Evaluation of Dynamic Speed Feedback Signs on Freeway Interchange Ramps

FINAL REPORT

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16. Abstract

Dynamic speed feedback signs (DSFS) are promising countermeasure to reduce curve speeds and subsequent lane departures at freeway interchange ramps, although their use in such contexts has been limited. Consequently, the impact of DSFS on driver performance at interchange ramps remains unproven. To that end, research was performed to determine the effect of DSFS installed at freeway interchange ramps on measures of driver behavior, particularly speeds approaching and entering the ramp curve. To accomplish this objective, a series of field evaluations were conducted at six freeway interchange ramps possessing significant horizontal curvature. Various DSFS configurations were tested during these evaluations, including: sign messaging strategy, longitudinal positioning of the sign with respect to the ramp curve entry point, lateral positioning of the sign with respect to the side of the ramp, sign dimensions and other physical characteristics, radar activation range, and temporal changes in driver behavior. Overall, the presence of a DSFS positioned near the start of the curve resulted in curve entry speeds that were, on average, 1.5 mph to 4.0 mph lower than without a DSFS present at the site. When the DSFS was present near the start of the curve, the lowest curve entry speeds were observed for cases where the feedback message activated when vehicles were within 250 to 400 ft of the start of the curve. Regarding DSFS lateral position, both the right-side-mounted and forward-mounted (i.e., ramp gore area) installations resulted in similar curve entry speeds. Furthermore, there were no discernable differences in curve entry speeds between 15-inch and 18-inch display panels, nor were speeds impacted by the inclusion of an advisory speed panel. In terms of feedback message, the most effective strategy was to display the measured speed alternating with a SLOW DOWN message. The effects on driver behavior associated with the DSFS were consistent between system interchanges and service interchanges, and across all vehicle types. Finally, there was no evidence of temporal changes in driver behavior during the initial 14 months of operation of the permanent DSFS installation evaluated here. Based on these findings, the continued use of DSFS as a speed reduction treatment at freeway interchange ramps is recommended. Additional guidance towards utilization of DSFS is provided within the report.

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EVALUATION OF DYNAMIC SPEED FEEDBACK SIGNS ON FREEWAY INTERCHANGE RAMPS

FINAL REPORT

January 23, 2022

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EXECUTIVE SUMMARY

Lane departure crashes have been a long-standing safety issue given the severe injury outcomes associated with such crashes. The risk of such crashes is elevated where horizontal curves are present. One particularly vulnerable area for curve-related lane departure crashes is freeway ramps, which, due to right-of-way constraints and other factors, often include horizontal curves requiring a significant reduction in speed to be safely negotiated. A promising countermeasure to reduce curve speeds on freeway interchange ramps can be the dynamic speed feedback sign (DSFS), which uses real-time speed detection to provide targeted warning messages to drivers. These devices have been successfully implemented across Michigan, although typically in work zones, school zones, and general municipal speed control applications, within limited application on horizontal curves. However, their use on freeway interchange ramps has been limited nationwide, and the effectiveness of the signs in such settings has consequently remained unproven. To this end, research was undertaken to determine effective applications for DSFS when used as a speed control measure on freeway ramps with sharp horizontal curvature.

A series of field evaluations were performed at six freeway interchange ramps to assess the impacts of speed feedback signs on various measures of driver behavior, particularly speed on the approach and entry to the ramp curve. Three commercially available speed feedback signs, which varied in size, border type, and radar detection range, were utilized during the field evaluations. The three signs are displayed on the following page along with details of the study sites. The field evaluations were performed across multiple phases, each of which assessed important aspects related to the design, operation, and/or installation of the DSFS, which included:

- sign messaging strategy,
- longitudinal positioning of the sign relative to the ramp curve,
- lateral positioning of the sign with respect to the side of the ramp,
- sign dimensions and other physical characteristics,
- radar activation range,
- time of day,
- interchange type, and
- temporal changes in driver behavior.

Interchange Ramp Sites for Field Evaluations

Interchange Ramp Site	Speed Limit, Ramp Advisory Speed (mph)	Interchange Type	Test Conditions
EB I-69 to WB I-69	55, 30	System	Message type, sign location with respect to curve
WB I-96 to SB I-69	70, 30	System	Changes in sign effectiveness over time
NB US-127 to Round Lake Rd	75, 30	Service	Time of day, light condition, sign lateral position, sign activation range, sign size, sign border type
EB I-96 to 36th St	70, 20	Service	Sign location with respect to curve
NB US-127 to Dunckel Rd	70, 25	Service	Sign location with respect to curve, sign lateral position
EB I-96 to NB US-127	70, 25	System	Sign location with respect to curve, mainline speeds

Note: MUTCD-compliant signage, including W13-6, E5-1a, and W1-8R, were present at all sites during all phases.

a. TraffiCalm, 15-inch Display

b. TraffiCalm 18-inch Display

c. All Traffic Solutions, 18-inch Display

Dynamic Radar Speed Feedback Test Signs

Data were collected from each study location broadly in two phases: 1) under the existing site conditions without the DSFS present and 2) after the installation of the DSFS or after modifying the DSFS setup or operation. After collection of data under the existing site condition, the DSFS was installed at the site by MDOT crews and was programmed and validated by the research team. The existing signage at each site was not modified in any way. The sign remained operational for seven days prior to initiating data collection in order to allow for dissipation of any driver novelty effects associated with the new traffic control device. The study utilized three different techniques for collection of vehicular speeds: 1) a series of high-definition video cameras, 2) handheld LIDAR, and 3) speed-trailer. Selection of the data collection technique was based on the site characteristics and types of data desired. The data collection procedures were consistent across all data collection periods for a given evaluation.

Considering all phases of the field evaluation, it was concluded that dynamic speed feedback signs are an effective countermeasure for reducing speeds of vehicles approaching and entering horizontal curves on freeway exit ramps. The most critical aspect influencing the effectiveness of the DSFS as a speed reduction countermeasure was the longitudinal positioning of the sign relative to the ramp curve. Generally speaking, the DSFS was effective across all sites and all test conditions as long as the sign was positioned within 250 ft of the start of the curve. Specifically, a DSFS positioned near the start of the curve resulted in curve entry speeds that were, depending on the condition, 1.5 mph to 4.0 mph lower than without a DSFS present. In contrast, the DSFS was consistently ineffective when positioned at greater distances upstream of the curve, perhaps due to drivers' tendencies to disregard warning messages that are provided too far in advance of the hazard.

Regarding the lateral sign position, the DSFS provided similar effects on driver behavior when installed in either the traditional right-side-mount or forward-mount positions, although the forward-mount contributed to speed reductions beginning further upstream. This was likely due to the greater visibility of the sign when positioned within the gore area, particularly for locations where a bridge overpass or other sight-obstruction immediately proceeds the ramp curve.

The strongest sign-related effects were related to the radar detection range. With the DSFS installed near the start of the curve, the lowest curve entry speeds were observed for cases where the feedback message activated for vehicles that were within 250 to 400 ft of the start of the curve. Activation of the display panel for vehicles further than 400 ft upstream of the curve did not provide additional speed reduction benefits. Not surprisingly, the DSFS was least effective when the feedback message did not activate until the vehicle was within 250 ft of the curve. This diminished effectiveness was likely due to drivers not being afforded adequate time to react and respond to the feedback message.

In terms of sign size, 15-inch and 18-inch display panels were found to be equally effective and may be used interchangeably at freeway exit ramps. A prominent yellow reflective border around the sign is recommended to help improve conspicuity during cases when the sign is activated late and/or when the sign is located in a visually cluttered environment. Interestingly, there was little difference in the speed reduction effects between the various sign messaging strategies, although slight benefits were observed when the speed number was alternated with a SLOW DOWN message, perhaps due to increased conspicuity of the alternating message frames. However, including an advisory speed panel within the DSFS assembly did not have a substantive impact on driver behavior.

Finally, while this research primarily evaluated the short-term effectiveness of DSFS, the speed reduction effects were sustained during the initial 14-months of operation for the lone permanent DSFS installation included in this study. Although the sample of heavy vehicles was somewhat limited across the field evaluations, the DSFS was similarly effective for heavy vehicles and passenger vehicles. In terms of interchange characteristics, the DSFS was equally effective irrespective of the mainline speed limit or ramp advisory speed. Additionally, the effectiveness of DSFS was similar between system interchanges and service interchanges. Finally, the DSFS did not show any significant effect on the speeds of mainline vehicles when activated.

Based on the study findings, the continued use of DSFS as a speed reduction treatment at freeway exit ramp curves is recommended. A series of specific recommendations related to the sign characteristics, operational performance, site selection, and installation details are provided in the body of the final project report. These recommendations were developed on the basis of providing optimal DSFS performance towards reducing curve entry speeds, lane departures, and associated crashes, along with practical considerations. Further, these recommendations may be utilized by MDOT towards development of guidelines for the use of DSFS at freeway ramps and other highway warning curve applications, which are not specifically addressed in the current MDOT special provision for speed feedback signs.

While this research provided substantial evidence of the effectiveness of DSFS as a speed reduction countermeasure at freeway exit ramps across a variety of contexts, a future evaluation should assess the effectiveness of DSFS towards reducing the frequency/severity of ramp lane departure crashes. Furthermore, additional long-term evaluations should be performed to further confirm whether the speed reduction effects of DSFS remain consistent or diminish with time.

1. INTRODUCTION AND BACKGROUND

1.1 Lane Departure Crashes

Between 2012 and 2016, 1.47 million crashes occurred on public roadways in Michigan, resulting in 4,790 fatalities, 26,367 severe injuries, and 340,441 other injuries (*1*). Among the most severe types of crashes are those involving lane departure, which occurs when a vehicle crosses over either the roadway centerline or edge line, often resulting in a head-on, sideswipe, or run-off-road crash. These lane departure crashes have been a long-standing safety issue given the severe injury outcomes associated with such crashes. These types of crashes are generally due to a variety of factors, including driver distraction, drowsiness, limited visibility, and poor pavement surface conditions. The initial (1998) AASHTO Strategic Highway Safety Plan (SHSP) identified numerous safety emphasis areas of nationwide importance related to lane departure crashes (*1*). The SHSP culminated in the publication of NCHRP Report 500, which provided guidance towards lane departure mitigation strategies to reduce head-on and cross-median collisions, keep vehicles on the roadway, and minimize the consequences of leaving the roadway (*1*, *2*). Shortly after the publication of the AAHSTO SHSP, the Michigan Governor's Traffic Safety Advisory Commission (GTSAC) began the process of developing the initial SHSP for the State of Michigan, which included the identification of 12 traffic safety emphasis areas (*4*). Lane departure crashes were identified as an emphasis area, and an action plan was subsequently developed.

Lane departure crashes have also remained a significant roadway safety problem in Michigan. Although lane departure crashes accounted for 18.0 percent of all crashes in the state from 2012-2016, such crashes accounted for 46.5 percent of all fatalities and 37.4 percent of all serious injuries (*3*). Not long after the development of the initial SHSP in Michigan, MDOT began several high-profile statewide initiatives aimed at reducing lane departure crashes. These initiatives included installation of rumble strips on non-freeways and cable median barriers on freeways, and each program showed substantial reductions in target lane departure crashes (*5,6*). Despite numerous statewide highway safety initiatives to address lane departures, such crashes have continued to occur at relatively steady annual rates. As a result, the prevention of lane departures has remained as a primary emphasis area in each edition of the Michigan SHSP (*4–6*).

A recent safety evaluation of rural highways in Michigan showed that the risk of a lane departure crash is elevated where horizontal curves are present (*7*). One particularly vulnerable area for curve-related lane departure crashes is freeway ramps, which, due to right-of-way constraints and other factors, often include horizontal curves requiring a significant reduction in speed to be safely negotiated. A query of Michigan crash data coded as "freeway crash - entrance/exit ramp related" found 39,276 such crashes to have occurred between 2012 and 2016, of which 12,581 (32.0 percent) involved lane departure (*3*). Table 1 displays these data categorized by crash type versus vehicle type, crash severity, road condition, and lighting condition.

Table 1. Freeway interchange ramp-related crashes in Michigan, 2012 - 2016 (*1*)

VEHICLE TYPE	Fixed Object		Overturn		Other		Total Lane Departure	
	Crashes	% of Lane Departure	Crashes	% of Lane Departure	Crashes	% of Lane Departure	Crashes	% of Lane Departure
Truck/bus over 10,000 lbs	213	45.3%	127	27.0%	130	27.7%	470	100.0%
Truck under 10,000 lbs	103	71.0%	32	22.1%	10	6.9%	145	100.0%
Passenger Vehicle	8,771	78.8%	1,280	11.5%	1,085	9.7%	11,136	100.0%
Other Vehicle	489	56.5%	155	17.9%	222	25.6%	866	100.0%
CRASH SEVERITY	Fixed Object		Overturn		Other		Total Lane Departure	
	Crashes	% of Lane Departure	Crashes	% of Lane Departure	Crashes	% of Lane Departure	Crashes	% of Lane Departure
Fatal (K)	27	48.2%	20	35.7%	9	16.1%	56	100.0%
Incapacitating (A)	143	53.2%	83	30.9%	43	16.0%	269	100.0%
Non-Incapacitating (B)	482	54.2%	286	32.2%	121	13.7%	889	100.0%
Possible Injury (C)	1,073	63.9%	426	25.4%	180	10.7%	1,679	100.0%
No Injury (O)	7,851	81.0%	779	8.0%	1,058	10.9%	9,688	100.0%
ROAD CONDITION	Fixed Object		Overturn		Other		Total Lane Departure	
	Crashes	% of Lane Departure	Crashes	% of Lane Departure	Crashes	% of Lane Departure	Crashes	% of Lane Departure
Dry	3,065	70.7%	849	16.6%	648	12.7%	5,102	100.0%
Wet	2,369	76.6%	387	12.5%	337	10.9%	3,093	100.0%
Ice/Snow/Slush	3,539	82.3%	348	8.1%	415	9.6%	4,308	100.0%
Other/Unknown	63	75.0%	10	11.9%	11	13.1%	84	100.0%
LIGHTING CONDITION	Fixed Object		Overturn		Other		Total Lane Departure	
	Crashes	% of Lane Departure	Crashes	% of Lane Departure	Crashes	% of Lane Departure	Crashes	% of Lane Departure
Daylight	5,144	76.5%	834	12.4%	746	11.1%	6,724	100%
Dawn/Dusk	480	74.8%	79	12.3%	83	12.9%	642	100%
Dark	3,907	75.7%	680	13.2%	573	11.1%	5,160	100%
Other/Unknown	45	81.8%	1	1.8%	9	16.4%	55	100%

Table 1 presents several interesting findings. First, lane departure crashes were overrepresented among severe ramp crashes, accounting for 59.2 percent of total fatal and A-injury crashes on freeway ramps. Furthermore, the specific type of lane departure crash clearly influences severity outcome. Overturning crashes on ramps result in an alarming rate of severe injuries, as 6.5 percent (approximately 1 in 15) result in a fatal or A-injury, compared to 1.2 percent for all other ramp crashes. Consequently, crashes involving an overturn were greatly overrepresented among all severe ramp crashes, accounting for 18.8 percent of all fatal and A-injury ramp crashes, but only 4.1 percent of total ramp crashes.

Table 1 also clearly indicates the influence of vehicle type on the risk of an overturn crash. Lane departure crashes were far more likely to result in an overturn if a heavy truck or bus was involved (overturn in 27.0 percent of lane departure crashes) compared to a passenger vehicle (overturn in 11.5 percent of lane departure crashes). However, passenger vehicles were more likely to collide with a fixed object (78.8 percent of lane departure crashes) compared to heavy trucks/buses (45.3 percent of lane departure crashes).

Table 1 also provides insight into the environmental conditions that influence the occurrence of a lane departure crash. Lane departure ramp crashes are far more likely to occur during wet conditions and especially ice/snow/slush conditions compared to all other ramp crashes. While only 15.4 percent of non-lane departure ramp crashes occurred during wet road conditions, 24.6 percent of lane departure ramp crashes occurred under wet road conditions. Ice/snow/slush road conditions had an even greater influence on lane departure ramp crash occurrence, as 34.2 percent of all lane departure ramp crashes occurred during these conditions, compared to only 10.6 percent of all other ramp crashes. This implies that lane departure crashes were 3.2 times more likely to occur under ice/snow/slush conditions than other types of ramp crashes. Finally, 41 percent of lane departure ramp crashes occurred during darkness, which was more than double the proportion of dark crashes for non-lane departure ramp crashes.

Issues with lane departure crashes on interchange ramps in Michigan may be further exacerbated by the 2017 increase in speed limits from 70 to 75 mph for passenger vehicles on over 600 miles of rural freeways and from 60 to 65 mph for trucks and buses on all freeways. Recent research found that freeway segments where the aforementioned speed limit increases were applied experienced increases in free-flow speed ranging between 2.1 and 4.6 mph and overall speed increases ranging between 2.0 and 3.1 mph (*8*).

1.2 Dynamic Speed Feedback Signs and Other Lane Departure Countermeasures

The Michigan Department of Transportation (MDOT) has deployed various traffic control strategies to mitigate lane departure crashes on interchange ramps, including signs (W1-11, W1-13, W1-15, W13-6/7, chevrons, etc.), warning beacons (Figure 1a), and chevron pavement markings (Figure 1b). Despite these efforts, the problem continues to persist statewide and new treatments are needed. A recent SHSP engineering action plan for Michigan recommended implementation of innovative countermeasures to prevent lane departure crashes, including speed control technologies such as dynamic speed feedback signs (DSFS) (*9*). Utilizing a speed measuring device, typically a radar unit embedded in the sign face, DSFS display real-time feedback to the driver in a variety of formats, including:

- the measured speed of the approaching vehicle,
- a speed warning message (e.g., "SLOW DOWN" or "TOO FAST"), or
- activation of warning lights or beacons on signs with static warning messages.

The feedback messages are typically activated only when drivers are exceeding a preset speed threshold. The signs may be programmed to provide different messages based on a preset speed threshold; for example, providing the measured speed below a certain threshold and "SLOW DOWN" above that threshold. Furthermore, combinations of messages may also be used; for example, the measured speed alternating with "SLOW DOWN".

a. Flashing Ramp Warning Sign **b. Chevron Markings at Ramp** **c. DSFS on US-2**

Figure 1. Innovative speed control treatments used by MDOT

1.3 Research Problem and Objectives

DSFS have been widely implemented across Michigan, although almost exclusively as temporary/portable installations in work zones, school zones, and general municipal speed control applications. Permanent installations of DSFS, such as that previously installed on US-2 west of

St. Ignace (Figure 1c), have seen limited use in Michigan and mostly in school zone applications. Although DSFS have been found to be an effective crash reduction countermeasure at horizontal curves (*10*), they have experienced only very limited installation at such locations in Michigan. Furthermore, prior to the onset of this research project, DSFS had seen very little implementation on freeway interchange ramps both within Michigan and nationwide, and the effectiveness of the signs in such settings has consequently remained unproven.

DSFS possess the potential to reduce lane departure crashes on interchange ramps, particularly when used on ramps with substantial horizontal curvature, such as loop ramps at typical cloverleaf interchanges. To this end, research was undertaken to determine effective applications for DSFS when used as a speed control measure on freeway ramps with sharp horizontal curvature. The primary objective of this research was to determine the effect of various DSFS configurations at freeway ramp curves on measures of driver behavior, particularly speed approaching and entering the ramp curve. The findings and conclusions from this study allowed for development of guidance towards further deployment of DSFS on interchange ramps in Michigan in support of efforts to reduce lane departure crashes and associated injuries and fatalities statewide.

1.4 Research Tasks

The research described herein evaluated the effectiveness of DSFS when used on interchange ramps in order to provide guidance related to where DSFS should be deployed and what types of DSFS to deploy in this context. The specific tasks of this research study were as follows:

- Using a literature review and state agency survey, determine the nationwide state-of-the-art and state-of-the-practice for DSFS, with particular emphasis on deployment at interchange ramps;
- Procure and test one or more prototype portable DSFS along with all necessary components for deployment and evaluation at interchange ramps;
- Perform a series of field studies at freeway interchange ramps in Michigan to evaluate the impacts of DSFS on the behavior of motorists approaching and entering the ramp curves, including assessment of various characteristics related to the DSFS, including:
    - sign messaging strategy,
    - longitudinal positioning of the sign relative to the ramp curve,

  - lateral positioning of the sign with respect to the side of the ramp,
  - sign dimensions and other physical characteristics,
  - radar activation range,
  - time of day,
  - interchange type, and
  - changes in driver behavior over time.
- Provide recommendations regarding the use of DSFS on interchange ramps in Michigan, including DSFS specifications, installation conditions, and future deployment locations.

