, Alternating Current |
| 400 | Ft | Conduit, DB, 1, 3 inch |
| 100 | Ft | Conduit, Schedule 80, 2 inch |
| 6 | Ea | Hh, Round, Elec |
| 10 | Sft | Sign, Type IIIB |
| 35 | Sft | Sign, Type VB |
| 8 | Ea | Sign, Type III, Rem |
| 2 | Ea | Sign, Type V, Rem |
| 10 | Ea | Ground Mtd Sign Support, Rem |
| 10 | Ea | Reflective Panel for Permanent Sign Support, 6 Foot |

MDOT
Michigan Department of Transportation
FILE: D-209388 - Person Highway.dgn
DESIGN UNIT: PITTMAN
CS: 46101
JN: 209388
TSC: JACKSON TSC
US-12 at Person Highway
US12W-MM1449
DATE: 12/19/22
DRAWING ITS 001
SHEET SECT 13

# Appendix B - Placement and Angles of Chevron Signs at US-12, Deer Run Court


QUANTITIES THIS SHEET – FOR INFORMATION ONLY

| | | |
|---|---|---|
| 192 | Ft | Post, Wood, 4 Inch by 6 Inch |
| 6 | Ea | Flashing LED Border Sign, Solar |
| 30 | Sft | Sign, Type IIIB |
| 12 | Ea | Sign, Type III, Rem |
| 12 | Ea | Ground Mtd Sign Support, Rem |
| 12 | Ea | Reflective Panel for Permanent Sign Support, 6 Foot |

SIGN PLACEMENT DETAILS

| NO | STATION | OFFSET |
|---|---|---|
| ① | 1194+23 | RT 17.76 |
| ② | 1193+59 | RT 27.55 |
| ③ | 1192+40 | RT 27.31 |
| ④ | 1191+22 | RT 28.36 |
| ⑤ | 1189+97 | RT 29.98 |
| ⑥ | 1188+76 | RT 28.91 |

Before: 136°E
After: 109°E

Before: 130°E
After: 99°E

Before: 123°E
After: 92°E

Before: 206°SW
After: 224°SW

Before: 189°SW
After: 216°SW

Before: 190°SW
After: 217°SW

EXISTING W1-8 SIGNS TO BE REMOVED AND REPLACED WHERE NEW SIGNS ARE SPECIFIED ON THIS SHEET.

CONTRACTOR TO CONFIRM RADAR PLACEMENT AND FUNCTION WITH ENGINEER FOR LEADING CHEVRON IN EACH DIRECTION.

# Appendix C - Top 50 Curves with Highest Lane Departure Crash Frequency on Two-Lane Rural Trunkline Highways in Michigan

| Rank | PR Number | BMP | EMP | Speed Limit | Advisory Speed | Route Name | Coordinates | AADT | Total Crashes | Total Lane Departure Crashes | Lane Departure Crash Rate |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 993501 | 0 | 0.10 | 55 | 40 | M-113 | 44.583833, -85.414361 | 4697 | 21 | 12 | 9.589 |
| 2 | 992606 | 2.74 | 3.09 | 55 | 45 | M-37 | 44.554333, -85.676028 | 7718 | 24 | 11 | 2.217 |
| 3 | 1147410 | 26.71 | 26.94 | 55 | 35 | M-22 | 44.993472, -85.769250 | 2467 | 15 | 11 | 10.373 |
| 4 | 946402 | 10.65 | 11.02 | 55 | 45 | US-223 | 41.943389, -84.189500 | 9066 | 44 | 10 | 1.622 |
| 5 | 946403 | 9.09 | 9.43 | 55 | 35 | US-12 | 42.061472, -84.187639 | 4931 | 23 | 10 | 3.23 |
| 6 | 3350838 | 21.34 | 21.97 | 65 | 60 | M-65 | 44.455972, -83.768944 | 2500 | 14 | 9 | 3.171 |
| 7 | 946402 | 22.86 | 23.21 | 55 | 40 | US-223 | 41.872861, -83.999750 | 9208 | 14 | 9 | 1.55 |
| 8 | 860003 | 10.64 | 11.04 | 55 | 50 | M-120 | 43.383667, -86.134028 | 6337 | 14 | 8 | 1.728 |
| 9 | 3050060 | 8.16 | 8.27 | 55 | 35 | M-88 | 44.932389, -85.198583 | 3667 | 12 | 8 | 10.487 |
| 10 | 579901 | 8.58 | 8.86 | 55 | 50 | M-40 | 42.187694, -85.853083 | 8257 | 13 | 8 | 1.878 |
| 11 | 3460109 | 0.52 | 0.82 | 55 | 40 | US-12 | 42.071472, -84.094528 | 7113 | 9 | 8 | 2.054 |
| 12 | 524603 | 19.17 | 19.52 | 55 | 45 | US-131 Business | 43.729028, -85.502333 | 9301 | 27 | 7 | 1.192 |
| 13 | 900409 | 11.62 | 12.03 | 55 | 45 | M-50 | 42.326556, -84.471861 | 5301 | 35 | 7 | 1.762 |
| 14 | 361110 | 3.54 | 3.81 | 55 | 35 | M-36 | 42.564389, -84.389556 | 2181 | 9 | 7 | 6.584 |
| 15 | 964703 | 2.02 | 2.17 | 55 | 35 | M-136 | 43.038722, -82.485389 | 5347 | 17 | 7 | 5.016 |
| 16 | 1147907 | 5.09 | 5.56 | 55 | 45 | M-204 | 44.996657, -85.674383 | 3377 | 20 | 6 | 2.049 |
| 17 | 3281379 | 13.68 | 13.92 | 55 | 45 | M-113 | 44.584500, -85.416361 | 4697 | 17 | 6 | 2.865 |
| 18 | 961905 | 13.02 | 13.24 | 55 | 35 | M-19 | 43.100694, -82.766833 | 5260 | 20 | 6 | 2.797 |
| 19 | 1588008 | 2.61 | 2.75 | 55 | 25 | M-154 | 42.575556, -82.577500 | 9024 | 25 | 6 | 2.621 |
| 20 | 3050060 | 14.50 | 14.90 | 55 | 30 | M-88 | 45.018389, -85.212222 | 1778 | 9 | 6 | 4.611 |
| 21 | 3170005 | 2.12 | 2.36 | 55 | 20 | M-80 | 46.259417, -84.476250 | 2365 | 8 | 6 | 5.6 |
| 22 | 518501 | 0.35 | 0.79 | 55 | 45 | M-34 | 41.885194, -84.547361 | 3615 | 14 | 6 | 2.081 |
| 23 | 976409 | 0 | 0.08 | 55 | 35 | M-19 | 43.101778, -82.767694 | 5260 | 8 | 6 | 4.922 |
| 24 | 1260502 | 3.45 | 3.69 | 55 | 40 | M-123 | 46.564222, -85.290222 | 1064 | 7 | 6 | 12.996 |