1.5 Report Structure

This report has been structured to reflect each of the research tasks. As the field evaluation represented the most extensive task in this study, discussion of this task and the subsequent findings have been divided into multiple chapters based on the evaluated characteristics. The chapter structure for the remainder of this report is provided as follows:

- Chapter 2: Literature review and state agency survey
- Chapter 3: General field evaluation methodology
- Chapter 4: Field evaluation of DSFS messaging strategy and longitudinal sign position relative to the ramp curve
- Chapter 5: Field evaluation of longitudinal position, interchange type, and time-of-day
- Chapter 6: Field evaluation of DSFS physical characteristics (e.g., display size, border type/size, radar detection range) and lateral position with respect to the side of the ramp
- Chapter 7: Field evaluation of longitudinal and lateral sign position and mainline activation
- Chapter 8: Field evaluation of changes in DSFS effectiveness over time
- Chapter 9: Identification of potential sites for future DSFS installation by MDOT
- Chapter 10: Overall conclusions and recommendations

2. LITERATURE REVIEW AND STATE AGENCY SURVEY

Dynamic speed feedback signs (also known as speed feedback signs, dynamic speed display signs) provide active information to the drivers on a digital display by detecting speed of the approaching vehicles. The speed feedback display can be alternated with any feedback message including “SLOW DOWN,” “YOU ARE SPEEDING SLOW DOWN,” “HIGH SPEED SLOW DOWN,” “REDUCE SPEED IN WORK ZONE,” and “EXCESSIVE SPEED SLOW DOWN.” It has been used to reduce speed and crash occurrence in different empirical settings that require a high level of attention from the drivers. The DSFS utilization area includes work zones, sharp horizontal curves, speed transition zones, high-speed arterials, school zones, and residential neighborhoods. To support the use of DSFS in various critical locations, different state agencies have recommended policies to install DSFS, in addition to the general guidelines provided by the Manual on Uniform Traffic Control Devices (MUTCD).

2.1 Policies or Guidelines for DSFS

To better understand policies and guidelines for the use of DSFS at different locations requiring speed management, a review of the existing federal and state guidelines was conducted. MUTCD and different state agencies provide guidelines for installing and maintaining DSFS within the rights-of-way of the state-maintained roadways. The policies cover both permanent and temporary installation along with guidance specific to a location including school zones, work zones, and transition zones.

2.1.1 MUTCD guidance for DSFS

MUTCD guidance specific to DSFS are provided in sections 2B.13 (Speed Limit Sign) and chapter 2L (Changeable Message Signs). Speed Limit Sign Guidance in section 2B.13 suggested that “If a changeable message sign displaying approach speeds is installed, the legend YOUR SPEED XX MPH or such similar legend should be displayed. The color of the changeable message legend should be a yellow legend on a black background or the reverse of these colors.” The specific guidance for the DSFS (changeable message sign (CMS) in MUTCD) include (*11*):

- The message sign should be “blank-out signs that display only single-phase, predetermined electronic-display legends that are limited by their composition and arrangement of pixels or other illuminated forms in a fixed arrangement…”

- The message displays should be consistent along the roadway corridor and adjacent corridors when DSFS are used at multiple locations.
- DSFS used on roadways with speed limits of 55 mph or higher should be visible from 1/2 mile under both day and night conditions.
- DSFS message should be legible from a minimum distance of 600 feet for nighttime conditions and 800 feet for normal daylight conditions.
- DSFS should be used as a supplement to and not as a substitute for conventional signs and markings.
- DSFS message shall consist of no more than two phases and a phase shall consist of no more than three lines of text.
- Permanent DSFS should be located sufficiently upstream of known bottlenecks, high crash locations, major diversion decision points such as interchanges to provide adequate response distance.
- Permanent DSFS should not be installed within an interchange except for toll plazas or managed lanes, at a location with already high information load on drivers, or at the locations where frequent lane-changing maneuvers are performed.

2.1.2 General guidance for the deployment of DSFS

Several state agencies have provided guidance on the identification of the need for a DSFS and general guidance to install one. The Vermont Agency of Transportation (VTrans), in their guidelines for the use of radar speed feedback signs on the state highway system recommended a study of the 85th percentile speed to first identify if the posted speed limit is appropriate (*12*). A comprehensive study by Veneziano et al. (*13*) recommended several criteria on when or how DSFS can be deployed and operated to address speeding and safety issues effectively. The study suggested, DSFS may be considered when

1. the observed 85th percentile or mean speeds at a site exceed the posted speed limit by 5 mph or more,
2. average daily traffic exceeds 500 vehicles,
3. sites exhibit a correctable speed-related crash history within a recent time period,
4. sites have a pedestrian-related crash history, and
5. the posted speed limit at a site is 25 mph or greater.

The Montana Department of Transportation (MDT) and VTrans outlined a list of technical requirements for both permanent and temporary DSFS installation. Both of these agencies recommended to first confirm the MUTCD guidance and standards for DSFS installation. The additional technical requirements for the permanent installation include (*12*, *14*):

1. Installation shall be in conjunction with a speed limit sign (standard or school speed zone),
2. Installation is restricted to one DSFS in each direction for the area being addressed,
3. The changeable display shall be programmed to go blank/no display or an optional word display of "SLOW DOWN" when the vehicle speed exceeds 15 MPH over the posted speed. In either option, the speed of the vehicle will not be displayed when the speed exceeds 15 MPH over the posted speed.
4. When activated, the DSFS display shall give drivers immediate feedback on their individual driving speed when the posted speed is exceeded without animation, rapid flashing, or other dynamic elements.
5. When installed in association with school speed zones, the DSFS shall operate only when the school speed zone is in effect. Use of DSFS in conjunction with school speed zones "when children are present" is not allowed. If this same school zone location experiences documented speed issues, this DSFS can be utilized during 'non-school-hours' also.
6. DSFS sign support assembly and installation should meet the requirements for crash-worthiness as defined in the National Cooperative Highway Research Program (NCHRP) Report 350 (*15*) or Manual for Assessing Safety Hardware (MASH) (*16*).
7. The installation shall not interfere with the visibility and general effectiveness of any other signs in the area.
8. Identification and contact information for the local government in which it is installed shall be displayed on the case of the DSFS.

The technical requirements for the temporary installation of DSFS in the form of speed trailer include:

1. Speed trailers should be in place for a maximum of 2 weeks; (if needed longer than two weeks, the District Administrator can grant the extra time by email or other documentation) (*12*, *14*).

2. Speed trailers should not replace any other safety measures already in place, i.e., school crossing guards, existing warning signs, enforcement (*14*).
3. Speed trailers shall not interfere with the operation of the highway for motor vehicles, bicyclists, or pedestrians (*12*, *14*).
4. Care should be taken for the placement of the speed trailers in relationship to the clear zone or other signs. This would include placing behind guardrail and if that is not practicable then placement on the shoulder of the highway with proper delineation of retroreflective temporary traffic control devices such as drums or cones (*14*).
5. Speed trailers shall include the legend "Speed Limit xx MPH" that is consistent with the regulatory speed limit of the road on which it is used (*12*, *14*).

2.1.3 Location-specific guidelines for deployment of DSFS

The FHWA's ENTERPRISE Pooled Fund Study developed initial planning guidance for several Intelligent Transportation System (ITS) devices to assist agencies to make informed decisions while implementing those (*17*). A list of warrants for application of DSFS on the three most common areas was compiled and has focused on the transition zones (*15*, *16*), posted speed adherence (*14–16*), and intelligent work zones (*12*, *14–16*, *18*). The purpose of DSFS in these locations is to promote speed limit adherence in general while focusing on high-speed vehicles or temporary speed reduction due to construction. DSFS should be considered if certain warrants are met at each location.

At the speed transition zones, DSFS should be considered if

1. The 85th percentile speed (as determined by a speed study) at a location within the lower speed limit area exceeds the posted speed limit by at least 10 mph, and
2. The zone experiences a posted speed limit reduction of at least 10 mph, and
3. There are no other DSFS along the route encountering the speed transition, within 5 miles in either direction (excluding DSFS within school zones).

At the posted speed adherence locations, DSFS should be considered if,

1. The 85th percentile speed (as determined by a speed study) exceeds the posted speed limit by at least 5 mph, or by at least 5 mph in a school zone, and

2. The area is within 500 yards of a major pedestrian generator (e.g., school, park, library, senior center, office building) or the area is primarily a residential area or a heavily traveled pedestrian area, and
3. The posted speed limit is 35 mph or less, and
4. There are no other DSFS along the route within a 5 mile in either direction of the proposed sign (excluding DSFS within school zones).

At the intelligent work zones, DSFS should be considered if,

1. The work zone is currently in operation and observations suggest that the 85th percentile speed at a location within the work zone exceeds the posted speed limit by at least 10 mph or hazardous roadway conditions, such as a temporary unusually tight curve, or a rough road surface, requiring extra driving precaution, and
2. The posted speed limit is 35 mph or greater.

2.2 Operational Benefits of DSFS

2.2.1 DSFS in work zones

DSFS was first used as a speed control measure at the work zones. It has been used in different forms including portable changeable message signs, speed trailers, and dynamic speed feedback signs. Prior studies have consistently shown the effectiveness of DSFS in reducing speed in the work zones. In 1994, Garber and Patel (*19*, *20*) evaluated the change in travel speed by using four different feedback messages at seven work zones on two Interstate highways in Virginia work zones. DSFS were placed on 65 mph highways, intended to drop the speed to 55 mph. While all four types of feedback messages significantly reduced the average speed of vehicles traveling 59 mph or faster, "YOU ARE SPEEDING SLOW DOWN" was the most effective, followed by "HIGH SPEED SLOW DOWN", "REDUCE SPEED IN WORK ZONE" and "EXCESSIVE SPEED SLOW DOWN". Results showed a speed reduction of 8 to 10 mph following the installation of the speed feedback signs. The study also found a reduced percentage of vehicle speeding by any amount over 55 mph including by 5 mph and 10 mph.

In 1995, McCoy et al. (*21*) evaluated DSFS in work zones on an interstate highway in South Dakota. The study tested a 20-inch by 28-inch speed display panel in a trailer combined with additional signs including a WORK ZONE warning sign, an advisory speed limit sign, and a YOUR SPEED guide sign. Two DSFS were positioned at the edge of the shoulder on either side and 310 feet upstream of the first taper. Before and after speed data collected from the sites indicated a reduction in average speed by 4 mph for the vehicles with two axles and by 5 mph for the vehicles having more than 2 axles. A significant reduction by 20 to 40 percent in the number of vehicles traveling 10 mph over the speed limit was also observed.

In 2001, Pesti and McCoy (*22*) evaluated the long-term effectiveness of DSFS in work zones on rural interstate highways that required dropping speeds from 75 mph to 55 mph. Three temporary speed trailers showing the driver speed on a panel with 24-inch LED numerals and having a "SPEED LIMIT 55" sign on top of it were installed before three critical segments. The study found a significant reduction of 3 to 4 mph in average speed, 2 to 7 mph in the 85th percentile speed, and 20 to 40 percent increase in the vehicle compliance of speed limit and speed threshold. The results were consistent over the 5 weeks of operation.

In 2002, a study by the Maine Department of Transportation evaluated a radar-activated trailer-mounted portable speed feedback sign (*23*). The sign was installed at the Interstate I-95 work zone that required dropping the speed to 45 mph. The sign was programmed to display "YOU ARE SPEEDING!!!" alternated with "SPEED LIMIT 45 MPH". A before and after comparison found a reduction in average speed by 7 mph and along with an 11 percent reduction in vehicles exceeding the speed limit.

In 2003, a study by Wang et al. (*24*) evaluated the potential of fluorescent orange sheeting, innovative message signs, and DSFS for reducing speeds in highway work zones. The DSFS displayed "YOU ARE SPEEDING, SLOW DOWN NOW" for vehicles traveling 5 mph over the posted work zone speed limit of 45 mph and displayed "ACTIVE WORK ZONE, REDUCE SPEED" for vehicles traveling below 50 mph. The reduction in average operating speed for fluorescent orange sheeting was 1 to 3 mph, for innovative message signs, it was 0.2 to 1.8 mph. But when DSFS was installed, the average speed significantly reduced by 7 to 8 mph, in addition to the reduction in speed variance. The influence of the DSFS remained similar throughout the implementation period of three weeks.

In 2006, a study conducted by Sorrell et al. (*25*) in South Carolina work zones evaluated four messaging sequences including "YOU ARE SPEEDING" followed by "SLOW DOWN", "YOUR SPEED IS______" followed by "SLOW DOWN", "YOUR SPEED IS______" followed by "THANKS FOR NOT SPEEDING" or "SLOW DOWN", and "YOU ARE SPEEDING" followed by "MINIMUM FINE $200". The study found a reduction in average speed by 3 to 10 mph. A comparison of the messaging strategies showed that providing positive feedback did not significantly increase the speed reduction, neither did negative feedback.

In 2007, Mattox et al. (*26*) evaluated the effectiveness of a speed-activated sign at the work zones to reduce speeds on two-lane primary and secondary highways, a multilane divided highway, and an interstate freeway. The 4-feet by 4-feet plastic reflective "YOU ARE SPEEDING IF FLASHING" sign was equipped with radar and flashing lights that get triggered when the speed exceeds by 5 mph. The study showed a significant reduction in average speed by 2 to 6 mph and a reduction in speeding 3 mph over the posted speed limit by 15 to 41.5 percent.

In 2013 a study by Thapa et al. (*27*) used time series traces to analyze the change in driver response from the upstream of work zones to different work zone features on four-lane roadways with both shoulder and lane closure using naturalistic driving study data. The analysis found drivers were 5.07 times more likely to respond when a work zone sign included a DSFS in it. The study also found drivers driving over the speed limit to be more likely to show response than the drives maintaining the speed limit and likelihood of showing a response increase by 1.06 times with a 1 mph increase in speed over the speed limit.

In 2014, a study by Huang and Bai (*28*) evaluated different messaging strategies on a PCMS at a work zone on two-lane rural highways in reducing speeds while approaching one. The results of the analysis found typical text message (i.e., WORKZONE AHEAD SLOWDOWN, FLAGGER AHD PREP TO STOP) to reduce average speed by 13 percent, text message alternating with a graphic depicting the same messages at every 3 seconds by 10 percent, and only graphic message to reduce average speed by 17 percent. In the extended study (*29*), the graphic was redesigned following a survey that showed some confusion in understanding the graphic by around 12 percent of respondents. The redesigned graphic that alternated with text message reduced the average speed by 13 percent. The authors recommended a well-designed graphic to aid the text message to be effective in reducing speeds. The study also reported 52 to 71 percent of drivers prefer graphics in the PCMS messages.

In 2021, a study by Anderson et al. (*30*) evaluated DSFS on high-speed work zones on Kansas roadways. A speed feedback sign was installed on 70 mph roadways having a work zone speed limit of 55 mph. The sign was installed with a static work zone speed limit sign, and it was capable of displaying the speed of the approaching vehicle. The study found DSFS to be effective in reducing speeds at one site by reducing average speed by 2 mph.

2.2.2 DSFS at horizontal curves

DSFS have been successfully implemented on horizontal curves at several locations and they have been found to improve the level of safety on horizontal curves by reducing speeds and crash rates. In 2000, a study by Tribbett et al. (*31*) evaluated five dynamic curve warning signs equipped with speed detection radar installed on interstate 5 in the Sacramento River Canyon. The sites had curve advisory speeds between 50 and 60 mph and upstream speeds of 55 mph and 65 mph. The findings of the study were mixed as some sites experienced a reduction in average speed while others have experienced no change or increase. The results also varied for different vehicle types. However, there have been some concerns about the stopwatch method utilized for the speed data collection.

In 2005, a study by Ullman and Rose (*32*) evaluated two horizontal curve sections on a 55 mph speed limit roadway with 20 mph advisory speeds. The study found average car speed to drop by 2.1 to 3.5 mph in the short-term. The impact on the truck speed was not similar, where one site experienced a slight increase in average speed and another one experienced a slight decrease. However, at both study sites, the percentage of vehicles exceeding posted speed limit significantly decreased both in short-term and long-term. Speeding over the curve advisory speeds dropped by 26 percent for cars and 28 percent for trucks at one site, where it dropped by 13 percent for cars and 24 percent for trucks at another site in the short-term.

In 2006, a before-after study by Bertini et al. (*33*) evaluated two overhead speed feedback signs on a horizontal curve in Interstate 5 in Oregon. The overhead sign displayed the fastest speed within the detection zone. The message displayed "SHARP CURVE AHEAD" when vehicle speeds are less than 50 mph, "YOUR SPEED XX MPH" when detected speeds are 50 to 70 mph, and "YOUR SPEED IS OVER 70 MPH" when detected speeds exceeded 70 mph. Even though the feedback was not for an individual vehicle, the strategy significantly reduced average speed as the study found a reduction in average car and truck speed by 3 mph in one direction and by 2 mph in another direction.

In 2015, a nationwide DSFS study on horizontal curves by Hallmark et al. (*34*) on 22 two-lane rural horizontal curve sections evaluated two different speed feedback signs. The signs include a speed display sign showing the speed of the approaching vehicle and posted speed limit when speed is 20 mph over the posted speed limit, and a curve warning sign showing a curve sign and an alternating slowdown message to the vehicles exceeding 50th percentile speed. The results showed a significant reduction in average speed by 1.82 mph, 2.57 mph, and 1.97 mph after 1 month, 12 months, and 24 months of installation, respectively. The results also showed a significant reduction in the percent of vehicles traveling 5 mph over the advisory speed or posted speed limit by 11.8 percent, 18.6 percent, and 19.8 percent after 1 month, 12 months, and 24 months of installation, respectively. The reduction in the percentage of vehicles exceeding the advisory or posted speed limit by 10 mph, 15 mph, or 20 mph was even higher.

2.2.3 DSFS at speed transition zones

DSFS has been successfully installed at the speed transition zones with various upstream speeds transitioning to different reduced speed limits. It has been successful to effectively convey the information pertaining to the pending reduced speed limit to approaching drivers.

In 2005, a study by Ullman and Rose (*32*) evaluated two transition zones dropping the speed limit from 55 mph to 45 mph. After the installation of the DSFS, the average speed dropped by 3.4 mph and 2.6 mph at two sites in the short-term and by 1.4 mph in the long-term at both sites. The study also found the drivers traveling above the posted speed limit to significantly reduce their speed compared to the drivers complying with the speed limits.

In 2009, a study by Cruzado and Donnell (*35*) evaluated a total of 12 speed transition zones on two-lane rural highways in Pennsylvania to evaluate the effectiveness of DSFS in reducing the speed while entering the rural communities. The study sites had upstream speed limits between 45-55 mph, which transitioned to reduced speed limit areas with speeds between 25-40 mph. Results showed free-flowing average passenger car speed reduction in the transition zones to increase by 6.3 mph following the installation of the DSFS. The effectiveness of the DSFS in reducing the average free-flowing speed continued during the time DSFS was activated but faded as soon as they were removed.

In 2015, Hallmark et al. (*36*) evaluated different types of DSFS installed at the transition zones in three small rural communities in Iowa. A simple feedback sign displaying only drivers' speeds at a transition site from 55 mph to 25 mph found a decrease in average speed by 8 mph and driving 5 mph over the speed limit by 45 percent after one month of installation. A similar setup including a static "YOUR SPEED" sign and a separate display showing the driver's speed found a decrease of 5 mph in average speed one month after the installation. Another DSFS capable of showing alphanumeric messages was installed at a 55 mph to 25 mph transition zone and programmed to display vehicle speed when the approach speed was between 26 and 39 mph and display "Slow Down 25" when the approach speed was between 40 mph and 75 mph. The average speed decreased by 5 mph and vehicles exceeding the speed limit by 5 mph decreased by 76 percent. Another type of DSFS assembly included a speed limit sign with embedded LED lights around the outside of the sign found inconsistent results, where one sign location experienced only a 0.4 mph decrease in average speed and another one had a 6 mph decrease in average speed following the installation.

2.2.4 DSFS on high-speed arterials

DSFS has been installed and evaluated on high-speed arterials as a speed regulating feature, particularly in advance of the intersections, or horizontal curves. In 2005, a study by Ullman and Rose (*32*) evaluated two high-speed roadways with target speed limits of 55 mph and 45 mph in advance of signalized intersections. The study found the average speed to drop by 3.4 to 3.6 mph in the short-term. However, in the long term, the speed reduction effects were mixed, where at one site average speed returned to the prior conditions, and at another, average speeds were 4.0 mph lower than the prior conditions.

In 2008, a study by Walter and Broughton (*37*) evaluated 10 sites on two-way single carriageway roads with a 30 mph speed limit. The study found a significant reduction in average free-flow speed by 1.4 mph and a 12 percent decrease in vehicles exceeding the speed limit. However, speeds return to their previous levels after the removal of DSFS from the sites.

In 2009, the city of Bellevue's Transportation Department (*18*) evaluated 11 arterials streets with curves having posted speed limits of 30 or 35 mph. Results showed a significant reduction in the 85th percentile speeds during multiple years of observations ranging from 1-6 years. The reduction in the 85th percentile speeds was between 2.0 to 6.3 mph over the years.

In 2014, a study by Ardeshiri and Jeihani (*38*) evaluated both short-term and long-term effects of DSFS showing only speed numbers on arterial roads with speed limits of 25 mph, 35 mph, and 45 mph. The study found an increase in speed limit compliance by 5 percent and speed reduction in 40 percent cases. However, the study also found drivers to increase their speed after passing the DSFS and DSFS losing its effectiveness in the long-term. The study suggested the implementation of the DSFS only at the critical locations (i.e., locations with high crash rates, school zones, work zones) and should be supplemented with occasional speed enforcement.

In 2020, Krimpour et al. (*39*) evaluated a major signalized arterials in Arizona with a speed limit of 45 mph. A total of 4 DSFS was installed along the corridor to quantify the impact of DSFS on the link and intersection level. The study found no significant difference in the signal performance, but significantly lower average speed (average reduction of approximately 1 mph) at three out of the four links following the installation of the DSFS.

In 2021, an extended study by Krimpour et al. (*40*) evaluated speed feedback signs in combination with law enforcement at nine high-speed arterials with speed limits ranging from 40 to 50 mph in Arizona. The results showed that only speed feedback sign decreases average speeds by 0.8 mph to 5.8 mph at two sites. However, at one site with a higher speed limit (50 mph) average speed increased at the location with speed feedback sign. Additionally, when speed feedback sign was supported with periodic law enforcement, reductions in average speeds continued beyond the location of the speed feedback sign. A decrease of 0.3 mph to 2.5 mph at speed feedback sign and an additional decrease of 2.5 mph to 3.5 mph beyond that point was observed with the presence of enforcement.

2.2.5 DSFS in school zones

DSFS has been widely used at the school zones to implement lower regulatory speed limits during school arrival and dismissal times around the school zones. The sign has been effective in conveying the reduced speed limit information and subsequently reducing school zone approaching speeds.

In 2005, a study by Ullman and Rose (*32*) evaluated DSFS installed in advance of 3 school zones with speed limits of 35 mph to 45 mph. The study found a short-term average speed reduction of 9.2 mph and a long-term speed reduction of 8.8 mph following the installation of DSFS. Additionally, the number of drivers exceeding the speed limit also dropped from 95 percent to 34 percent and 44 percent in the short-term and long-term after the installation of the DSFS, respectively.

In 2006, Ash (*41*) evaluated four different schools zones with a 35 mph approach speed and 20 mph school zone speed limit in Utah following the installation of speed feedback signs. A 24- inch by 30-inch "YOUR SPEED" display sign displayed driver speed and small LED lights in the number provided flashing sign when the speed was 5 mph over the school-zone speed limit. The short-term effect after two months found drivers to drop their speed to or below the speed limits. The average speed reduction in this study was between 1 to 2 mph. In the long-term after six months, though average speed values slightly increased compare to the two-months after results, it was still around the school zone speed limits.

In 2012, a study by O'Brien and Simpson (*42*) evaluated a DSFS installed in a North Carolina school zone as part of the Safe Routes to School (SRTS) program. The DSFS assembly included "SCHOOL" sign, speed limit sign, school hours sign, and "YOUR SPEED" sign with a display capable of showing approaching vehicle speeds. The study found a significant reduction of 3 to 4.5 mph over a 12-month post-installation period.

In 2016, Williamson et al. (*43*) studied the long-term effectiveness of speed display signs in a university environment. The study found 85.6 percent of drivers to decrease their speed immediately after the deployment of the speed display sign and the percentage was 80 percent after one year, suggesting the long-term effect of the sign.

2.2.6 DSFS in residential neighborhoods

DSFS has been installed as part of the traffic calming measure in residential neighborhoods and the effect was positive. The sign was usually installed in the residential areas when other traffic calming measures were not effective in reducing speeds to the intended levels. In 1998, Bloch (*44*) evaluated DSFS in the residential areas with or without enforcement and compared the results with photo-radar. The study was conducted on three sites in Riverside, California, along two-lane, residential roads with speed limits of 25 mph. Results from the study indicated an average speed reduction of 6.1 mph at the location of the speed trailer. The speed reductions downstream of the trailer were 2.9 mph and 5.9 mph without and with enforcement, respectively. One week after removal of the speed trailer, speed reductions of 0.6 mph (at the former trailer location) and 1.7 mph (downstream) were observed for deployments that did not coincide with enforcement. Where enforcement was used in conjunction with the speed trailer, one week after sign removal, speed reductions of 0.6 mph occurred both at the trailer location and downstream of the trailer.

In 2005, a study by Chang et al. (*45*) evaluated four 24-inch by 30-inch radar signs installed at the 25 mph residential neighborhood. The sign was assembled under the speed limit sign and designed to display drivers' speeds and to start blinking once the speed reaches 5 mph over the posted speed limit. The study found a significant reduction of 1.2 to 2.2 mph at three out of the four sites. One site experienced an increase of 0.5 mph following the installation of the DSFS, however, this site had the lowest prior average speed suggesting the implementation of DSFS at the locations with greater speeding-related issues was more effective.

In 2009, the city of Bellevue's Transportation Department (*18*) evaluated 20 residential streets with a speed limit of 25 mph. The study showed a significant reduction in the 85th percentile speeds between 0.3 to 6.8 mph during multiple years of observations ranging from 1-7 years.

In 2012, a study by Gehlert et al. (*46*) evaluated three types of DSFS messaging strategies including a standard DSFS showing driver's actual speed, a standard DSFS showing driver's actual speeds highlighted in red or green depending on whether the driver complied with or exceeded the speed limit, and a verbal colored DSFS that shows "THANK YOU" message in green letters when the speed is within the speed limit or "SLOW" in red letters when the driver exceeded the speed limit. The study was conducted on a residential road with a speed limit of 30 kmh (18.6 mph). Results showed providing the verbal feedback was the most effective in reducing the average speed, followed by showing derivers' speed in red or green color and showing just the driver's speed. Results indicate that providing a hint of the drivers' action along with the personalized speed feedback was more efficient.

In 2016, a study by Churchill and Mishra (*47*) evaluated a trailer-mounted speed feedback sign on residential roads with 50 kmh (31 mph) and 60 kmh (37 mph). The study found the average speed to significantly reduce by 1.6 to 5.6 mph during the operation. The study also found a significant reduction in the percentage of vehicles traveling over speed limits. A permanent installation of speed feedback sign on 30 kmh (18.6 mph) roadways found a significant reduction in the percentage of vehicles triggering the sign as the sign was programmed to be triggered for only the vehicles with a speed of 35 kmh (21.8 mph) or above. The study indicated that putting a lower threshold for sign triggering works better in reducing average speed. The results of long-term evaluation of the sign were inconclusive.

In 2020, a case study in the City of Campbell, CA by Jue and Jarzab (*48*) analyzed the effectiveness of a radar speed sign over 5 years. The study deployed 30-inch by 42-inch speed feedback signs at 10 different locations with speed limits of 25 mph (one site had variable speed limits of 25 and 35 mph). The average reduction in speed after three months was 0.5 mph, after 6 months was 0.4 mph, after one year was 0.8 mph, after 3 years was 0.5 mph, and after 5 years was 0.2 mph. All the local streets had reduced speed and one collector street had increased speed following the installation of the speed feedback sign.

2.3 Safety Benefits of DSFS

There have been relatively few studies evaluating the safety benefits of DSFS. One reason may be the limiting number of locations used to study the operational effect of DSFS in every setting, in addition to the installation of DSFS mainly for the short-term speed reduction purpose in many instances. However, the limited number of studies that evaluated the safety effects of DSFS reported a significant reduction in crashes.

In 2000, a study Tribbett et al. (*31*) in California evaluated safety effects after installing five dynamic curve warning signs. The study reported a reduction in total truck-related crashes and mixed results for passenger vehicle crashes. However, the study could not draw a conclusion due to limited after-period crash data.

In 2015, a study by Hallmark et al. (*10*, *34*) conducted a comprehensive crash evaluation after the installation of DSFS at horizontal curves on two-lane rural highways. The study evaluated twenty-two study sites with two different DSFS systems and 37 control sites (similar sites where no DSFS was installed) to develop crash modification factors using Bayes modeling approach. The research found a 5 to 7 percent reduction in crashes during the first three years after the installation of DSFS.

In 2020, an empirical Bayes (EB) analysis by Wu et al. (*49*) on 192 DSFS installed on arterial and collector roads within the city of Edmonton, Alberta, Canada showed a significant reduction in crashes of all severity. The before-after EB analysis found a significant reduction in collisions that ranged from 32.5 percent to 44.9 percent with the greatest reduction in speed-related severe crashes. The overall reduction in total crashes was 36.1 percent including a reduction in rear-end by 38.0 percent, improper lane-changing by 32.5 percent, and speed-related by 38.2 percent. A detailed economic analysis using three different methods including direct costs, human capital, and willingness to pay further showed the benefit-cost ratio of installing DSFS ranged from 8.16 and 20.19 for 2-year service life and 19.84 to 49.06 for 5-year service life.

2.4 Public Perception of DSFS

Driver's acceptance and perception of the sign can also impact how their driving behavior will be changed. Several studies conducting a public perception survey of DSFS reported positive feedback of the sign. A survey done in California as part of a DSFS study reported an average of 80.0 percent of drivers to find the information provided by the sign to be useful (*31*). A questionnaire survey conducted on the students of the Morgan State University revealed most of the respondents reduce the speed to the speed limit when they encounter a DSFS (*50*). The perception towards the DSFS was also very positive as 82.0 percent of the responses suggest DSFS to increase safety or improve traffic flow or both. Another questionnaire survey on the use of DSFS in school zones conducted in Utah found very positive responses from the drivers (*41*). The survey found 72.9 percent of drivers believe speed feedback signs increased awareness of the potential danger ahead and 84.3 percent considered the signs effective for speed reduction in school zones.

2.5 Message Type and Position of DSFS Installation

The effectiveness of dynamic speed feedback signs depends on their positioning and message. The location of warning signs is an important factor, not only to provide enough prior warning to the driver but also because drivers tend to increase their speed once they are past the sign. On straight sections of roadway, the greatest speed reduction has been observed to be 1200 feet to 1400 feet upstream of the sign (*37*, *51*) and speeds began to increase 300 feet to 500 feet downstream of the sign (*51*). This speed increase shortly after the sign leads researchers to recommend their installation be at critical points on the roadway where safety is of the utmost importance (*38*). Another study evaluated the spatial effectiveness of the DSFS using vehicle trajectory data on a rural two-lane highway in Wisconsin (*51*). DSFS with flashing speed readings have shown greater speed reductions in advance of the sign compared to beyond the sign, with the greatest speed reductions observed 1200 - 1400 feet upstream of the DSFS and diminished effects 300 - 500 feet beyond the sign (*51*). The study suggests that once drivers pass the DSFS, the sign loses its effectivity significantly. A driving simulator study by Zhao et al. (*52*) also evaluated the effect of warning sign position on driving behavior in a sharp horizontal curve. The optimal location of DSFS on horizontal curves was found to be about 330 feet to 650 feet prior to the curve (*52*).

The type of feedback message has also been shown to affect the DSFS effectiveness. Full matrix displays that are able to provide messages such as ‘SLOW DOWN’ when the driver is exceeding the speed threshold have been found to outperform signs that simply display the driver’s speed (*26*, *32–34*, *46*).

2.6 State Agency Survey

A state DOT was developed to ascertain the state of the practice in terms of the deployment of DSFS, including at freeway interchange ramps. The questionnaire (found in Appendix A) included general questions on DSFS utilization by roadway type and context, sign specifications, sign calibration, message display rules, ability for the sign to communicate with an operations center or sensors, site selection, sign installation position with respect to the curve, measures to limit interference from mainline traffic, maintenance requirements, and lessons learned.

The survey was sent to 49 state DOTs in the United States (excluding Michigan). A total of 22 responses were received. As reflected in Figure 2, 9 states indicated that DSFS were not utilized on highway curves, 13 indicated the utilization of DSFS as a speed control measure on highway curves, although only four of these states (Illinois, Mississippi, Pennsylvania, and Wisconsin) indicated DSFS use on freeway exit ramp curves. Note: although the survey was not sent to the Michigan DOT, DSFS have recently been utilized on freeway ramp curves within Michigan, and is indicated in the map as such. Detailed survey responses are provided in Appendix A.

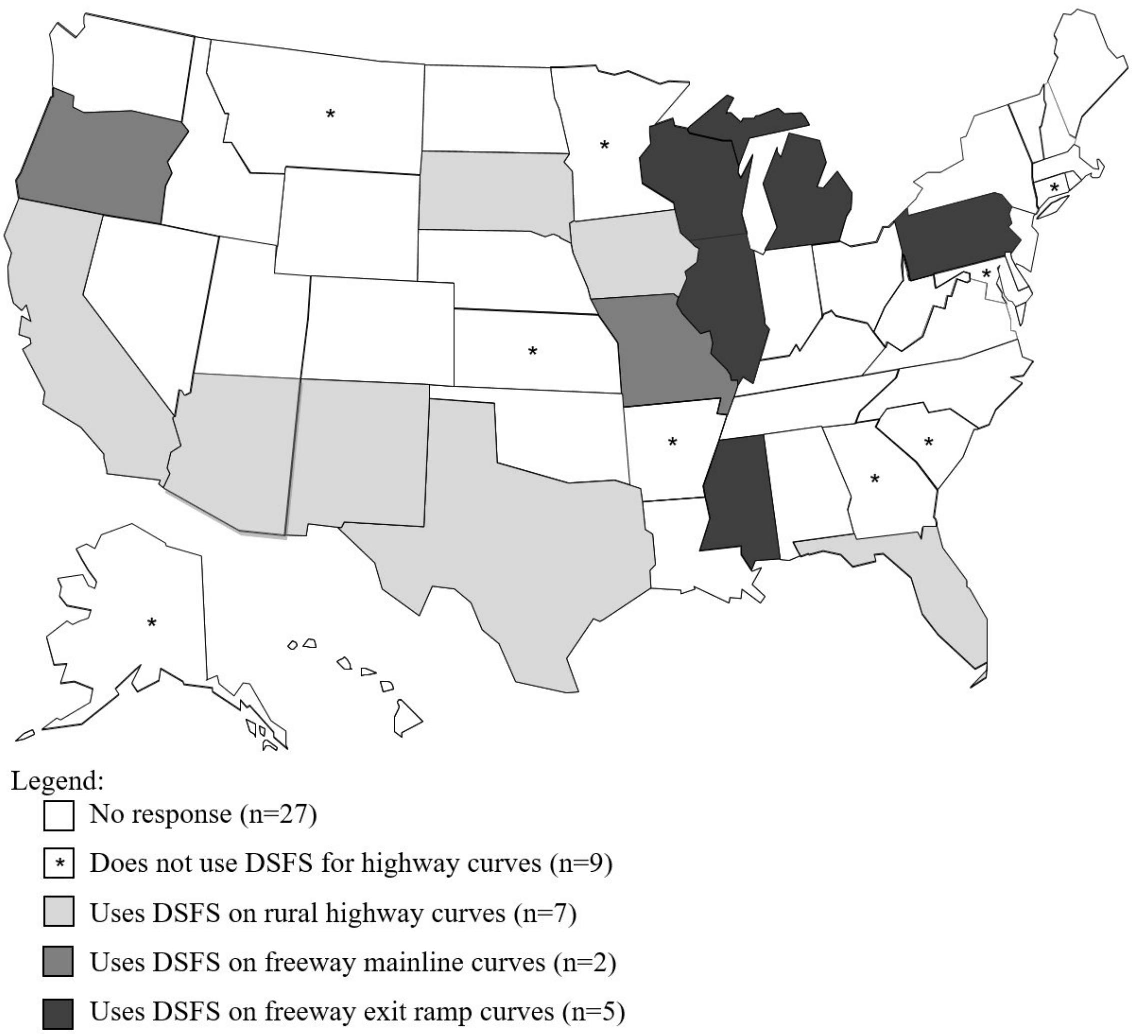


Figure 2. State DOT use of DSFS on horizontal curves

A particularly noteworthy comment mentioned by several agencies that use DSFS on ramp curves was that interference from adjacent mainline traffic is common, which frequently causes unnecessary activation of the feedback sign, but may also cause missed activations for ramp vehicles. Interference from mainline traffic is occurs because the forward facing radar cannot isolate ramp traffic from mainline, and is most common at locations where the ramp runs immediately adjacent to the mainline. Panels designed to occlude mainline vehicles from the radar have proven ineffective. Narrow band radar (e.g., 10 degrees or less) may help, but is not common in "off the shelf" signs. Some agencies use a maximum speed threshold (65 mph) to minimize interference from mainline vehicles. However, caution must be exercised such that ramp vehicles approaching at excessive speeds are not excluded, which becomes less of an issue when the DSFS is posted near the start of the curve.

2.7 Summary of Literature Review and State-of-the-Practice Survey

Collectively, the research literature suggests that DSFS are effective for reducing speeds and subsequent speed-related crashes across various roadway contexts, including rural highway curves. However, no prior studies considered the effects of DSFS when installed at interchange ramp curves. Furthermore, guidance towards the use of DSFS provided within the MUTCD and state agency specifications does not specifically focus on freeway ramps applications of DSFS. Of the 23 state agencies responding to the survey on DSFS use, only five indicated experience with using DSFS at freeway ramp curves. Several agencies noted issues associated with mainline traffic interfering with operation of feedback signs when used at freeway exit ramps. Given the recent freeway speed limit increases coupled with the persistent lane departure crash issues on interchange ramps in Michigan, additional research was warranted to evaluate the effects of DSFS on driver behavior and provide MDOT with guidance and direction towards further deployment of DSFS at freeway interchanges.

3. FIELD EVALUATION METHODOLOGY

A series of field evaluations were performed at multiple freeway interchange ramps to assess the impacts of speed feedback signs on various measures of driver behavior, particularly speed while approaching and entering the ramp curve. It was ultimately intended for the results of these field evaluations to inform future deployment of DSFS at freeway interchange ramps across Michigan. Thus, the field evaluations were performed across multiple phases, each of which assessed important aspects related to the design, operation, and/or installation of the DSFS. The following subsections provide a general overview of the field evaluations, including DSFS selection, DSFS programming, site selection, field data collection techniques, and analytical methods. Specific details related to the individual field evaluations are provided in subsequent chapters.

3.1 DSFS Selection

An initial step of the research was to identify the specific signs to be used in the field test. The research team contacted vendors and other state DOTs with experience using DSFS at horizontal curves to identify several viable sign options, which were presented to the MDOT research advisory panel for review and vetting. Each of these signs was compliant with MDOT's draft special provision for DSFS, which called for a yellow "YOUR SPEED" sign with an embedded radar and a speed feedback panel that possessed the ability to display either the speed digits or a "SLOW DOWN" message to approaching vehicles. The MDOT research advisory panel collectively decided to select a sign that MDOT had previous experience with and was a likely candidate for future installations. The selected 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. This test sign, which was manufactured by TraffiCalm, is shown displaying example messages in Figure 3.

In addition to the 15-inch TraffiCalm sign that was utilized in the preliminary field evaluations, two additional signs were included in the field evaluations performed during the later phases of this project. This included a larger version of the aforementioned TraffiCalm sign that consisted of a 48-inch by 36-inch sign with an 18-inch full matrix amber feedback display. The third sign evaluated in this study was from All Traffic Solution (ATS). The ATS sign with an 18-inch full matrix amber feedback display with a smaller black-on-white "YOUR SPEED" panel on top of the display panel. This sign did not include an additional border and was consequently a much smaller overall size (30-inch by 20-inch) compared to the TrafficCalm signs. All three signs tested in this study are shown in Figure 4.