| Rank | PR Number | BMP | EMP | Speed Limit | Advisory Speed | Route Name | Coordinates | AADT | Total Crashes | Total Lane Departure Crashes | Lane Departure Crash Rate |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 25 | 1218506 | 7.43 | 7.66 | 55 | 40 | M-32 | 44.985129, -84.254010 | 3180 | 9 | 5 | 3.746 |
| 26 | 932308 | 11.28 | 11.44 | 55 | 30 | M-36 | 42.466500, -83.854222 | 14301 | 17 | 5 | 1.161 |
| 27 | 962408 | 8.131 | 8.418 | 55 | 30 | M-136 | 43.051639, -82.602250 | 5617 | 7 | 5 | 1.705 |
| 28 | 503406 | 8.839 | 9.232 | 55 | 50 | M-21 | 43.000778, -85.017556 | 5442 | 14 | 5 | 1.281 |
| 29 | 1365901 | 2.833 | 3.082 | 55 | 30 | M-140 | 41.898528, -86.267361 | 1333 | 6 | 5 | 8.265 |
| 30 | 1427301 | 1.854 | 2.223 | 55 | 45 | US-12 | 42.090944, -83.922639 | 10147 | 9 | 5 | 0.73 |
| 31 | 3450711 | 9.916 | 10.288 | 55 | 40 | M-22 | 44.998250, -85.635056 | 5059 | 10 | 5 | 1.457 |
| 32 | 23403 | 2.628 | 2.757 | 55 | 30 | M-43 | 42.415389, -85.438111 | 5814 | 7 | 5 | 3.653 |
| 33 | 361110 | 3.731 | 4.015 | 55 | 35 | M-36 | 42.564389, -84.389556 | 2181 | 7 | 5 | 4.415 |
| 34 | 594510 | 11.337 | 11.516 | 55 | 50 | M-60 | 41.897278, -86.051167 | 4012 | 8 | 5 | 3.815 |
| 35 | 860003 | 11.473 | 11.863 | 55 | 45 | M-120 | 43.391417, -86.121056 | 6337 | 7 | 5 | 1.108 |
| 36 | 900409 | 14.464 | 14.621 | 55 | 45 | M-50 | 42.298750, -84.436278 | 5302 | 17 | 5 | 3.292 |
| 37 | 984708 | 8.856 | 9.082 | 55 | 40 | M-43 | 42.535454, -85.395301 | 3170 | 9 | 5 | 3.824 |
| 38 | 1053202 | 0.509 | 0.786 | 55 | 50 | M-18 | 44.165167, -84.617806 | 1164 | 5 | 5 | 8.489 |
| 39 | 3450711 | 9.541 | 9.805 | 55 | 45 | M-22 | 45.003444, -85.630556 | 5058 | 13 | 5 | 2.055 |
| 40 | 946403 | 9.356 | 9.536 | 55 | 35 | US-12 | 42.061751, -84.184214 | 4931 | 6 | 4 | 2.47 |
| 41 | 859103 | 4.195 | 4.531 | 55 | 45 | M-37 | 43.266278, -85.810361 | 7984 | 11 | 4 | 0.816 |
| 42 | 711701 | 3.983 | 4.279 | 55 | 50 | M-37 | 43.352766, -85.809849 | 8629 | 27 | 4 | 0.858 |
| 43 | 711907 | 12.744 | 12.96 | 55 | 35 | M-37 | 43.604583, -85.771722 | 3010 | 9 | 4 | 3.371 |
| 44 | 899407 | 12.17 | 12.398 | 55 | 40 | M-60 | 42.225639, -84.492222 | 14310 | 14 | 4 | 0.672 |
| 45 | 502809 | 9.421 | 9.834 | 55 | 45 | M-21 | 42.973139, -85.125778 | 5108 | 13 | 4 | 1.04 |
| 46 | 524603 | 18.797 | 19.142 | 55 | 45 | US-131 Business | 43.726944, -85.495972 | 9301 | 19 | 4 | 0.682 |
| 47 | 984708 | 17.246 | 17.539 | 55 | 40 | M-43 | 42.632028, -85.345611 | 3170 | 15 | 4 | 2.36 |
| 48 | 593706 | 5.700 | 6.067 | 55 | 50 | M-62 | 41.969667, -86.069250 | 2851 | 10 | 4 | 2.09 |
| 49 | 23707 | 0.242 | 0.703 | 55 | 40 | M-43 | 42.411722, -85.445889 | 5814 | 8 | 4 | 0.82 |
| 50 | 993501 | 2.763 | 3.194 | 55 | 45 | M-113 | 44.540306, -85.413000 | 5390 | 10 | 4 | 0.94 |