Figure 3. Dynamic radar speed feedback sign displaying example feedback messages

a. **TraffiCalm with 15-inch Display**
b. **TraffiCalm with 18-inch Display**
c. **ATS with 18-inch Display**

Figure 4. Dynamic radar speed feedback signs tested during the field evaluations

Apart from the sign size and border, the radar systems utilized for vehicular detection varied between the two sign manufacturers, as follows:

- The two TraffiCalm signs utilized a forward-facing radar with a 30-degree cone embedded into the sign face.
- The ATS sign utilized a radar unit that was mounted independently from the sign and employed a more focused 10-degree radar cone, which was intended to better isolate the ramp vehicles and minimize the activation of the sign by the mainline vehicles.

The radar units on all signs were calibrated in the field to achieve vehicle detection ranges that were as similar as possible. However, it was not possible to achieve identical performance due to differences in the radar designs. Specifically, after calibration, the TraffiCalm signs (both 15-inch and 18-inch) had a typical vehicle detection range (i.e., the location where vehicles would typically be detected by the radar) of approximately 400 feet for passenger cars, which extended up to approximately 600 feet for large trucks. However, the ATS sign, with its more concentrated radar band had a typical vehicle detection range of approximately 600 ft for passenger cars, which extended up to approximately 1,000 ft for trucks. Each of the signs 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. During the evaluations, the signs were powered using a 140 amp-hour portable battery system that powered the sign for two weeks on a single charge.

3.2 DSFS Programming

The DSFS utilized in this study afforded substantial flexibility to modify the message display and radar performance settings. Sign programming was performed using manufacturer-specific software and/or smartphone applications in the field prior to each evaluation. Details on the sign programming are provided in the following subsections.

3.2.1 TraffiCalm Sign

The TraffiCalm sign was programmed using either a smartphone app or a computer software program named SafetyCalm. The SafetyCalm software allows connection using Bluetooth, serial port, or dialup connections for the computer version and via Bluetooth for the Android app. The software provides direct access to the TraffiCalm driver feedback display's configurable features, day plans, schedules, and data captured by the sign. A layout of the sign programming home screen is shown in Figure 5. Detailed information on the software can be found in the user manual (*53*). The sign is programmed by clicking on "Edit Display" or from the "Edit" menu. The TraffiCalm signs allowed for programming different message displays based on four speed thresholds. For this study, the following message display settings were applied:

- "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, etc.) from activating the sign. For this study, the measured speed was displayed for vehicles exceeding the minimum speed.
- "Speed limit" was set to match the ramp advisory speed at the site. For this study, no additional change was made to the message display, and the measured speed was displayed for vehicles exceeding the speed limit.
- "Excess speed" was set to match the ramp advisory speed+10 mph at the site. For this study, the message was modified to include a "SLOW DOWN" message alternating with the measured speed at 1 hz cycles. To achieve this programming, the feedback message was set to flash mode, "Strobe" was ON, and "Strobe Modes" was set to SLOW DOWN. Please note that while a beacon/strobe was present as a part of the sign, it was not enabled during any portion of the testing.
- "Max speed" sets the maximum speed, beyond which the sign displays a blank screen or static "SLOW DOWN" or "TOO FAST" feedback message. For this study, the feedback panel was programmed to go blank for vehicles exceeding 85 mph. This strategy is used to prevent motorists from accelerating in an attempt to achieve high speed feedback values displayed on the sign.
- 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 to use 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.
- The color was set to amber for all speed levels. Furthermore, a brightness level of 3 was found to provide proper message visibility during both night and daytime.

Figure 5. TraffiCalm sign programming using SafetyCalm software

3.2.2 All Traffic Solution Sign

The DSFS from All Traffic Solution is programmed using TraffiCloud Sign Manager software provided by the sign vendor (*54*), which connects to the sign via laptop using USB, Bluetooth, serial port, or remotely from the TraffiCloud website. A typical layout of the sign homepage is shown in Figure 6. Once the sign is connected, it can be programmed as desired. For the purpose of this study, changes were made only to the sections that include:

- “Sign Mode”, which is a dropdown menu in the top left which includes eight sign programming modes: Display Off, Speed Limit Sign, Speed Display, Single Message, All Messages, Dependent Messages, Daily Schedules, and Weekly Schedules. For the purpose of this study, the sign was on “dependent messages” mode. This mode allows feedback messages to be programmed based on the approaching speed measured by the radar device.

- “Speed”, which are the data entry values below the “Sign Mode” menu. The speed limit was set to match the ramp advisory speed at the site, and the speed display was allowed from 15 mph to 85 mph, which matched the TraffiCalm sign programming. Radar sensitivity was kept at low (level 2), as this resulted in a detection range of approximately 600 ft for the passenger cars and even higher for the heavy vehicles.
- “Messages on sign”, which are the data entry values to the right of the “Speed” area. The messaging strategy can be programmed with a set number of conditions based on different speed bins from the “Messages on sign” section. This sign afforded greater flexibility in feedback messaging than the TraffiCalm sign, allowing for selection from a robust library of pre-set messages, in addition to custom text messages. This sign also affords the ability to define any number of messaging screens for each speed threshold that can be programmed to display in an alternating manner after a vehicle is detected. For this study, the sign was programmed to display a blank message for no vehicles (one screen), speed number only for vehicle speeds less than ramp advisory speed+10 mph (one screen), and speed number alternating with SLOW DOWN message for vehicle speed 10 mph or above the ramp advisory speeds (two screens). For the two-screen messages, the duration of each screen was set to 0.5 seconds to match the TraffiCalm programming.

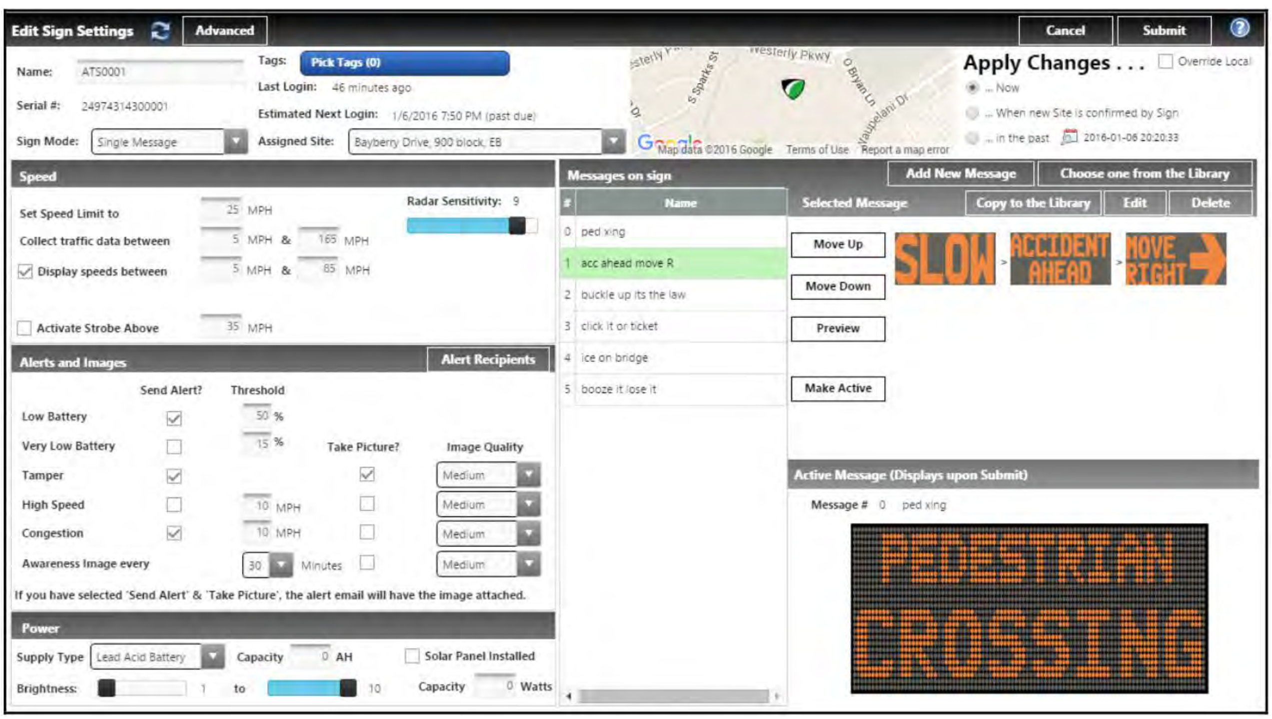


Figure 6. ATS sign programming using TraffiCloud sign manager software

3.3 Site Selection

Several potential candidate interchange ramps for the field evaluation were identified by the research team based on the following characteristics:

- Frequent lane departure ramp crashes (reported and/or on-site evidence of such),
- Posted ramp advisory speeds at or below 35 mph,
- Presence of existing MUTCD complaint curve warning devices,
- High ramp AADT, including a considerable proportion of trucks,
- DSFS sign installation capability, and
- Suitability for data collection.

A total of six interchange ramps were ultimately selected, including a balance between system and service interchanges. The general site characteristics and test conditions are displayed in Table 2. Five of the six sites were exit ramps, while the remaining ramp (Site 1) was a business route connection ramp onto a freeway. Although the primary intent of this study was to investigate the effects of DSFS at freeway exit ramps, this ramp was selected for the initial evaluation as it was completely isolated, thereby eliminating sign activations from non-ramp traffic.

Table 2. Interchange ramps selected for DSFS field evaluation

Site No.	Interchange Ramp Location	Speed Limit, Ramp Advisory Speed (mph)	Interchange Type	Test Conditions
1	EB I-69 to WB I-69	55, 30	System	Message type, sign location with respect to curve
2	WB I-96 to SB I-69	70, 30	System	Changes in sign effectiveness over time
3	NB US-127 to Round Lake Rd	75, 30	Service	Time of day, light condition, sign lateral position, sign activation range, sign size, sign border type
4	EB I-96 to 36th St	70, 20	Service	Sign location with respect to curve
5	NB US-127 to Dunckel Rd	70, 25	Service	Sign location with respect to curve, sign lateral position
6	EB I-96 to NB US-127	70, 25	System	Sign location with respect to curve, mainline speeds

Note: MUTCD-compliant signage, including W13-6, E5-1a, and W1-8R, were present at all sites during all phases.

Note that the mainline ran adjacent to the exit ramp at sites 2-6. While activation of the DSFS by the mainline vehicles occurred at these locations, in all cases, the feedback message reflected the ramp vehicle's speed immediately upon entering the radar detection range. This was partially due to the sign being positioned closer to ramp traffic than mainline traffic, but also the design of the radar detection algorithms, which prioritize vehicles near the center of the radar.

3.4 Data Collection Methods

Data were collected from each study location broadly in two phases: 1) under the existing site conditions without the DSFS present and 2) after the installation of the DSFS or after modifying the DSFS setup or operation. After collection of data under the existing site condition, the DSFS was first installed by MDOT crews on dual aluminum sign posts, with a 7-ft bottom mounting height from the pavement surface, and at an offset distance of approximately 12-ft from the near edge of the ramp travel way. The existing signage at each site was not modified in any way. Shortly after DSFS installation, the sign was programmed by the research team, and the accuracy of the displayed speed message was validated with a handheld LIDAR gun for a sample of vehicles. The sign remained operational for seven days prior to initiating data collection in order to allow for dissipation of any driver novelty effects associated with the new traffic control device. For each subsequent change to the DSFS condition, a period of two days was allowed to pass prior to data collection. The study utilized three different techniques for collection of vehicular speeds: 1) a series of high-definition video cameras, 2) handheld LIDAR, and 3) speed-trailer. Selection of the data collection technique was based on the site characteristics and types of data desired. The same data collection procedures were utilized across all data collection periods for a given evaluation. All data were collected under dry daylight conditions on weekdays between the hours of 10:00 AM and 4:00 PM, with the exception of the speed trailer, which collected data continuously. The following sections provide additional details of the data collection methods.

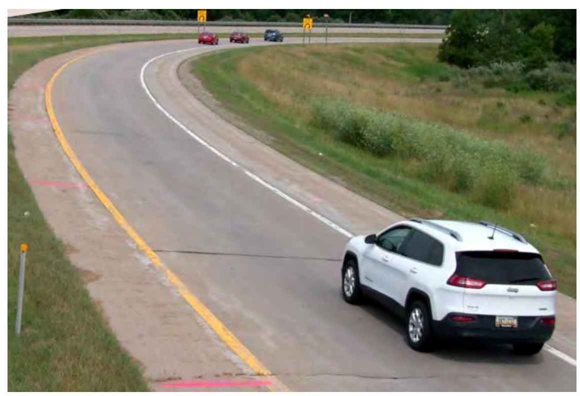
3.4.1 Data collection using cameras

This method, which was utilized as sites 1, 2, 3, and 4, involved temporary installation of a series of elevated high-definition video cameras mounted on aluminum poles that were temporarily attached to a roadside signpost behind the respective sign were used to collect the data. The cameras were elevated to a height of 15 feet and aimed towards a pre-determined location on the roadway. Each camera recorded approximately 3 hours of video per data collection period, after which they were removed from the site. Setup and removal of each camera/pole took approximately 5 minutes and the cameras were installed in the same locations to provide approximately identical views during each data collection period. A total of three cameras were utilized at each site, which were positioned to provide full visible coverage of vehicles approaching and entering the curve. The three setup locations, with examples displayed in Figure 7, included:

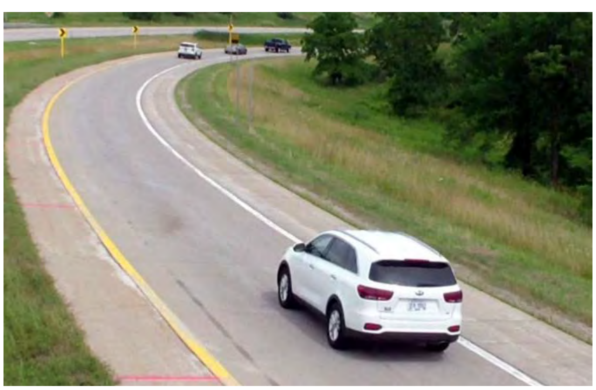
- Around 1,000 feet upstream of the PC and aimed downstream to provide coverage of the area upstream of the DSFS detection zone;
- Around 450 feet upstream of the PC and aimed downstream to provide coverage of the area where the DSFS typically became illuminated for approaching vehicles, in addition to the curve approach and entry; and
- Around 150 feet after the PC and aimed upstream to provide coverage of the entry to the curve and approximately 100 feet beyond the PC.

An example camera setup (middle location) is displayed in Figure 7 along with a screenshot of the general field of view provided by video from each of the three cameras.

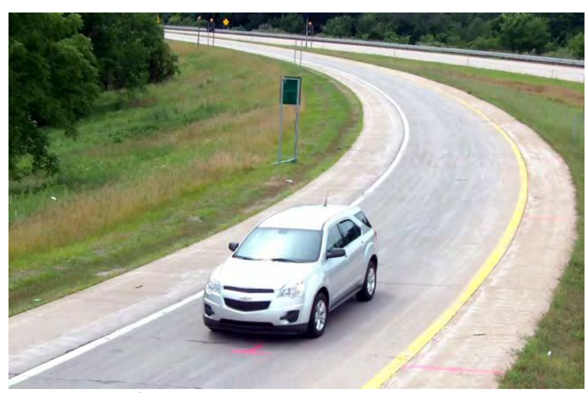
a. Example camera setup (middle location)



b. View from upstream camera



c. View from middle camera



d. View from curve camera

Figure 7. Example camera setup and field of view provided by each camera

After completion of the camera-based field data collection, the videos were manually reviewed by a team of trained technicians to assess various characteristics of driver behavior. The view afforded by the elevated camera setups allows direct observation of numerous vehicular and operational attributes, including vehicle type, headway, speed, deceleration rate, brake light indication, lateral positioning within the lane, and occurrence of edgeline or shoulder encroachments. Further, it was also possible to assess various additional aspects related to the DSFS and site condition from the videos, including location of the vehicle at DSFS message onset, DSFS message displayed to each approaching vehicle, traffic volumes, weather, and interference from vehicles parked on the shoulder.

The videos were reviewed and each vehicle was sequentially tracked through the videos across the three camera setups. Quicktime software was utilized, which allowed for frame-by-frame review to determine the relevant vehicular location and time information. The videos were recorded at a rate of 60 frames per second, allowing time to be recorded to the nearest 0.0167 seconds based on the frame number displayed in the video player. Paint marks placed on the shoulder at 50-ft intervals (visible in Figure 7) were used as field reference markers for determining the relative location of a vehicle with respect to the curve PC at any point in time. The following information was obtained from the videos for each vehicle traveling through the site:

- Time to traverse the following speed measurement zones:
  - 1000-ft upstream of the PC (prior to the DSFS detection area),
  - 400-ft upstream of the PC (after entering the DSFS detection area),
  - At curve PC, and
  - 100-ft after curve PC.
- Deceleration rate over the initial 100-ft beyond the PC,
- Time headway from the prior vehicle,
- Location (with respect to the PC) at the initial point of brake-light illumination,
- Whether a message was displayed on the DSFS, and
- Vehicle type:
  - Passenger vehicle (car, SUV, pickup, van, minivan, motorcycle) without trailer,
  - Passenger vehicle with trailer,
  - Tractor trailer truck, and
  - Single unit truck /bus/RV.

Lateral lane positioning information was also collected from the videos for vehicles entering the ramp curve during the initial evaluation at Site 1. The lateral lane positioning of vehicles upon curve entry was found to be consistent across all test conditions. Specifically, vehicles generally tracked to the right of center while traversing the curve, and no vehicles committed an encroachment onto the outer (left) edge line or shoulder. Thus, no further analysis of lateral lane positioning was performed during subsequent evaluations.

3.4.2 Data collection using LIDAR

This method, which was utilized at sites 3, 5, and 6, involved the use of handheld LIDAR guns to continuously track vehicle speeds along the entire exit ramp lane, beginning from the start of the upstream taper for the speed-change lane, and continuing to the curve entry point on the ramp. To track vehicles continuously over this distance, which typically exceeded 1,000 ft, a sequence of two handheld LIDAR guns operated by technicians from within separate vehicles parked just beyond the shoulder was used. The LIDAR guns utilized in this study were ProLaser III manufactured by Kustom Signals Inc. These devices are able to measure vehicular speed and distance three times per second with an accuracy of ±1 mph at a range of 6,000 ft. For purposes of this study, each LIDAR gun was typically only utilized over a range of 1,000 feet due sight limitations caused by geometry or encroachment of other vehicles.

Typically, the upstream and downstream LIDAR data collection vehicles were positioned on the roadside at strategic locations that were away from any critical speed measurement points (e.g., start of taper, feedback sign, start of the curve, etc.) to minimize influence of the data collection vehicle on drivers. A sample data collection setup is shown in Figure 8, where the upstream and downstream vehicles were positioned 1,350 ft and 500 ft, respectively, upstream of the PC. The GPS coordinates were recorded for each data collection vehicle, in addition to the distance to a common reference point, such as a permanent traffic sign. Data were collected from the same location for each test condition.