# Appendix D - Top 50 Curves with Highest Lane Departure Crash Rate on Two-Lane Rural Trunkline Highways in Michigan

| Rank | PR Number | BMP | EMP | Speed Limit | Advisory Speed | Route Name | Coordinates | AADT | Total Crashes | Total Lane Departure Crashes | Lane Departure Crash Rate |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1560808 | 17.341 | 17.448 | 55 | 25 | M-35 | 46.283639, -87.463000 | 565 | 4 | 3 | 27.152 |
| 2 | 148907 | 14.826 | 14.915 | 55 | 35 | US-41 | 47.430731, -87.982708 | 1076 | 3 | 3 | 17.302 |
| 3 | 1560808 | 17.368 | 17.615 | 55 | 25 | M-35 | 46.283861, -87.464944 | 565 | 5 | 4 | 15.69 |
| 4 | 1560808 | 20.43 | 20.554 | 55 | 40 | M-35 | 46.297972, -87.522861 | 565 | 2 | 2 | 15.599 |
| 5 | 1260502 | 3.452 | 3.69 | 55 | 40 | M-123 | 46.564222, -85.290222 | 1064 | 7 | 6 | 12.996 |
| 6 | 1177509 | 14.339 | 14.482 | 55 | 20 | M-203 | 47.242472, -88.521750 | 648 | 3 | 2 | 11.831 |
| 7 | 1277410 | 0.455 | 0.68 | 55 | 25 | M-73 | 46.040222, -88.799333 | 416 | 2 | 2 | 11.71 |
| 8 | 1560808 | 20.083 | 20.426 | 55 | 40 | M-35 | 46.297972, -87.513444 | 565 | 4 | 4 | 11.318 |
| 9 | 3050060 | 8.163 | 8.277 | 55 | 35 | M-88 | 44.932389, -85.198583 | 3667 | 12 | 8 | 10.487 |
| 10 | 1147410 | 26.71 | 26.946 | 55 | 35 | M-22 | 44.993472, -85.769250 | 2467 | 15 | 11 | 10.373 |
| 11 | 1560808 | 32.082 | 32.27 | 55 | 30 | M-35 | 46.432889, -87.598333 | 565 | 2 | 2 | 10.362 |
| 12 | 535910 | 0.035 | 0.313 | 55 | 45 | M-18 | 44.510694, -84.578278 | 789 | 5 | 4 | 10.008 |
| 13 | 1277410 | 3.926 | 4.199 | 55 | 35 | M-73 | 46.058083, -88.737139 | 416 | 2 | 2 | 9.636 |
| 14 | 993501 | 0 | 0.106 | 55 | 40 | M-113 | 44.583833, -85.414361 | 4697 | 21 | 12 | 9.589 |
| 15 | 1560808 | 32.19 | 32.297 | 55 | 30 | M-35 | 46.433972, -87.598778 | 565 | 2 | 1 | 9.064 |
| 16 | 1177509 | 14.402 | 14.592 | 55 | 20 | M-203 | 47.243361, -88.520917 | 648 | 3 | 2 | 8.899 |
| 17 | 1053202 | 0.509 | 0.786 | 55 | 50 | M-18 | 44.165167, -84.617806 | 1164 | 5 | 5 | 8.489 |
| 18 | 1277410 | 2.995 | 3.311 | 55 | 40 | M-73 | 46.052167, -88.752639 | 416 | 3 | 2 | 8.328 |
| 19 | 1365901 | 2.833 | 3.082 | 55 | 30 | M-140 | 41.898528, -86.267361 | 1333 | 6 | 5 | 8.265 |
| 20 | 1277410 | 4.84 | 5.163 | 55 | 30 | M-73 | 46.068722, -88.723833 | 416 | 7 | 2 | 8.167 |
| 21 | 3170009 | 41.428 | 41.623 | 55 | 50 | M-123 | 46.632750, -85.128694 | 1064 | 5 | 3 | 7.888 |
| 22 | 1277410 | 5.443 | 5.788 | 55 | 40 | M-73 | 46.074278, -88.714778 | 416 | 5 | 2 | 7.618 |
| 23 | 3050060 | 15.996 | 16.134 | 55 | 35 | M-88 | 45.019472, -85.238694 | 1778 | 9 | 3 | 6.701 |
| 24 | 361110 | 3.543 | 3.811 | 55 | 35 | M-36 | 42.564389, -84.389556 | 2181 | 9 | 7 | 6.584 |
| 25 | 1277410 | 7.511 | 7.836 | 55 | 40 | M-73 | 46.090361, -88.680056 | 1023 | 6 | 4 | 6.583 |

| Rank | PR Number | BMP | EMP | Speed Limit | Advisory Speed | Route Name | Coordinates | AADT | Total Crashes | Total Lane Departure Crashes | Lane Departure Crash Rate |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 26 | 148403 | 0.897 | 1.074 | 55 | 25 | M-26 | 47.468583, -88.055306 | 1424 | 4 | 3 | 6.515 |
| 27 | 1109710 | 8.669 | 8.866 | 55 | 20 | M-32 | 45.081556, -84.913417 | 1748 | 7 | 4 | 6.373 |
| 28 | 1560808 | 18.073 | 18.231 | 55 | 25 | M-35 | 46.288722, -87.474333 | 565 | 2 | 1 | 6.138 |
| 29 | 1560808 | 20.474 | 20.959 | 55 | 40 | M-35 | 46.297972, -87.522861 | 565 | 5 | 3 | 5.998 |
| 30 | 1147410 | 38.607 | 38.804 | 55 | 20 | M-22 | 45.110250, -85.635944 | 1412 | 6 | 3 | 5.906 |
| 31 | 1560808 | 30.073 | 30.414 | 55 | 45 | M-35 | 46.417500, -87.569889 | 565 | 4 | 2 | 5.688 |
| 32 | 3170005 | 2.12 | 2.369 | 55 | 20 | M-80 | 46.259417, -84.476250 | 2365 | 8 | 6 | 5.6 |
| 33 | 148806 | 0.321 | 0.524 | 55 | 40 | M-26 | 47.395330, -88.277727 | 986 | 2 | 2 | 5.491 |
| 34 | 148403 | 0.994 | 1.207 | 55 | 25 | M-26 | 47.468664, -88.053033 | 1424 | 4 | 3 | 5.418 |
| 35 | 231210 | 0 | 0.058 | 55 | 20 | M-86 | 41.925639, -85.625361 | 4368 | 8 | 4 | 5.121 |
| 36 | 1147410 | 38.724 | 38.877 | 55 | 20 | M-22 | 45.110111, -85.634194 | 1412 | 4 | 2 | 5.096 |
| 37 | 964703 | 2.027 | 2.17 | 55 | 35 | M-136 | 43.038722, -82.485389 | 5347 | 17 | 7 | 5.016 |
| 38 | 976409 | 0 | 0.087 | 55 | 35 | M-19 | 43.101778, -82.767694 | 5260 | 8 | 6 | 4.922 |
| 39 | 1350405 | 15.667 | 15.88 | 55 | 40 | M-183 | 45.736861, -86.607722 | 529 | 3 | 1 | 4.89 |
| 40 | 1109710 | 7.547 | 7.676 | 55 | 40 | M-32 | 45.084278, -84.933500 | 1748 | 3 | 2 | 4.852 |
| 41 | 1560808 | 28.552 | 28.755 | 55 | 40 | M-35 | 46.401167, -87.552667 | 565 | 3 | 1 | 4.777 |
| 42 | 148806 | 5.231 | 5.348 | 55 | 30 | M-26 | 47.428111, -88.237306 | 986 | 2 | 1 | 4.752 |
| 43 | 1154306 | 5.036 | 5.208 | 55 | 30 | M-22 | 44.350667, -86.218139 | 2718 | 13 | 4 | 4.688 |
| 44 | 3050060 | 14.503 | 14.904 | 55 | 30 | M-88 | 45.018389, -85.212222 | 1778 | 9 | 6 | 4.611 |
| 45 | 1283507 | 4.849 | 5.05 | 55 | 20 | M-42 | 44.389608, -85.246804 | 1787 | 4 | 3 | 4.564 |
| 46 | 1023804 | 6.98 | 7.115 | 65 | 45 | M-65 | 45.161944, -83.698528 | 1772 | 4 | 2 | 4.56 |
| 47 | 1119307 | 13.796 | 13.958 | 55 | 30 | M-18 | 44.091000, -84.606278 | 1499 | 3 | 2 | 4.513 |
| 48 | 1465606 | 9.716 | 9.943 | 55 | 50 | M-48 | 46.071528, -84.236028 | 543 | 2 | 1 | 4.432 |
| 49 | 361110 | 3.731 | 4.015 | 55 | 35 | M-36 | 42.564389, -84.389556 | 2181 | 7 | 5 | 4.415 |
| 50 | 1350405 | 15.8 | 16.041 | 55 | 40 | M-183 | 45.736861, -86.607722 | 529 | 1 | 1 | 4.285 |