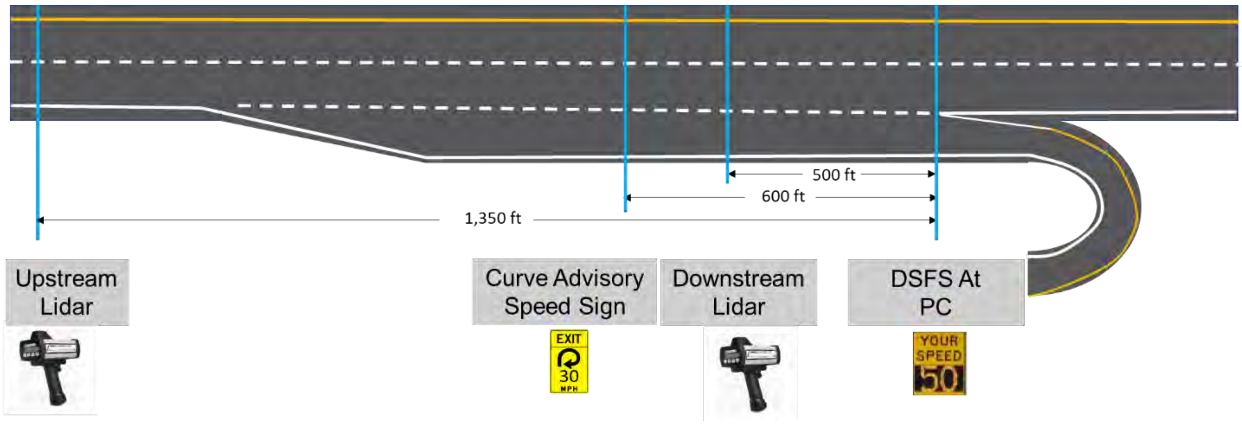
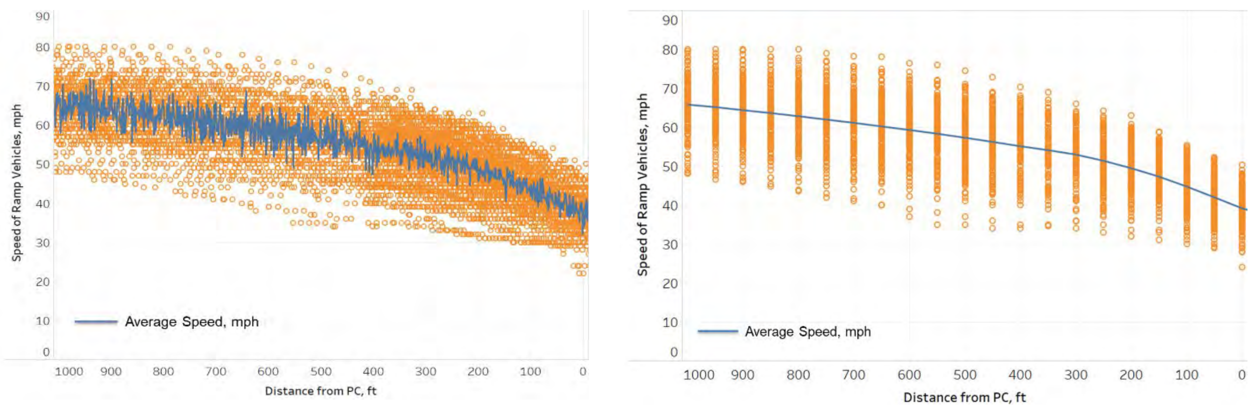


Figure 8. Typical two-person LIDAR data collection setup

The upstream data collector would begin to track each subject vehicle near the start of the taper for the auxiliary lane, and continue tracking at least 100 ft beyond the downstream LIDAR technician. At this point, the tracking responsibilities were then transferred to the downstream technician, who would track each subject vehicle over the remaining distance to slightly beyond the PC. The data collectors communicated via cellular communications to ensure a seamless "hand-off" of the LIDAR speed tracking as each subject vehicle proceeded along the ramp. In doing so, the upstream technician would convey the type and color of each subject vehicle to the downstream LIDAR collector. In order to isolate driver response to the speed feedback sign, only freely flowing vehicles (e.g., minimum 5 second headway) were included.

Each LIDAR gun was connected to a laptop using a data transfer cable, which allowed for all measurements to be recorded in real-time using proprietary software. The computer LIDAR recordings included timestamp, distance, and speed for each measurement. After completion of the LIDAR tracking for each subject vehicle, both data collectors entered remarks on the type and color of the vehicle, in addition to any other comments. This information was later used to combine the two data sets into a continuous speed profile for each subject vehicle approaching and entering the ramp curve. Collecting data using this LIDAR tracking method provides a significant advantage over cameras or pneumatic tubes, as it provides continuous speed measurements over the entire segment of interest, as opposed to spot speeds at fixed points.

After completion of the LIDAR tracking data collection from the field, both files from the upstream and downstream LIDAR collector were joined using vehicle sequence, type, and color. As the relative distances between the LIDAR collectors and the PC were known, all distances were converted to be relative to the PC. An example representation of the output of this process is shown in Figure 9a. Because LIDAR speeds can't be measured at the same locations on the roadway for every vehicle, it was necessary to convert this data to a series of spot speeds using an interpolation technique, thereby allowing speeds to be assessed at specific reference points. The combined raw data were linearly interpolated at 1-ft increments using the adjacent speeds. Interpolated speeds were then selected at every 50 ft interval starting from the PC, as shown in Figure 9b. Compiling the LIDAR data in this manner provides a robust array of spot speeds at numerous points along the ramp. The data were compiled separately for passenger cars and heavy vehicles (e.g. trucks and buses). Vehicles that were found to be missing data for substantial distances during the speed tracking process were excluded.



a. Raw LIDAR data (n=203 vehicles) **b. LIDAR data interpolated at 50-ft increments**

Figure 9. Raw and interpolated vehicle speed data from LIDAR

3.4.3 Data collection using speed trailer

Although collection of driver behavior data using video cameras and two-person LIDAR hand-off method afford vehicle tracking capabilities, their use is limited to daylight conditions and data extraction is very labor-intensive, which further limits sample sizes. Thus, in order to obtain a comprehensive sample of curve entry speeds across various times of day and light conditions, a speed data collection trailer was utilized at one site (Site 3: US127/Round Lake Rd) just beyond the right shoulder near the point of curvature (Figure 10). The speed trailer utilized an elevated side-firing Wavetronix SmartSensor HD radar unit, which was aimed and calibrated to continuously measure speed and length data for vehicles at the ramp curve entry point. Note that LIDAR speed data were also collected using the aforementioned methods during the DSFS evaluations performed at this site.

The speed trailer remained in a fixed position and continuously recorded data for the entire field test period. To limit data file size, the radar was programmed to bin data into 30-second intervals. To isolate free-flowing vehicles, the data were screened to include only those intervals that included a single vehicle. Further screening was conducted to remove potential mainline observations and other anomalies. Vehicle length information was utilized to distinguish between passenger vehicles and heavy vehicles. After an extensive reliability assessment of the vehicle length data, all vehicles with a length of 32 ft or less were considered as passenger vehicles, while the remainder were considered heavy vehicles.

Figure 10. Speed trailer at NB US-127 exit ramp to Round Lake Rd

3.5 Measures of Effectiveness and Analytical Methods

Several measures of effectiveness related to speed, deceleration rate, and initial braking location were analyzed to determine the effects of the various DSFS conditions and other factors. To determine any obvious trends in the data, sources for potential bias, and data distributions, a preliminary comparison of the descriptive statistics (i.e., mean, standard deviation, percentiles, etc.) and graphical representations (i.e., frequency distribution, box plot, scatterplot) for the vehicular data was performed across the data collection periods. From there, three primary behavioral measures of effectiveness (MOE) associated with the DSFS were analyzed using appropriate statistical procedures, which are described in greater detail in the paragraphs that follow. The MOE for these analyses included:

- Speed at PC (i.e., curve entry speed),
- Initial braking occurring between 200 and 600 ft upstream of the PC; this range was selected as it corresponded with the detection range of DSFS in the upstream position and afforded a comfortable braking distance prior to curve entry, and
- Curve entry speed within 15 mph of the curve advisory speed; this MOE was used to assess the effect of the DSFS at limiting excessive curve entry speeds.

The same general set of predictor variables were entered into all models and included: upstream approach speed (to control for general driver speed selection), DSFS test condition, and vehicle type (when separate models were not developed for different vehicle types). All analyses were performed using statistical software RStudio. Speeds were analyzed using multiple linear regression, while logistic regression was utilized to analyze the binary response variables, which included the probability of initial braking in advance of the curve and the probability of vehicles entering the curve at speeds exceeding 15 mph above the curve advisory speed. The general form of the multiple linear regression is shown in Equation 1:

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

where Y_i is the measured speed at the PC for vehicle i, X_{i1} to X_{ik} are independent variables affecting the dependent variables (including DSFS test condition), β_0 is an intercept, β_1 to β_k are estimated regression coefficients for each independent variable, and ε_i is a normally distributed error term with variance σ^2. When analyses were conducted using the data from multiple sites or from a single site on multiple dates, the linear regression included a random effect (intercept) term in the model, with the form shown in Equation 2:

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \cdots + \beta_k X_{ik} + \varepsilon_i + \delta_i \qquad (2)$$

where, δ_i term is a random intercept term. This accounts for unobserved factors affecting driver behavior between the data collection periods. A site-specific random intercept term was utilized when video speed data were collected from multiple sites to account for the unobserved differences between sites. As the speed trailer was only used at a single site for multiple days, a date-specific random intercept term was utilized for these models to account for unobserved day-to-day differences.

Binary logistic regression was utilized to analyze the binary response variables, which included the probability of braking 200-600 ft in advance of the curve and the probability of a vehicle entering the curve within 15 mph of the advisory speed. Binary logistic regression is a technique used to predict the probability of a dichotomous outcome based on values of a set of predictor variables (continuous or categorical) and is similar to linear regression except that the response variable is categorical rather than numeric. The binary logistic regression model has the form as shown in Equation 3:

$$Y_i = logit(P_i) = ln\left(\frac{P_i}{1 - P_i}\right) = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \cdots + \beta_k X_{ik} \quad (3)$$

where the response variable, Y_i, is the logistic transformation of the probability of vehicle *i* braking 200-600 ft in advance of the curve or entering the curve within 15 mph of the advisory speed. This probability is denoted as P_i. As in the linear regression model, X_{i1} to X_{ik} are independent variables affecting driver behavior (including DSFS test condition), β_0 is an intercept, β_1 to β_k are estimated regression coefficients for each independent variable.

4. EVALUATION OF MESSAGE TYPE AND LONGITUDINAL SIGN POSITION

4.1 Study Design and Site Characteristics

This initial field evaluation included an assessment of the general effectiveness of DSFS on driver behavior, in addition to assessment of various messaging strategies and longitudinal sign positioning relative to the curve. To control for external site biases, a single DSFS (15-inch TraffiCalm Sign) would be utilized at a single freeway interchange ramp (Site 1: EB I-69 to WB I-69) during this initial field evaluation. This site possessed an upstream speed limit of 55 mph and a curve advisory speed of 30 mph. Although the primary intent of this research was to investigate high speed to low speed transitions (e.g., freeway exit), this particular entrance ramp was selected for the initial evaluation as it was completely isolated, thereby eliminating sign activations from non-ramp traffic. Existing 60-inch by 48-inch "EXIT 30 MPH" (W13-6a) signs with overhead beacons were present on both sides, approximately 450-ft upstream of the curve, and chevrons were present within the curve. A plan view of the study site, including the three DSFS locations is provided in Figure 11.

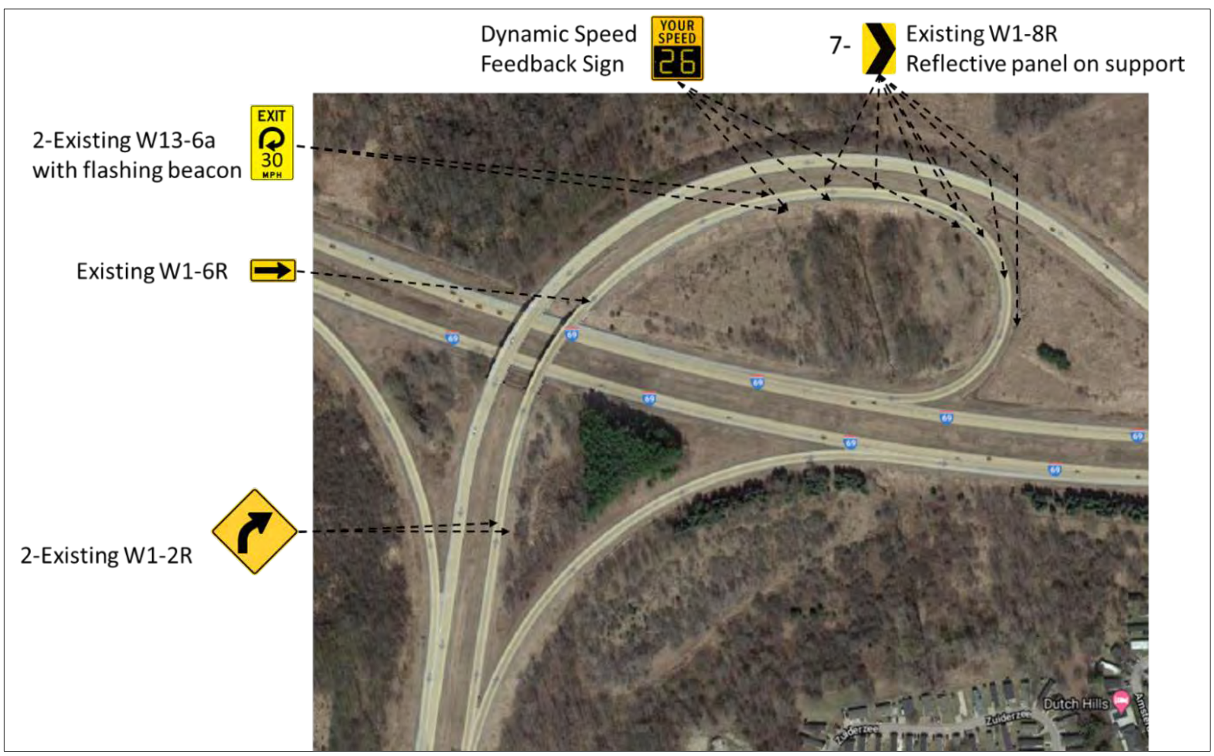


Figure 11. EB Business I-69 ramp to WB I-69 (Site 1)

Three feedback messaging strategies were evaluated at three sign positions in advance of the curve, as follows:

- DSFS feedback messages:
    - Message Strategy 1: Display the measured speed.
    - Message Strategy 2:
        - For speeds at or below 40 mph (i.e., advisory speed + 10 mph), display the measured speed;
        - For speeds above 40 mph, display the measured speed alternating with a "SLOW DOWN" message on 1 hz cycles. This messaging strategy followed the current MDOT draft special provision for DSFS.
    - Message Strategy 3: Same feedback message as Strategy 2, but with a 30-inch square advisory speed panel (black text on fluorescent yellow reflective sheeting) mounted immediately below the speed feedback sign. Although oversized advance warning signs displaying the 30 mph advisory speed along with flashing beacons existed on the approach to the curve, it was hypothesized that reinforcement of the curve advisory speed may improve driver response to the approaching curve.
- DSFS longitudinal position relative to the curve (see Figure 12):
    - Location 1: At the point of curvature (PC)
    - Location 2: 255-ft upstream of the PC, to correspond with the minimum braking distance necessary to accommodate deceleration at 11.2 ft/s^2 from the 85^{th} percentile speed (measured as 53 mph) to the 30 mph advisory speed upon entry to the curve, plus a 1 second perception-reaction time.
    - Location 3: 400-ft upstream of the PC and hung under the existing right most flashing "EXIT 30 MPH" warning sign.

a. DSFS at Point of Curvature

b. DSFS 255 ft Upstream of Curve (with 30 mph Advisory Speed Panel)

c. DSFS 450 ft Upstream of Curve (Under Existing Curve Warning Sign)

Figure 12. Example DSFS messaging conditions and installation locations (Site 1)

In order to test the effects of the three messaging strategies at each of the three sign locations compared to the existing condition without the DSFS, a total of nine data collection periods were required. Note that because the DSFS was positioned under the existing ‘‘EXIT 30 MPH’’ sign at the 450 ft upstream location, it was not possible to test the DSFS without the advisory speed at this position. Thus, a total of eight DSFS messaging and sign positioning combinations were tested and compared with the existing site condition without the DSFS.

Existing condition without the DSFS data were collected both before the installation of the DSFS and after completing data collection with all other test conditions. The order of the sign test conditions and corresponding data collection periods were as follows:

1. Existing site condition prior to DSFS installation,
2. DSFS at PC with speed number feedback only,
3. DSFS at PC with speed number alternating with SLOW DOWN message (Figure 12a),
4. DSFS at PC with speed number alternating with SLOW DOWN message and advisory speed panel,
5. DSFS at 255 feet upstream of PC with speed number alternating with SLOW DOWN message and advisory speed panel (Figure 12b),
6. DSFS 255 feet upstream of PC with speed number alternating with SLOW DOWN message,
7. DSFS 255 feet upstream of PC with speed number feedback only,
8. DSFS 400 feet upstream of PC with speed number feedback and advisory speed panel,
9. DSFS 400 feet upstream of PC with speed number alternating with SLOW DOWN message and advisory speed panel (Figure 12c), and
10. Existing site condition after completion of all the data collection with the DSFS.

4.2 Data Summary

Driver behavior data were collected using a series of three elevated high-definition video cameras mounted on aluminum poles that were temporarily attached to a roadside signpost. The videos were reviewed using QuickTime software and each vehicle was sequentially tracked through the videos across the three camera setups. The vehicular observation data were then tabulated, organized, and coded into a single data file for detailed analysis. The initial data set included complete records for 3,442 vehicles collected across the ten data collection periods. To eliminate the effects of platooning, vehicles with headways below 3.0 seconds were excluded from further analysis. Furthermore, the six cases where no message was displayed on the DSFS were also removed from the dataset. Table 3 presents the descriptive statistics for each variable included in the final dataset, which included 2,212 vehicles.

Table 3. Descriptive statistics (Site 1)

Variable	Unit	Min	Max	Mean	Std. Dev
Speed 1000 ft Upstream of the PC	mph	30.080	77.187	47.957	5.388
Speed at PC	mph	26.914	63.920	42.323	5.159
Speed <45 mph at PC (1 = yes)		0	1	0.742	0.438
Braking first initiated 200-600 ft prior to PC (1 = yes)		0	1	0.238	0.426
Existing site condition (No DSFS)		0	1	0.168	0.374
DSFS at PC with:					
Speed number only		0	1	0.121	0.326
Speed number alternating with slow down message		0	1	0.113	0.317
Speed number alternating with slow down message plus advisory speed panel		0	1	0.103	0.304
DSFS at 255 ft upstream with:					
Speed number only		0	1	0.094	0.291
Speed number alternating with slow down message		0	1	0.082	0.275
Speed number alternating with slow down message plus advisory speed panel		0	1	0.086	0.280
DSFS at 450 ft upstream with:					
Speed number and advisory speed panel		0	1	0.120	0.325
Speed number alternating with slow down message plus advisory speed panel		0	1	0.113	0.316
Passenger Vehicle Without Trailer		0	1	0.909	0.287
Passenger Vehicle With Trailer		0	1	0.029	0.168
Tractor Trailer Truck		0	1	0.025	0.156
Single Unit Truck/Bus/RV		0	1	0.037	0.189

N = 2,212 vehicles

4.3 Results and Discussion

Preliminary models suggested large differences in the speeds of passenger vehicles and heavy vehicles. As a result, separate models were generated for passenger vehicles, single-unit trucks/buses, and tractor-trailer trucks. For the passenger vehicle models, DSFS test conditions (e.g., sign message and position) were included as separate binary variables and evaluated against the existing site condition without the DSFS. However, for the heavy vehicle models, because of small sample sizes, the DSFS was evaluated as a single binary variable (No DSFS and with DSFS) combined across all test conditions.

Three measures of effectiveness related to speed and initial braking location were analyzed to determine the effects of the various DSFS conditions and other factors. The dependent variables for these analyses included:

- Speed at the PC (curve entry),
- Probability of initial braking occurring between 200 and 600 ft upstream of the PC, and
- Probability of a vehicle entering the curve below 45 mph.

The linear regression results for curve entry speeds (e.g., at the PC) are displayed for each vehicle type in Table 4. The logistic regression results for the probability of initial braking in advance of the curve and the probability of vehicles entering the curve at speeds below 45 mph are displayed in Tables 5 and 6. Further discussion is provided in the following sections.

4.3.1 Curve entry speeds

A review of the parameter estimates in Table 4 indicates that curve entry speeds were generally lower across all DSFS test conditions and vehicle types compared to the site without the DSFS. Also, as expected, the speed of vehicles measured 1,000 ft prior to the curve was strongly correlated with the speed at the point of curvature for each of the speed models. This finding is aligned with prior research and suggests that faster drivers tended to maintain such behaviors regardless of the DSFS characteristics. Further discussion of the primary variables of interest, including sign position, messaging strategy, and vehicle type is provided in the sections that follow.