# Appendix E - Top 25 Curves with Highest Lane Departure Crash Frequency on Freeways in Michigan

| Rank | PR Number | BMP | EMP | Speed Limit | Advisory Speed | Route Name | Coordinates | Directional AADT | Total Crashes | Total Lane Departure Crashes | Lane Departure Crash Rate |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1426110 | 18.02 | 18.27 | 70 | 60 | WB I-94 | 42.282806, -83.784750 | 26052 | 72 | 46 | 3.794 |
| 2 | 1426109 | 18.01 | 18.31 | 70 | 60 | EB I-94 | 42.283111, -83.785222 | 26052 | 73 | 44 | 3.085 |
| 3 | 410203 | 13.37 | 13.52 | 70 | 50 | NB US-131 | 42.959359, -85.671747 | 55716 | 86 | 41 | 2.688 |
| 4 | 1497903 | 5.00 | 5.14 | 70 | 55 | NB I-475 | 42.992333, -83.681222 | 19627 | 50 | 39 | 7.777 |
| 5 | 646106 | 4.15 | 4.41 | 70 | 60 | SB I-75 | 42.503222, -83.115306 | 52318 | 136 | 34 | 1.370 |
| 6 | 406305 | 8.34 | 8.67 | 65 | 45 | EB I-196 | 42.968528, -85.700389 | 31580 | 57 | 32 | 1.683 |
| 7 | 1497904 | 4.93 | 5.28 | 70 | 55 | SB I-475 | 42.990861, -83.682333 | 19627 | 36 | 28 | 2.233 |
| 8 | 646106 | 9.62 | 10.20 | 70 | 65 | SB I-75 | 42.559389, -83.154833 | 33230 | 48 | 20 | 0.569 |
| 9 | 646106 | 7.71 | 8.52 | 70 | 55 | SB I-75 | 42.558315, -83.121124 | 40831 | 48 | 15 | 0.249 |
| 10 | 647308 | 9.62 | 10.20 | 70 | 55 | NB I-75 | 42.559472, -83.154333 | 33230 | 44 | 14 | 0.398 |
| 11 | 646106 | 1.18 | 1.33 | 70 | 60 | SB I-75 | 42.460778, -83.106056 | 51664 | 90 | 13 | 0.919 |
| 12 | 647308 | 1.02 | 1.15 | 70 | 60 | SB I-75 | 42.460111, -83.105139 | 51664 | 49 | 13 | 1.061 |
| 13 | 1431202 | 16.88 | 17.2 | 70 | 60 | NB US-23 | 42.323472, -83.692167 | 35167 | 17 | 13 | 0.633 |
| 14 | 469902 | 2.90 | 3.11 | 70 | 60 | NB I-675 | 43.439889, -83.948694 | 11628 | 15 | 12 | 2.693 |
| 15 | 1497903 | 6.99 | 7.24 | 70 | 55 | NB I-475 | 43.018750, -83.684639 | 23865 | 16 | 11 | 1.010 |
| 16 | 355201 | 0.94 | 1.10 | 70 | 50 | WB I-496 | 42.726139, -84.583972 | 15661 | 16 | 10 | 2.187 |
| 17 | 647308 | 7.71 | 8.37 | 70 | 65 | NB I-75 | 42.557500, -83.119361 | 40831 | 55 | 10 | 0.203 |
| 18 | 355110 | 0.96 | 1.10 | 70 | 50 | WB I-496 | 42.725914, -84.583785 | 21734 | 16 | 9 | 1.621 |
| 19 | 355201 | 4.92 | 5.13 | 70 | 60 | WB I-496 | 42.723512, -84.506295 | 26095 | 19 | 9 | 0.900 |
| 20 | 1497904 | 7.36 | 7.54 | 70 | 55 | SB I-475 | 43.021512, -83.684190 | 23865 | 18 | 9 | 1.148 |
| 21 | 406809 | 8.80 | 8.96 | 65 | 45 | WB I-196 | 42.972472, -85.697472 | 31580 | 10 | 8 | 0.868 |
| 22 | 498503 | 12.30 | 12.45 | 75 | 65 | NB US-127 | 43.292167, -84.582083 | 9381 | 15 | 8 | 3.115 |
| 23 | 1427103 | 0.50 | 0.70 | 70 | 60 | WB M-14 | 42.290361, -83.798556 | 13071 | 16 | 8 | 1.677 |
| 24 | 498502 | 12.30 | 12.57 | 75 | 65 | SB US-127 | 43.293056, -84.582528 | 9381 | 19 | 7 | 1.514 |
| 25 | 769407 | 1.04 | 1.20 | 75 | 65 | EB US-10 | 43.598306, -84.154778 | 17976 | 12 | 7 | 1.334 |