Table 4. Multiple linear regression results for curve entry speed (Site 1)

Passenger Vehicles (N=2,075)				
Parameter	**Estimate**	**Std. Error**	**t-value**	**p-value**
Intercept	13.126	0.787	16.680	<0.001
Speed 1000 ft Upstream of the PC	0.626	0.016	40.144	<0.001
Passenger Vehicle without Trailer	*Base Condition*			
Passenger Vehicle with Trailer	-1.615	0.471	-3.432	<0.001
Existing Site Condition (No DSFS)	*Base Condition*			
DSFS at PC with:				
Speed number only	-0.681	0.302	-2.252	0.024
Speed number alternating with slow down message	-1.076	0.310	-3.475	0.001
Speed number alternating with slow down message plus advisory speed panel	-0.879	0.323	-2.723	0.007
DSFS at 255 ft upstream of PC with:				
Speed number only	-0.544	0.329	-1.654	0.098
Speed number alternating with slow down message	-1.472	0.343	-4.290	<0.001
Speed number alternating with slow down message plus advisory speed panel	-1.220	0.336	-3.628	<0.001
DSFS at 450 ft upstream of PC with:				
Speed number and advisory speed panel	-0.011	0.303	-0.038	0.970
Speed number alternating with slow down message plus advisory speed panel	-0.501	0.312	-1.604	0.109
Single Unit Trucks and Buses (N=82)				
Parameter	**Estimate**	**Std. Error**	**t-value**	**p-value**
Intercept	11.168	3.418	3.267	0.002
Speed 1000 ft Upstream of the PC	0.638	0.076	8.371	<0.001
Existing Site Condition (No DSFS)	*Base Condition*			
With DSFS in Operation	-1.541	0.964	-1.599	0.114
Tractor Trailer Trucks (N=55)				
Parameter	**Estimate**	**Std. Error**	**t-value**	**p-value**
Intercept	26.306	4.147	6.343	<0.001
Speed 1000 ft Upstream of the PC	0.314	0.093	3.365	0.001
Existing Site Condition (No DSFS)	*Base Condition*			
With DSFS in Operation	-5.070	1.212	-4.183	<0.001

Response Variable = Speed at Point of Curvature (PC)

R^2 = 0.459 (Passenger Vehicles), R^2 = 0.458 (Single Unit Trucks and Buses), R^2 = 0.365 (Tractor Trailer Trucks)

4.3.1.1 Effect of DSFS Position

In terms of the sign position, the DSFS had the greatest effect on curve entry speeds for passenger vehicles when located 255 ft upstream of the point of curvature. As noted previously, this sign position corresponded to the minimum AASHTO braking distance to achieve the 30 mph curve advisory speed, plus a 1 second perception-reaction time. With the DSFS installed 255 ft upstream of the curve, depending on the messaging strategy, the curve entry speeds were 0.54 to 1.47 mph lower than when the DSFS was not present. The sign was only slightly less effective when positioned directly at the point of curvature, as the curve entry speeds were 0.68 to 1.08 mph lower than when the DSFS was not present. The DSFS did not have a significant effect on curve entry speeds when installed at the position that was furthest upstream of the curve (450 ft). Figure 13 provides a graphical representation of the DSFS marginal effects on curve entry speeds (passenger vehicles only) across the sign positions and messaging strategies.

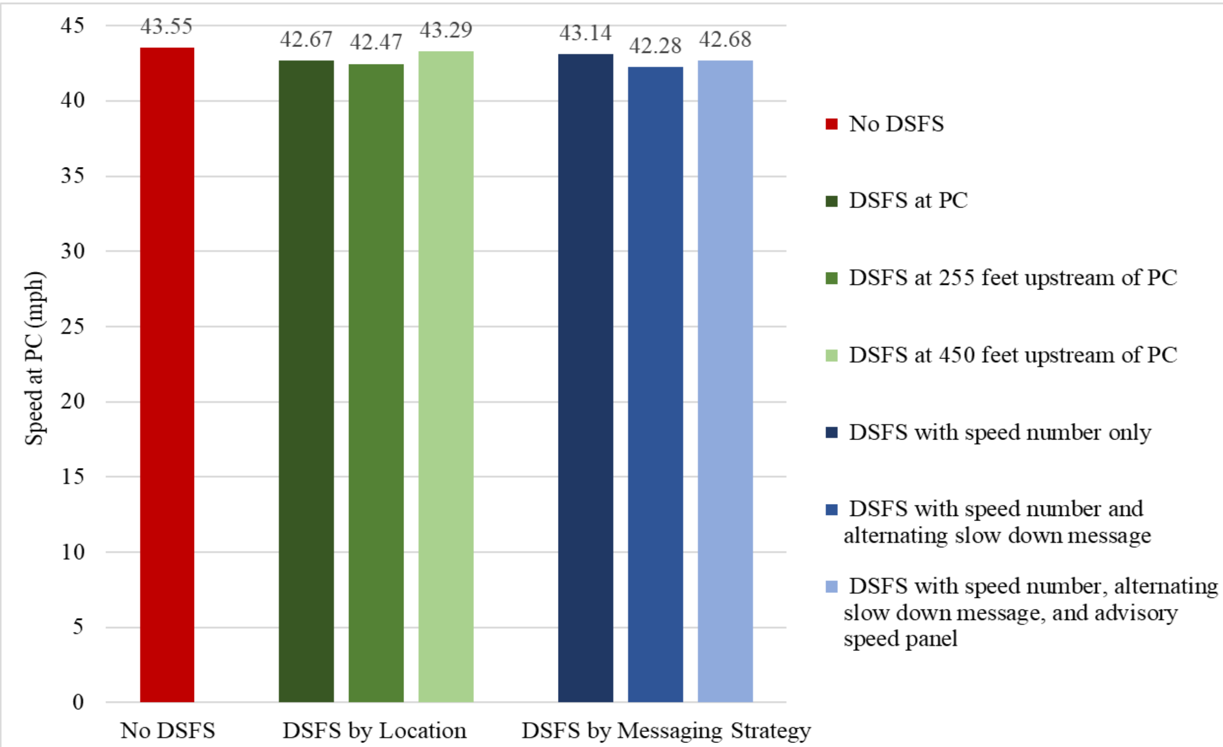


Figure 13. Mean curve entry speeds by DSFS position and messaging strategy (passenger vehicles only)

4.3.1.2 Effect of DSFS Messaging Strategy

Turning to the effects of the messaging strategy, the DSFS had the greatest effect on curve entry speeds when displaying the speed number combined with an alternating SLOW DOWN message for vehicles that were 10 mph over the advisory speed. The inclusion of an advisory speed panel with the DSFS did not substantively change this effect. However, the removal of the SLOW DOWN message, such that only the speed digits were displayed as feedback, significantly degraded this effect to the point where the curve entry speeds were only marginally lower than without the DSFS installed.

4.3.1.3 Effect of Vehicle Type

The effectiveness of the DSFS at reducing curve entry speeds varied greatly by vehicle type. While passenger vehicles showed curve entry speeds that, depending on sign position and message strategy, were generally on the order of 0.5 to 1.5 mph lower with the DSFS installed at the site, the sign had an even greater effect on heavy vehicles, especially tractor-trailer trucks. For single-unit trucks and buses, curve entry speeds were, on average, 1.54 mph lower with the DSFS installed than without the DSFS. However, for tractor-trailer trucks, curve entry speeds were 5.07 mph lower when the DSFS was operating at the site. Due to the relatively small sample sizes of heavy vehicles, it was not possible to test the effects of DSFS messaging strategies or position with respect to the curve. Finally, the impact of the DSFS on curve entry speeds for passenger vehicles was not affected by whether the vehicle was towing a trailer. Figure 14 provides a graphical representation of the DSFS marginal effects on curve entry speeds across the three primary vehicle type categories.

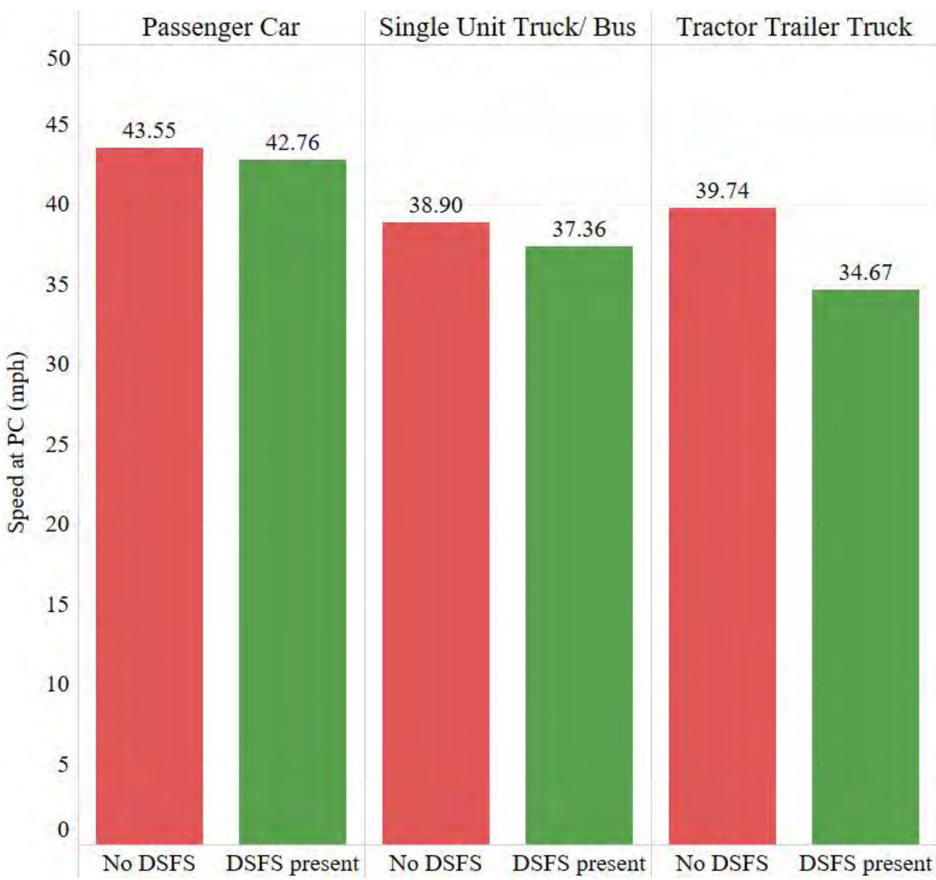


Figure 14. Mean curve entry speeds by DSFS presence and vehicle type

4.3.2 Extreme curve entry speeds

It was also important to assess the impacts of the DSFS on extreme curve entry speeds, which for purposes of this study, were defined as speeds that were in excess of 45 mph (e.g., 15 mph above the posted advisory speed of 30 mph). To simplify the interpretation of the results with respect to the DSFS condition, the logistic regression models were formulated to estimate the probability of a vehicle entering the curve below 45 mph.

Table 5. Binary logistic regression results for curve entry speed < 45 mph (Site 1)

Passenger Vehicles (N=2,075)					
Parameter	**Estimate**	**Std. Error**	**t-value**	**p-value**	**Exp(B)**
Intercept	15.047	0.778	19.339	<0.001	3426329
Speed 1000 ft Upstream of the PC	-0.290	0.015	-19.020	<0.001	0.748
Passenger Vehicle without Trailer	*Base Condition*				
Passenger Vehicle with Trailer	0.719	0.511	1.405	0.160	2.052
Existing Site Condition (No DSFS)	*Base Condition*				
DSFS at PC with:					
Speed number only	0.222	0.207	1.075	0.282	1.249
Speed number alternating w/slow down message	0.537	0.219	2.453	0.014	1.711
Speed number alternating w/slow down message plus advisory speed panel	0.522	0.228	2.290	0.022	1.686
DSFS at 255 ft upstream of PC with:					
Speed number only	0.133	0.237	0.562	0.574	1.142
Speed number alternating w/slow down message	0.933	0.271	3.450	0.001	2.543
Speed number alternating w/slow down message plus advisory speed panel	0.485	0.240	2.020	0.043	1.624
DSFS at 450 ft upstream of PC with:					
Speed number and advisory speed panel	0.266	0.210	1.268	0.205	1.305
Speed number alternating w/slow down message plus advisory speed panel	0.335	0.225	1.490	0.136	1.398
Single Unit Trucks and Buses (N=82)					
Parameter	**Estimate**	**Std. Error**	**t-value**	**p-value**	**Exp(B)**
Intercept	11.646	4.454	2.615	0.009	114233
Speed 1000 ft Upstream of the PC	-0.206	0.091	-2.269	0.023	0.814
Existing Site Condition (No DSFS)	*Base Condition*				
With DSFS in Operation	0.749	0.961	0.779	0.436	2.114

Response Variable = Speed <45 mph at Point of Curvature (PC)

Note: all tractor-trailer trucks were below 45 mph at point of curvature and, as a consequence, were not analyzed.

The parameter estimates in Table 5 indicate that the likelihood of a vehicle entering the curve below 45 mph was generally greater across all DSFS test conditions and vehicle types compared to the site without the DSFS. Vehicles entering the curve with the DSFS present were 1.14 to 2.54 times more likely to enter the curve at a speed below 45 mph compared to the site without the DSFS. In terms of the sign position, the DSFS had the greatest effect on extreme curve entry speeds when located either at the point of curvature or 255 ft upstream of the point of curvature. Further, the most effective DSFS message included the speed number combined with an alternating SLOW DOWN message for vehicles that were 10 mph over the advisory speed. Considering vehicle type, the DSFS produced a greater reduction in extreme curve entry speeds when the vehicle was a single unit truck or bus. It was not possible to assess the effect on drivers of tractor-trailer trucks, as all possessed curve entry speeds that were below 45 mph.

4.3.3 Initial braking location

The parameter estimates in Table 6 indicate that the presence of the DSFS generally led to a greater occurrence of braking between 200 and 600 ft prior to the curve, which was considered the optimal range from a driver comfort standpoint. Further discussion of the effects of sign location and vehicle type is provided in the sections that follow. Note that no consistent trends related to the sign message were observed.

4.3.3.1 Effect of DSFS Position

Not surprisingly, the DSFS position affected the occurrence of braking within this comfortable range, which was greatest when the DSFS was positioned 255 ft upstream of the curve. Specifically, when the DSFS was present at this location, drivers were 1.83 to 2.72 times more likely to begin braking 200 to 600 ft upstream than when the DSFS was not present. The DSFS had the weakest effect on braking location when positioned at the point of curvature.

4.3.3.2 Effect of Vehicle Type

The effectiveness of the DSFS at influencing the initial braking location varied greatly by vehicle type. In general, the greater the vehicle size, the more effective the DSFS was at prompting braking within the 200 to 600 ft comfort range in advance of the curve. While drivers of passenger vehicles were 1.19 to 2.72 times more likely to initiate braking within the comfort range with the DSFS present than without, the sign had an even greater effect on heavy vehicles, especially tractor-trailer trucks. Specifically, drivers of single-unit trucks and buses were 1.75 times more likely to begin braking 200 to 600 ft upstream of the curve when the DSFS was present, while drivers of tractor-trailer trucks were 3.30 times more likely to begin braking in that range. Due to the relatively small sample sizes of heavy vehicles, it was not possible to test the effects of DSFS position or messaging strategies.

Table 6. Binary logistic regression results for braking 200-600 ft prior to the curve (Site 1)

Passenger Vehicles (N=2,075)					
Parameter	**Estimate**	**Std. Error**	**t-value**	**p-value**	**Exp(B)**
Intercept	-4.408	0.532	-8.280	<0.001	0.012
Speed 1000 ft Upstream of the PC	0.057	0.010	5.552	<0.001	1.059
Passenger Vehicle without Trailer	*Base Condition*				
Passenger Vehicle with Trailer	0.423	0.296	1.427	0.154	1.526
Existing Site Condition (No DSFS)	*Base Condition*				
DSFS at PC with:					
Speed number only	0.294	0.210	1.404	0.160	1.342
Speed number alternating w/slow down message	0.177	0.219	0.807	0.420	1.194
Speed number alternating w/slow down message plus advisory speed panel	0.194	0.227	0.854	0.393	1.214
DSFS at 255 ft upstream of PC with:					
Speed number only	0.603	0.220	2.742	0.006	1.827
Speed number alternating w/slow down message	1.000	0.218	4.588	<0.001	2.717
Speed number alternating w/slow down message plus advisory speed panel	0.768	0.217	3.531	<0.001	2.155
DSFS at 450 ft upstream of PC with:					
Speed number and advisory speed panel	0.318	0.210	1.512	0.130	1.375
Speed number alternating w/slow down message plus advisory speed panel	0.750	0.206	3.634	<0.001	2.117
Single Unit Trucks and Buses (N=82)					
Parameter	**Estimate**	**Std. Error**	**t-value**	**p-value**	**Exp(B)**
Intercept	0.695	2.137	0.325	0.745	2.004
Speed 1000 ft Upstream of the PC	-0.047	0.049	-0.967	0.333	0.954
Existing Site Condition (No DSFS)	*Base Condition*				
DSFS in Operation	0.560	0.637	0.878	0.380	1.750
Tractor Trailer Trucks (N=55)					
Parameter	**Estimate**	**Std. Error**	**t-value**	**p-value**	**Exp(B)**
Intercept	-4.083	3.184	-1.283	0.200	0.017
Speed 1000 ft Upstream of the PC	0.053	0.069	0.770	0.442	1.055
Existing Site Condition (No DSFS)	*Base Condition*				
With DSFS in Operation	1.193	1.133	1.054	0.292	3.298

Response Variable = Braking Initiated 200-600 ft Prior to Curve

4.4 Conclusion and Direction for Further Evaluation

This initial evaluation was utilized to assess the impacts on driver speed selection and braking associated with various DSFS messaging strategies and longitudinal positions of the sign relative to the ramp curve. The evaluation was performed at a single ramp and included three DSFS messaging strategies (speed number only, speed number alternating with SLOW DOWN message, and inclusion of an auxiliary advisory speed panel), as well as at three sign positions (point of curvature, 255 ft upstream of the curve, and 450 ft upstream of the curve).

Compared to the existing site condition, the DSFS reduced curve entry speeds and improved brake response across all test conditions, particularly for heavy trucks. Overall, considering the combination of both sign position and feedback messaging strategy, the greatest benefits to driver behavior were attained when the DSFS was positioned within approximately 250 ft of the curve and the feedback message included the speed number alternating with a SLOW DOWN message for vehicles that were greater than 10 mph over the curve advisory speed. This sign location corresponded to the minimum AASHTO braking distance to accommodate comfortable deceleration from the 85th percentile approach speed to the curve advisory speed (plus a 1 second perception-reaction time) upon entry to the curve. The inclusion of an advisory speed panel with the DSFS did not have a substantive impact on driver behavior.

The results of this preliminary evaluation were useful for determining effective messaging strategies and longitudinal sign positions for subsequent evaluation at additional locations, particularly at high speed freeway exit ramps and including system and service interchanges. It is also important to test the DSFS at locations where the freeway mainline runs adjacent to the ramp in order to determine the effect of mainline vehicles on sign activation and message display.

5. EVALUATION OF LONGITUDINAL SIGN POSITION, INTERCHANGE TYPE, AND TIME OF DAY

5.1 Study Design and Site Characteristics

Following the encouraging results of the initial DSFS evaluation at Site 1, a series of subsequent field evaluations were conducted at three freeway exit ramps possessing significant horizontal curvature. This series of evaluations tested the effectiveness of the feedback sign across various sign positions (at the point of curvature vs. 350 ft upstream), interchange types (system vs. service), times-of-day (peak vs. off-peak), light conditions (daylight vs. darkness), and vehicle types (passenger vehicles vs. trucks). Three exit ramp locations were selected for this study, which included westbound (WB) I-96 to southbound (SB) I-69 (Site 2), northbound (NB) US-127 to Round Lake Road (Site 3), and eastbound (EB) I-96 to 36th Street (Site 4). The same 15-inch TraffiCalm sign that was utilized in the preliminary evaluation was also utilized at each of the three exit ramp locations. To further confirm the effect of sign position, the DSFS was positioned at the PC at Sites 2 and 3 and 350 feet upstream of the PC at Site 4. Furthermore, Site 2 was a system (freeway-to-freeway) interchange, while Sites 3 and 4 were service (freeway-to-crossroad) interchanges, which further allowed for the assessment of differences in behavioral effects between the interchange types. Finally, time-of-day and light condition effects were assessed by using a data collection trailer to measure curve entry speeds before and after installation of the DSFS at Site 3. Detailed information on the three study sites, DSFS positions and feedback messaging strategy are provided in Table 7. Plan views of the three study sites, including the DSFS positions, are provided in Figures 15, 16, and 17, respectively.

One aspect that remained consistent between the three locations was the sign messaging strategy. During all test conditions, the DSFS was programmed to display the speed of vehicles that were approaching below 40 mph, alternating with a SLOW DOWN message at 0.5-sec intervals for vehicles traveling 40 mph and above. This messaging strategy followed the current MDOT draft special provision for DSFS and was found to provide the greatest impact on driver behavior in the initial field study. A standard advisory speed panel was also installed with the DSFS at Site 2. However, the use of an advisory speed panel was not found to impact the effectiveness of the DSFS during the initial field study.

Table 7. Site characteristics and DSFS test conditions

No	Location	Mainline Speed Limit/Ramp Advisory Speed (mph)	Interchange Type	Feedback Message	DSFS Position
2	WB I-96 to SB I-69	70/30	System	Speed number with alternating "Slow Down" message and advisory speed panel	PC
3	NB US-127 to Round Lake Rd	75/30	Service	Speed number with alternating "Slow Down" message	PC
4	EB I-96 to 36th St	70/20	Service	Speed number with alternating "Slow Down" message	350 feet upstream of PC

Note: PC = point of curvature. Speed data collection trailer was utilized at Site 3.