# Appendix F - Top 25 Curves with Highest Lane Departure Crash Rate on Freeways in Michigan

| Rank | PR Number | BMP | EMP | Speed Limit | Advisory Speed | Route Name | Coordinates | Directional AADT | Total Crashes | Total Lane Departure Crashes | Lane Departure Crash Rate |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1497903 | 5.00 | 5.14 | 70 | 55 | NB I-475 | 42.992333, -83.681222 | 19627 | 50 | 39 | 7.777 |
| 2 | 1426110 | 18.02 | 18.28 | 70 | 60 | WB I-94 | 42.282806, -83.784750 | 26052 | 72 | 46 | 3.721 |
| 3 | 498503 | 12.30 | 12.45 | 75 | 65 | NB US-127 | 43.292167, -84.582083 | 9381 | 15 | 8 | 3.115 |
| 4 | 1426109 | 18.01 | 18.31 | 70 | 60 | EB I-94 | 42.283111, -83.785222 | 26052 | 73 | 44 | 3.085 |
| 5 | 410203 | 13.37 | 13.52 | 70 | 50 | NB US-131 | 42.959359, -85.671747 | 55716 | 86 | 41 | 2.698 |
| 6 | 469902 | 2.90 | 3.11 | 70 | 60 | NB I-675 | 43.439889, -83.948694 | 11628 | 15 | 12 | 2.693 |
| 8 | 1497904 | 4.93 | 5.28 | 70 | 55 | SB I-475 | 42.990861, -83.682333 | 19627 | 36 | 28 | 2.233 |
| 7 | 355201 | 0.94 | 1.10 | 70 | 50 | WB I-496 | 42.726139, -84.583972 | 15661 | 16 | 10 | 2.187 |
| 9 | 406305 | 8.34 | 8.67 | 65 | 45 | EB I-196 | 42.968528, -85.700389 | 31580 | 57 | 32 | 1.683 |
| 11 | 1427103 | 0.50 | 0.70 | 70 | 60 | WB M-14 | 42.290361, -83.798556 | 13071 | 16 | 8 | 1.677 |
| 10 | 355110 | 0.96 | 1.10 | 70 | 50 | WB I-496 | 42.725914, -84.583785 | 21734 | 16 | 9 | 1.621 |
| 12 | 498502 | 12.3 | 12.57 | 75 | 65 | SB US-127 | 43.293056, -84.582528 | 9381 | 19 | 7 | 1.514 |
| 13 | 625912 | 0.12 | 0.66 | 70 | 55 | SB I-75 | 42.611612, -83.232305 | 4053 | 17 | 6 | 1.502 |
| 14 | 646106 | 4.15 | 4.41 | 70 | 60 | SB I-75 | 42.503222, -83.115306 | 52318 | 136 | 34 | 1.370 |
| 15 | 769407 | 1.04 | 1.20 | 75 | 65 | SB US-10 | 43.598306, -84.154778 | 17976 | 12 | 7 | 1.334 |
| 16 | 1497904 | 7.36 | 7.54 | 70 | 55 | SB I-475 | 43.021512, -83.684190 | 23865 | 18 | 9 | 1.148 |
| 17 | 647308 | 1.02 | 1.15 | 70 | 60 | SB I-75 | 42.460111, -83.105139 | 51664 | 49 | 13 | 1.061 |
| 18 | 1497903 | 6.99 | 7.24 | 70 | 55 | NB I-475 | 43.018750, -83.684639 | 23865 | 16 | 11 | 1.010 |
| 19 | 355201 | 4.92 | 5.13 | 70 | 60 | WB I-496 | 42.723512, -84.506295 | 26095 | 19 | 9 | 0.900 |
| 20 | 646106 | 1.18 | 1.33 | 70 | 60 | SB I-75 | 42.460778, -83.106056 | 51664 | 90 | 13 | 0.919 |
| 21 | 406809 | 8.80 | 8.96 | 65 | 45 | WB I-196 | 42.972472, -85.697472 | 31580 | 10 | 8 | 0.868 |
| 22 | 498503 | 11.69 | 12.07 | 75 | 65 | NB US-127 | 43.284889, -84.581778 | 9016 | 14 | 5 | 0.800 |
| 23 | 469901 | 3.17 | 3.41 | 70 | 60 | SB I-675 | 43.441378, -83.950221 | 11628 | 8 | 4 | 0.785 |
| 24 | 242006 | 11.70 | 12.05 | 75 | 65 | SB US-127 | 43.613611, -84.739222 | 6433 | 9 | 3 | 0.730 |
| 25 | 1431202 | 16.88 | 17.20 | 70 | 60 | NB US-23 | 42.323472, -83.692167 | 35167 | 17 | 13 | 0.633 |

# Appendix G - Approximate Costs of Speed Warning Treatments

| Speed Warning Treatment | Material Cost | Installation Cost | Total cost | Inflation Adjusted Prices, as of February, 2025 | | |
|---|---|---|---|---|---|---|
| | | | | Material Cost | Installation Cost | Total cost |
| Curve Warning System with 3 solar powered chevron signs* | $ 22,742.83 | $ 25,925.15 | $ 48,667.98 | $ 24,334.83 | $ 27,739.91 | $ 52,074.74 |
| Curve Warning System with 6 solar powered chevron signs* | $ 45,485.66 | $ 32,136.09 | $ 77,621.75 | $ 48,669.66 | $ 34,385.61 | $ 83,055.27 |
| Curve Warning System with 3 A/C powered chevron signs* | $ 55,711.58 | $ 26,011.09 | $ 81,722.67 | $ 59,611.39 | $ 27,831.86 | $ 87,443.26 |
| Curve Warning System with 6 A/C powered chevron signs* | $ 92,438.60 | $ 32,307.97 | $ 124,746.57 | $ 98,909.30 | $ 34,569.53 | $ 133,478.83 |
| Solar LED border light sign | $ 1,950.00 | $ 1,950.00 | $ 3,900.00 | $ 1,950.00 | $ 1,950.00 | $ 3,900.00 |
| A/C LED border light sign | $ 1,950.00 | $ 3,900.00 | $ 5,850.00 | $ 1,950.00 | $ 3,900.00 | $ 5,850.00 |
| Solar Dynamic Speed Feedback Sign (DSFS) | $ 4,660.00 | $ 4,660.00 | $ 9,320.00 | $ 4,660.00 | $ 4,660.00 | $ 9,320.00 |
| A/C Dynamic Speed Feedback Sign (DSFS) | $ 4,660.00 | $ 9,320.00 | $ 13,980.00 | $ 4,660.00 | $ 9,320.00 | $ 13,980.00 |
| Slippery Curve Warning Sign (10 LED border signs and RWIS sensor)** | - | - | $ 239,624.00 | - | - | $ 316,303.68 |

* price in 2022 (Inflation rate to February 2025: 1.07)

** price in 2016 (Inflation rate to February 2025: 1.32)

*Source: U.S. Bureau of Labor Statistics*