Figure 15. WB I-96 exit ramp to SB I-69 (Site 2)

Figure 16. NB US-127 exit ramp to Round Lake Rd (Site 3)

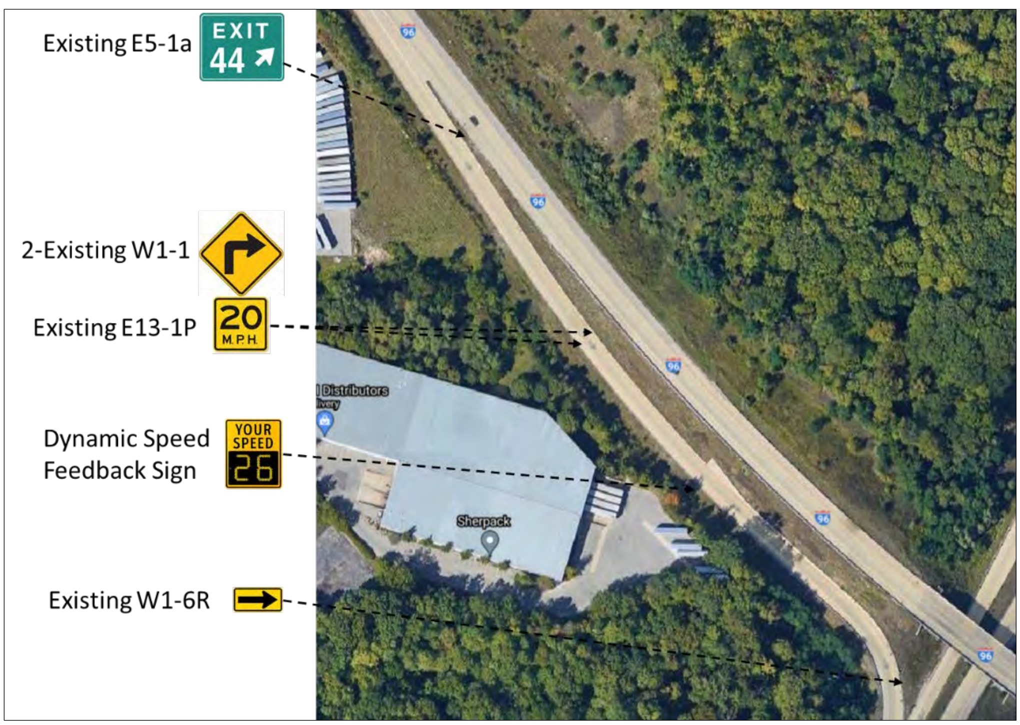


Figure 17. EB I-96 exit ramp to 36th St (Site 4)

5.2 Data Summary

Data were collected from each study location in two phases: 1) under the existing site conditions without the DSFS present and 2) after the installation of the DSFS. Data were primarily collected using a series of pole mounted cameras from the three sites. However, the speed trailer was deployed at Site 3 to continuously collect data for a longer period.

5.2.1 Speed data from video cameras

A series of three pole-mounted high-definition video cameras were installed at various points on the approach to and within the curve. The video data collected from three sites were combined, organized, and coded into a single file for detailed analysis. The data set was screened to include only vehicle observations with a headway of 3 seconds or greater to eliminate the effects of vehicle platooning. Cases where no feedback message was displayed on the DSFS for an approaching vehicle were also removed from the dataset. The final combined data set included a complete record for 1,758 vehicle observations collected from three sites. It should be noted that brake light data could not be discerned from one data collection period due to a slight misalignment of the camera, which reduced the sample size for the braking data to 1,651. Table 8 shows the descriptive statistics of the data collected using cameras from three test sites.

Table 8. Descriptive statistics: video camera data (Sites 2-4)

Video Camera Data (N = 1,758)					
Variable	**Unit**	**Min**	**Max**	**Mean**	**Std Dev**
Speed 1000 feet upstream of the PC	mph	30.303	83.832	58.949	7.701
Speed at PC (i.e., curve entry speed)	mph	17.045	57.273	38.388	5.496
Speed within 15 mph of advisory speed (1-Yes, 0-No)		0	1	0.656	0.475
Braking first initiated 200-600 ft prior to PC (1-Yes, 0-No)		0	1	0.321	0.467
Passenger vehicle without trailer		0	1	0.820	0.385
Passenger vehicle with trailer		0	1	0.018	0.132
Single unit truck/bus/RV		0	1	0.039	0.194
Tractor-trailer truck		0	1	0.123	0.329
Existing site condition (No DSFS)		0	1	0.557	0.497
DSFS at point of curvature - I-96/I-69		0	1	0.136	0.343
DSFS at point of curvature - US-127/Round Lake		0	1	0.133	0.340
DSFS at 350 ft upstream of point of curvature - I-96/36th		0	1	0.173	0.379

5.2.2 Speed data from speed trailer

To obtain a comprehensive sample of curve entry speeds across various times of day and light conditions, a speed data collection trailer was positioned at Site 3 (NB US-127 to Round Lake Rd) just beyond the right shoulder near the point of curvature. The speed trailer remained in a fixed position and continuously recorded data for a 36 day period. Data were collected under the existing site condition, without the DSFS, for the initial 20 days. The DSFS was then installed at the point of curvature (in front of the speed trailer), and the speed trailer remained operational for an additional 16 days. Figure 18 displays the DSFS and speed trailer installed at Site 3.

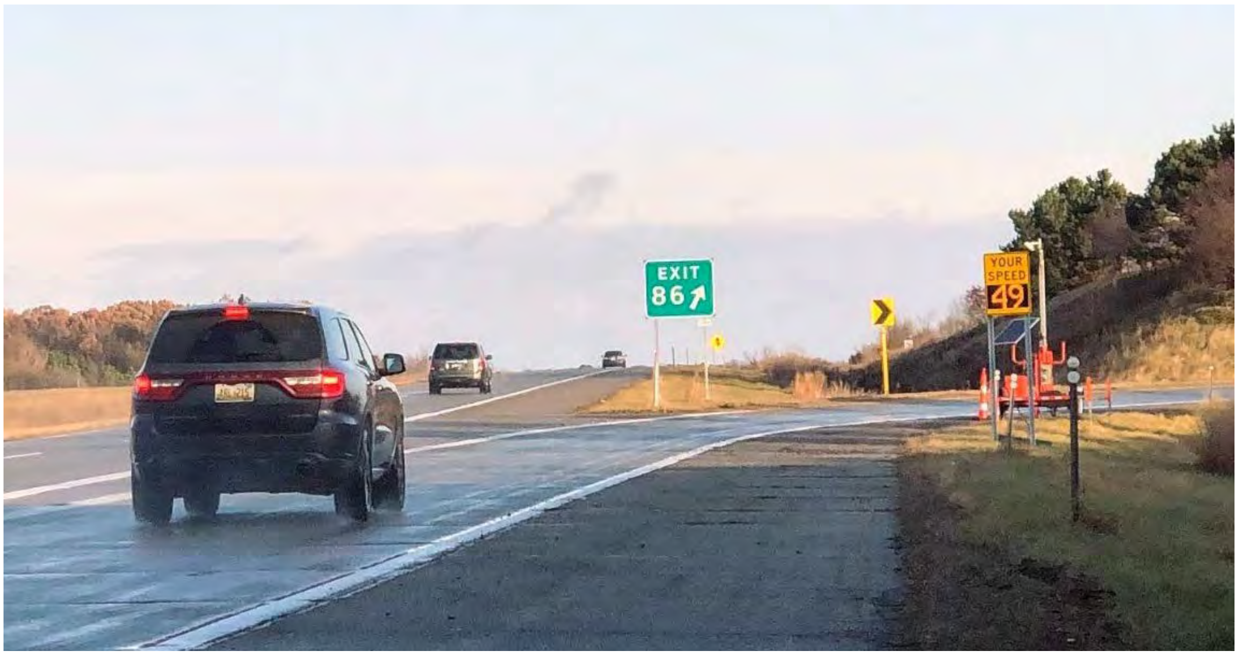


Figure 18. DSFS and speed trailer at US-127 exit to Round Lake Rd

To isolate free-flowing vehicles, all the speed-trailer data were screened to include only those intervals (30-second) that included a single vehicle. A total of 17,433 vehicles were included in the final dataset for further analysis. The dataset included 16,839 passenger vehicles and 594 heavy vehicles, which were defined in this study as vehicles longer than 32 feet. To account for changes in weather at the site, weather condition data were collected from a nearby National Weather Service station and combined with the speed data. Furthermore, sunrise and sunset data were also included to determine any differential effects of the DSFS on curve entry speeds under varied lighting conditions. The initial analysis found curve entry speeds to vary widely during poor weather conditions, including rain, sleet, ice, and snow. This is not surprising, but it is difficult to characterize the impacts on visibility and pavement surface during such conditions. Thus, the speed trailer data were limited to only those periods that occurred during clear, cloudy, or fair conditions. Using the timestamps of each data bin, the speed trailer data were also coded for further analysis based on times-of-day (peak vs. off-peak) and light conditions (daylight vs.

darkness). For this study, the peak period was defined as 7:00 – 9:00 AM and 3:30 to 6:00 PM. Daylight and darkness were coded based on sunrise (between 7:19 and 8:00 AM) and sunset (between 5:05 and 5:26 PM) for each day during the data collection period. The data were then classified for analytical purposes as follows: peak, daytime off-peak, and nighttime. Thus, all daytime off-peak occurred during daylight periods, all nighttime occurred during dark periods, while peak included a mix of daylight, twilight, and dark periods. In using this coding structure, it was possible to assess whether the DSFS had a variable effect on the behavior of peak (e.g. commuter) vs. off-peak drivers and during different lighting conditions. Table 9 presents the descriptive statistics of the combined dataset that 17,433 observations from the speed trailer.

Table 9. Descriptive statistics: speed trailer data (Site 3)

Speed Trailer Data (N = 17,433)					
Variable	**Unit**	**Min**	**Max**	**Mean**	**Std Dev**
Speed at PC (i.e., curve entry speed)	mph	25.100	54.900	39.039	5.459
Passenger vehicle		0	1	0.966	0.181
Heavy vehicle (longer than 32 ft)		0	1	0.034	0.181
Daytime Off-Peak (9:00 AM – 3:30 PM)		0	1	0.394	0.489
Peak (7:00 AM – 9:00 AM; 3:30 PM – 6:00 PM)		0	1	0.178	0.382
Nighttime (6:00 PM – 7:00 AM)		0	1	0.428	0.495
No DSFS		0	1	0.557	0.497
DSFS at point of curvature		0	1	0.443	0.497

5.3 Results and Discussions

Several measures of effectiveness related to curve entry speed and brake response were analyzed to determine the effects of the DSFS as a function of sign position, interchange type, and time of day. Three primary analyses were performed using appropriate statistical procedures. The dependent variables for these analyses included:

- Speed at the PC (curve entry),
- Probability of initial braking occurring between 200 and 600 ft upstream of the PC, and
- Probability of a vehicle entering the curve within 15 mph of the advisory speed.

Preliminary models suggested only minor differences in DSFS effectiveness between passenger vehicles and heavy vehicles and further analysis of vehicle-specific DSFS effects was not performed. For all models, the upstream approach speed was included as a covariate to control for general driving behavior. Curve entry speeds were analyzed using linear regression including a random effect (intercept) term. A site-specific random intercept term was utilized in the video speed data models to account for the unobserved differences between sites. As the speed trailer was only used at a single site, a date-specific random intercept term was utilized for these models to account for unobserved day-to-day differences. Binary logistic regression was utilized to analyze the binary response variables, which included the probability of braking 200-600 ft in advance of the curve and the probability of a vehicle entering the curve within 15 mph of the advisory speed.

The linear regression results for curve entry speeds (e.g. at the point of curvature) obtained from the video data are displayed in Table 10, while the binary logistic regression results for excessive curve entry speeds and brake response location are displayed in Tables 11 and 12, respectively.

Table 10. Random intercept linear regression results for curve entry speed (Sites 2-4)

Response Variable: Speed at Point of Curvature (N=1,758)				
Parameter	**Estimate**	**Std. Error**	**t-value**	**p-value**
Intercept	14.983	1.175	12.746	<0.001
Speed 1000-ft Upstream of the Point of Curvature	0.414	0.014	29.208	<0.001
Passenger Vehicle with No Trailer		*Base Condition*		
Passenger Vehicle with Trailer	-1.339	0.665	-2.015	0.044
Single Unit Truck/ Bus	-1.969	0.463	-4.252	<0.001
Tractor Trailer Truck	-3.290	0.309	-10.648	<0.001
Existing Site Condition (No DSFS)		*Base Condition*		
DSFS at Point of Curvature - I-96/I-69	-2.290	0.299	-7.665	<0.001
DSFS at Point of Curvature - US-127/Round Lake Rd	-1.975	0.331	-5.970	<0.001
DSFS at 350 ft upstream of Point of Curvature - I-96/36th	0.967	0.283	3.415	<0.001

Table 11. Random intercept logistic regression results for curve entry speed within 15 mph of the advisory speed (Sites 2-4)

Response Variable: Speed at Point of Curvature within 15 mph of the Advisory Speed (N=1,758)					
Parameter	**Estimate**	**Std. Error**	**t-value**	**p-value**	**Exp(B)**
Intercept	12.846	1.390	9.245	<0.001	379268
Speed 1000-ft Upstream of the Point of Curvature	-0.201	0.014	-13.936	<0.001	0.818
Passenger Vehicle with No Trailer			*Base Condition*		
Passenger Vehicle with Trailer	1.959	0.977	2.006	0.045	7.092
Single Unit Truck/ Bus	1.650	0.486	3.395	0.001	5.207
Tractor Trailer Truck	2.387	0.411	5.809	0.000	10.881
Existing Site Condition (No DSFS)			*Base Condition*		
DSFS at Point of Curvature - I-96/I-69	0.548	0.296	1.851	0.064	1.730
DSFS at Point of Curvature - US-127/Round Lake Rd	0.901	0.275	3.276	0.001	2.462
DSFS at 350 ft upstream of Point of Curvature - I-96/36th	-0.300	0.215	-1.395	0.163	0.741

Table 12. Random intercept logistic regression results for brake response location (Site 2-4)

Response Variable: Braking Began 200-600 ft Before Curve (N=1,651)					
Parameter	**Estimate**	**Std. Error**	**t-value**	**p-value**	**Exp(B)**
Intercept	-2.357	0.500	-4.713	<0.001	0.095
Speed 1000-ft Upstream of the Point of Curvature	0.026	0.008	3.155	0.002	1.026
Passenger Vehicle with No Trailer			*Base Condition*		
Passenger Vehicle with Trailer	-0.148	0.408	-0.364	0.716	0.862
Single Unit Truck/ Bus	-0.379	0.309	-1.230	0.219	0.685
Tractor Trailer Truck	-0.087	0.191	-0.458	0.647	0.419
Existing Site Condition (No DSFS)			*Base Condition*		
DSFS at Point of Curvature - I-96/I-69	0.368	0.155	2.375	0.018	1.445
DSFS at Point of Curvature - US-127/Round Lake Rd	0.599	0.151	3.953	<0.001	1.820
DSFS at 350 ft upstream of Point of Curvature - I-96/36th	-0.120	0.149	-0.803	0.422	0.887

Note: Each model included a random intercept for site. Represents data collected from video cameras.

First, as expected, the speed of vehicles measured 1,000 ft prior to the curve was strongly correlated with each of the driver response variables. Specifically, this suggests that faster drivers tended to maintain such behaviors regardless of the DSFS presence at the site and is aligned with prior behavioral research. Further discussion of the primary variables of interest, including the effects of sign position, interchange type, and time of day on DSFS performance are provided in the sections that follow.

5.3.1 Effect of sign position

The parameter estimates in Table 10 indicate that curve entry speeds were approximately 2.0 to 2.3 mph lower with the DSFS present at the two ramp locations where the sign was positioned directly at the point of curvature. The DSFS installed at the point of curvature also decreased the occurrence of excessive curve entry speeds, as indicated in Table 11. Specifically, compared to the existing site condition, drivers were 1.7 to 2.5 times more likely to enter the curve within 15 mph of the curve advisory speed with the DSFS installed at the point of curvature. Furthermore, Table 12 suggests that the DSFS also improved brake response when posted at the point of curvature. With the DSFS at this location, drivers were 1.4 to 1.8 times more likely to initiate braking between 200 and 600 ft upstream of the curve. It is also worth noting that the DSFS had a similar effect on driver response across all vehicle categories. These results are aligned with prior findings associated with DSFS use in similar freeway ramp settings in the earlier phase of this study.

In contrast, the DSFS was found to be ineffective across all measures of driver response when posted 350 ft upstream of the point of curvature. At this particular ramp location, curve entry speeds were found to increase by approximately 1 mph with the DSFS present. The DSFS had no significant effect on reducing excessive curve entry speeds or improving brake response at this particular site. These results are consistent with earlier phases of the research at an alternative ramp location, which found the DSFS to be less effective when positioned 450 ft upstream of the curve (Table 4). One possible reason for the diminishing effectiveness at increasing advance warning distances is that drivers may be more likely to disregard warning messages that are provided too far in advance of a hazard.

5.3.2 Effect of interchange type

It was also of interest to compare the effects of DSFS on driver response across different interchange types, including freeway-to-freeway system interchanges and service interchanges. This effect was evaluated by comparing the DSFS results between the I-96/I-69 (system interchange) and US-127/Round Lake Road (service interchange) ramps. Each of these ramps was a cloverleaf-type interchange with a 30-mph ramp advisory speed. The DSFS was installed directly at the point of curvature in both cases, which, as previously noted, elicited improved driver response compared to the further upstream sign position.

Considering curve entry speeds, the DSFS had a slightly (0.3 mph) greater speed reduction effect at the I-96 freeway-to-freeway interchange. However, the DSFS was somewhat more effective at reducing excessive curve entry speeds and improving brake response when used at the US-127 service interchange. These findings suggest that the DSFS is equally effective at system and service interchange exit ramps when installed at the point of curvature. Figure 19 provides a graphical representation of the site-specific marginal effects, which demonstrate the effects of the DSFS on curve entry speeds related to the sign position and interchange type.

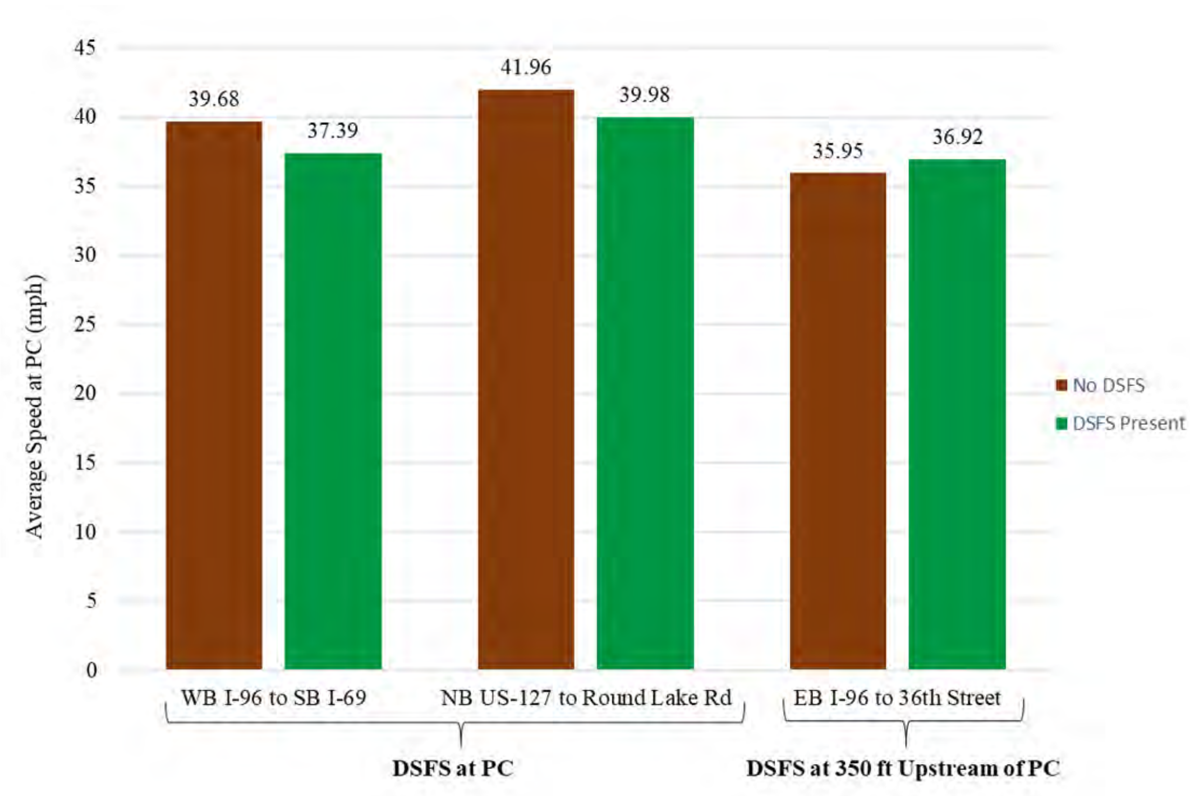


Figure 19. Mean curve entry speeds by site and DSFS presence

5.3.3 Effect of time of day

Analysis of the speed trailer data allowed for an assessment of the effects of the DSFS on curve entry speeds across various times of day and light conditions. Again, these data are specific to the US127/Round Lake Rd exit ramp, where the speed trailer, along with the DSFS for a portion of the 36 days, were positioned near the point of curvature. Separate regression models were generated for curve entry speeds based on time of day and light condition, including peak, daytime off-peak, and nighttime. Using these separate models, it was possible to assess whether the DSFS had different effects on the behavior of peak (e.g. commuter) vs. off-peak drivers and during different lighting conditions. The linear regression results for curve entry speeds are displayed in Table 13. Again, to control for unobserved variations between each daily data collection period, a date-specific random effect (intercept) was included in each model.

Table 13. Random intercept linear regression results for curve entry speed by peak/off-peak period and light condition (Site 3)

Parameter	Estimate	Std. Error	t-value	p-value
Daytime Off-Peak (9:00 AM – 3:30 PM) (N=6,869)				
Parameter	**Estimate**	**Std. Error**	**t-value**	**p-value**
Intercept	40.176	0.301	133.566	<0.001
Passenger Vehicle		*Base Condition*		
Heavy Vehicle	-4.911	0.294	-16.727	<0.001
Existing Site Condition (No DSFS)		*Base Condition*		
DSFS at Point of Curvature	-0.914	0.442	-2.068	0.048
Peak (7:00 AM – 9:00 AM and 3:30 PM to 6:00 PM) (N=3,096)				
Parameter	**Estimate**	**Std. Error**	**t-value**	**p-value**
Intercept	39.694	0.292	135.733	<0.001
Passenger Vehicle		*Base Condition*		
Heavy Vehicle	-5.597	0.517	-10.825	<0.001
Existing Site Condition (No DSFS)		*Base Condition*		
DSFS at Point of Curvature	-0.488	0.435	-1.123	0.270
Nighttime (6:00 PM – 7:00 AM) (N=7,468)				
Parameter	**Estimate**	**Std. Error**	**t-value**	**p-value**
Intercept	38.249	0.241	158.946	<0.001
Passenger Vehicle		*Base Condition*		
Heavy Vehicle	-3.671	0.453	-8.110	<0.001
Existing Site Condition (No DSFS)		*Base Condition*		
DSFS at Point of Curvature	-0.286	0.359	-0.796	0.432

Note: Data were collected by the speed trailer at US-127/Round Lake. Random intercept was data collection date.

Table 13 presents several interesting findings related to the effectiveness of the DSFS by time-of-day. Most notably, the DSFS has the greatest effect on reducing curve entry speeds during daytime off-peak periods. The magnitude of this DSFS speed reduction effect (0.9 mph) is nearly double that observed during peak periods (0.5 mph) and triple that observed during nighttime periods (0.3 mph). This finding suggests that the DSFS has the greatest effects on non-commuter drivers compared to commuter drivers, who are generally more familiar with the site. It should be noted that preliminary models did not show any discernable differences in the DSFS effects on curve entry speeds across the vehicle type categories. Graphical representations of the curve entry speeds by time-of-day and DSFS presence are provided in Figure 20.

It is important to note that unlike the video data, it was not possible to track vehicles through the site, as the speed trailer only records a single speed measurement for each vehicle. Thus, it was not possible to correlate driver speeding tendencies upstream of the site with their curve entry speed. As a driver's upstream speed was found to be highly correlated with curve entry speed during the analysis of the video data, the inability to control for general speed selection tendencies was an important limitation to any inference drawn from the speed trailer data.

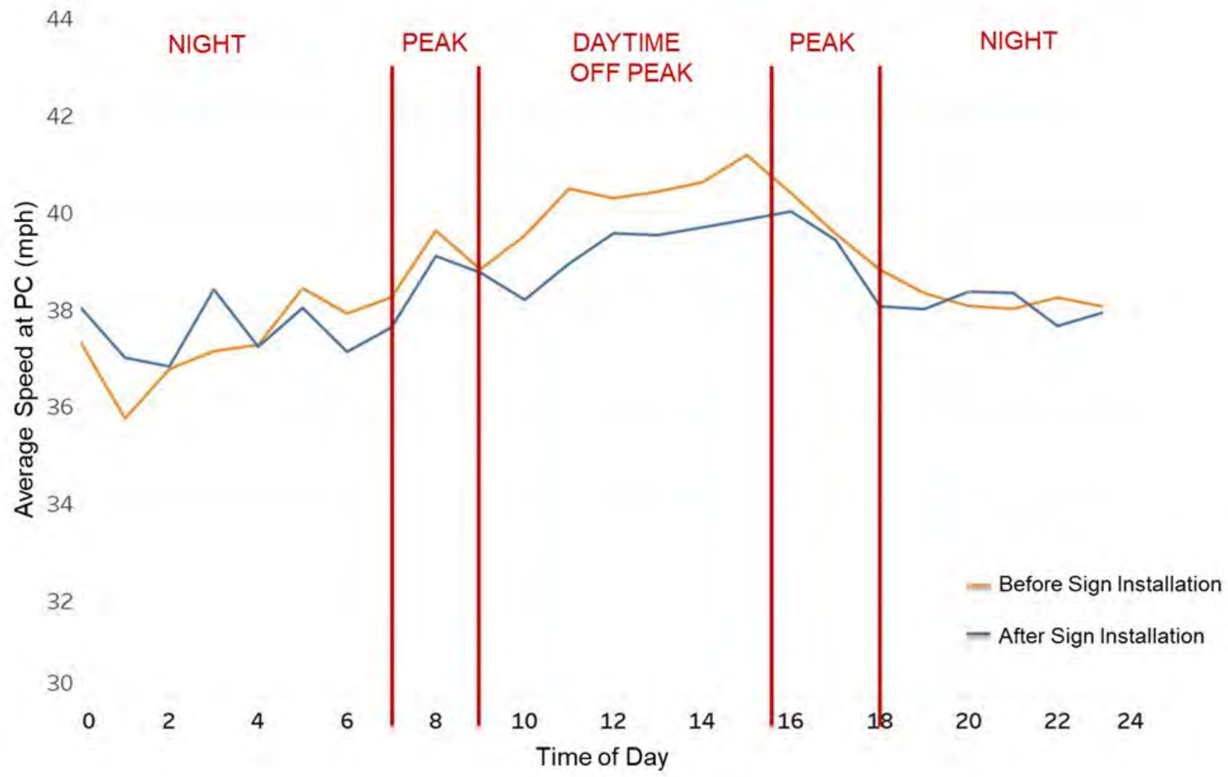


Figure 20. Mean curve entry speeds by DSFS presence and time of day

5.4 Conclusion and Direction for Further Evaluation

This chapter described a series of field evaluations at three freeway exit ramps with significant horizontal curvature to assess the effectiveness of the 15-inch TraffiCalm DSFS sign across various sign positions (at the point of curvature vs. 350 ft upstream), interchange types (system vs. service), times-of-day (peak vs. off-peak), light conditions (daylight vs. darkness), and vehicle types (passenger vehicles vs. trucks).

Compared to the pre-DSFS site condition, the DSFS reduced curve entry speeds and improved brake response at the two ramp locations where the sign was positioned at the point of curvature, during which curve entry speeds were reduced by approximately 2 mph compared to the pre-DSFS conditions. These findings were consistent between the system- and service-interchanges and across all vehicle types. The feedback sign was found to have an ineffective impact on driver behavior when positioned 350-ft upstream of the point of curvature. Consistent with the prior phase of this study, it was concluded that drivers are more likely to disregard speed warning messages when provided too far in advance of the curve.

The DSFS was also found to be more effective during daytime off-peak periods than during peak periods and during darkness. This finding suggests that the DSFS has the greatest effects on non-commuter drivers and may be reflective of such drivers being more likely to respond to the speed warning message due to a reduced familiarity with the ramp geometry. On the other hand, commuter drivers are less likely to respond to the DSFS due to familiarity with the site, which may also at least partially explain the lack of an effect for nighttime drivers.

While the evaluations described within this chapter this study provided further confirmation that the DSFS is most effective when placed near the PC, further evaluation of DSFS at freeway exit ramps under an expanded set of conditions and at additional ramp locations is recommended. This includes evaluating whether the behavioral effects diminish over time, effect of sign size (both the feedback display and the sign itself), effect of the side of the roadway (right-side vs. left-side/gore area), and the optimal radar detection settings to maximize driver response. These aspects were included in the next phase of field evaluations described in the following chapters.

6. EVALUATION OF SIGN SIZE, RADAR DETECTION RANGE, AND LATERAL SIGN POSITION

6.1 Study Design and Site Characteristics

Additional research was conducted at the NB US 127/Round Lake Road exit ramp to evaluate several additional aspects of the DSFS, including feedback message display size (15-inch vs. 18-inch), sign border type (yellow border vs. no border), sign lateral placement positions at the PC (right side-mount vs. forward-mount [i.e., gore area]), and vehicle detection range (normal detection vs. late detection). In addition to the 15-inch TraffiCalm sign, two additional full-matrix DSFS were included in this field evaluation, including an 18-inch TraffiCalm sign, and an 18-inch sign manufactured by All Traffic Solutions (ATS).

Each sign was individually installed and tested at identical locations near the start of the exit ramp curve, in both the traditional right-side-mount and an alternative forward-mount within the exit gore area. While the two TraffiCalm signs possessed a yellow border with reflective sheeting, the ATS sign did not include a border. Furthermore, the ATS sign utilized a radar system that provided greater vehicle detection ranges compared to the two TraffiCalm signs, consequently causing the ATS feedback message to be initially activated at a greater distance upstream, which may impact driver response while approaching the ramp curve. This was deemed a crucial variable for this evaluation and, consequently, the location of the approaching vehicle when the feedback message was initially activated (i.e., the sign activation location) was assessed for each subject vehicle, in addition to the other behavioral and vehicle related characteristics.

As previously noted, the NB US 127/Round Lake exit ramp was a service interchange with a mainline speed limit of 75 mph and a loop ramp with a curve advisory speed of 30 mph. This site possessed warning signage that was compliant with the MUTCD, including W13-6, E5-1a, and W1-8R signs. A plan view of the existing signage layout and DSFS positions for this site is provided in Figure 21. From the site, speed data and message activation location were collected for vehicles approaching and entering into the curve across the various sign test conditions using appropriate methods. Further information on the study design and collection of data is included later in this section.

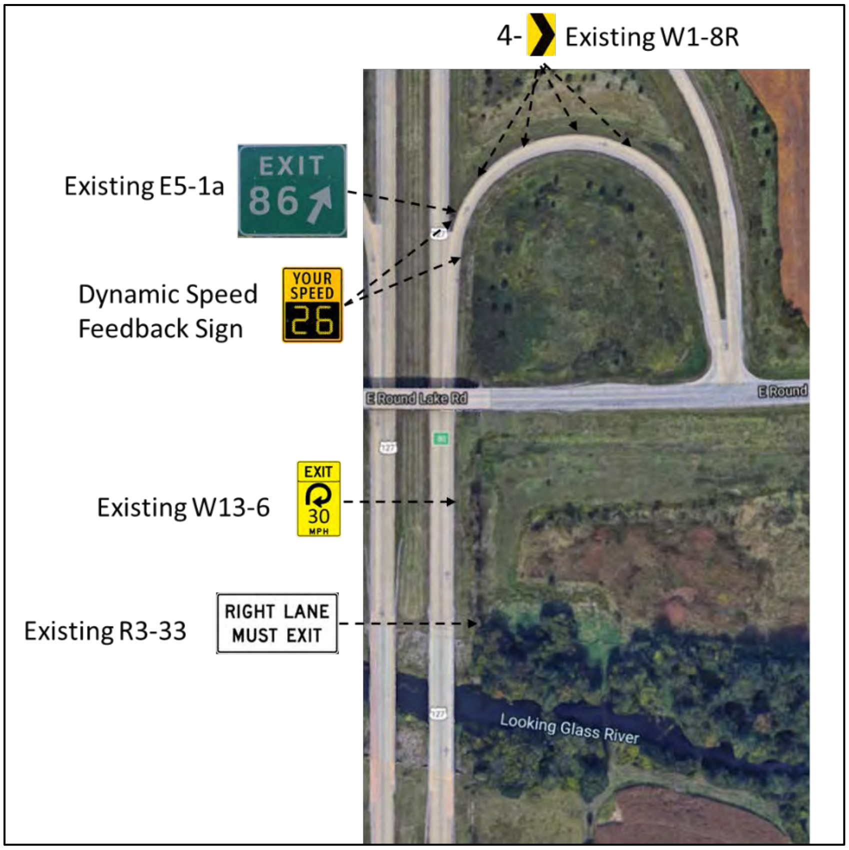


Figure 21. NB US-127 exit ramp to Round Lake Rd

6.1.1 Sign lateral installation position

A primary condition that was evaluated during the earlier phases of this research project was to vary the longitudinal position of the DSFS relative to the exit ramp curve. As previously noted, during these initial evaluations, the DSFS was consistently found to be most effective when positioned at or near the PC of the ramp curve, with the sign losing effectiveness at distances of 350 ft or greater upstream from the curve. However, at many exit ramp locations, the typical right-side-mount DSFS installation near the PC is not feasible due to terrain or obstructions, such as a bridge abutment or guardrail, which would potentially block the radar and/or the motorists' view of the sign.

To that end, a primary variable for the present evaluation was to vary the *lateral* position of the DSFS with respect to the side of the ramp. Specifically, in addition to the traditional right-side installation at the PC, the DSFS was installed and tested in the ramp gore area, which positioned the sign on the left side of the ramp, between the ramp and the mainline freeway near the green E5-1a Exit sign. In this position, the sign was approximately 40 feet beyond the PC, but directly in front of motorists while approaching the curve in the ramp auxiliary lane. This setup is referred to herein as the "forward-mount" setup, as displayed in Figure 22a along with the traditional right-side-mount setup (herein referred to as "side-mount") example in Figure 22b.

a. Forward-mounted DSFS **b. Side-mounted DSFS**

Figure 22. Forward-mounted vs. side-mounted DSFS installation

A total of six DSFS conditions were evaluated and compared to the existing site condition without the DSFS. The sign test conditions and corresponding data collection periods were sequenced as follows:

1. Existing site condition (prior to DSFS installation)
2. Side-mounted 18-in TrafficCalm sign
3. Side-mounted 15-in TrafficCalm sign
4. Side-mounted 18-in ATS Sign
5. Forward-mounted 18-in TrafficCalm sign
6. Forward-mounted 15-in TrafficCalm sign
7. Forward-mounted 18-in ATS Sign
8. Existing site condition (2 months after DSFS removal)

After collection of data under the existing site condition, the DSFS were then installed and evaluated according to the sequence shown above. The DSFS were mounted by MDOT maintenance crews on dual aluminum sign posts, with a 7-ft bottom mounting height from the pavement surface. The existing signage at the site was not modified in any way. The initial DSFS installation remained operational for seven days prior to initiating data collection to allow for dissipation of any driver novelty effects associated with the new traffic control device. For each subsequent change to the DSFS condition, a period of two days was allowed to pass prior to data collection. After completion of all DSFS test conditions, the sign was removed and data were again collected 2-months later under the pre-existing site conditions.

6.1.2 Feedback message activation location

It is crucially important for the DSFS to be activated when vehicles are at an appropriate distance in advance of the curve to allow enough time and space to react and decelerate accordingly. As noted previously, the vehicle detection ranges varied between the two radar systems, which subsequently affected when the feedback message would activate for approaching vehicles. To assess the relationship between the message activation point and driver response, the location of each subject vehicle during the initial display of the feedback message was recorded utilizing an elevated video camera temporarily installed on the roadside during each data collection period. The videos were later reviewed to extract the location of the vehicle to the nearest 10 feet using a series of reference markers painted on the shoulder. For consistency purposes, all sign activation measurements were referenced to the point of curvature. The sign activation location data were then merged with the LIDAR speed data for each corresponding subject vehicle, and were included as a predictor variable in the subsequent analysis. However, prior to analyzing the data, the sign activation data were first categorized, as follows:

- Less than 250 ft upstream of the PC (late activation);
- 250 to 400 ft upstream of the PC (normal activation); and
- Greater than 400 ft upstream of the PC (early activation).

The 250 ft threshold was selected to represent the approximate braking distance necessary for a vehicle to comfortably decelerate (at 11.2 ft/sec^2) from 60 mph (the approximate 85th percentile speed at this point) to the curve advisory speed of 30 mph. The 400 ft threshold was selected as it represented the typical passenger vehicle detection range of the TrafficCalm radar.

6.2 Data Summary

Speed data and message activation location were collected for vehicles approaching and entering into the curve across the various sign test conditions. Vehicle speeds were continuously tracked using the two-person LIDAR hand-off method for the entire exit ramp lane, beginning from the start of the taper, and continuing to the curve entry point. The location of each vehicle upon DSFS activation was determined using an elevated video camera temporarily installed on the roadside during each data collection period. The speed profile data and DSFS activation location data collected for each test condition were joined, organized, and coded into a single file for a comprehensive statistical analysis. The final data set included complete speed profiles for 2,047 vehicle observations, including 1,983 passenger vehicles and 64 heavy vehicles. The descriptive statistics for this data set are shown in Table 14. Table 15 shows the vehicle frequency and percentages based on vehicle detection ranges for different test conditions that include sign types and sign positions. To check for any obvious trends in the data, sources for potential bias, and data distributions, graphical representations of the data were reviewed and descriptive statistics were compared across each data collection condition.

Table 14. Descriptive statistics for ramp vehicles (Site 3)

Parameter	Minimum	Maximum	Mean	Std. Dev.
Speed 1,000-ft Upstream of PC, mph	37.606	86.000	66.513	5.916
Speed 400-ft Upstream of PC, mph	28.000	76.825	56.230	6.300
Speed 250-ft Upstream of PC, mph	27.000	71.434	52.460	5.900
Speed At PC, mph	22.000	58.720	41.192	5.011
Passenger Car	0	1	0.969	0.174
Heavy Vehicle	0	1	0.031	0.174
Without DSFS (prior to sign installation)	0	1	0.161	0.368
Side-mounted DSFS	0	1	0.323	0.344
Forward-mounted DSFS	0	1	0.428	0.353
Without DSFS (2 months after removal)	0	1	0.088	0.283

N = 2,047 vehicles

Table 15. Frequency distribution of vehicle detection ranges based on sign positions (Site 3)

Parameters	Activation Location (ft)	Frequency	Percentage
Without DSFS (prior to sign installation) (n=330)	NA	330	100.00%
Side-mounted DSFS			
15-in TrafficCalm (n=188)	<250	127	67.55%
	250-400	45	23.94%
	>400	16	8.51%
18-in TrafficCalm (n=151)	<250	55	36.42%
	250-400	53	35.10%
	>400	43	28.48%
18-in ATS Sign (n=321)	<250	4	1.25%
	250-400	37	11.53%
	>400	280	87.23%
Forward-mounted DSFS			
15-in TrafficCalm (n=200)	<250	86	43.00%
	250-400	51	25.50%
	>400	63	31.50%
18-in TrafficCalm (n=205)	<250	80	39.02%
	250-400	78	38.05%
	>400	47	22.93%
18-in ATS Sign (n=471)	<250	137	29.09%
	250-400	33	7.01%
	>400	301	63.91%
Without DSFS (n=180) (2 months after sign removal)	NA	180	100.00%

N = 2,047 vehicles

6.3 Results and Discussion

Several measures of effectiveness related to vehicle speed were analyzed to determine the effects of the DSFS as a function of sign size/type, lateral installation position, and activation location. The dependent variables for these analyses were selected to assess driver response to the feedback message and included:

- Speed at the point of curvature (i.e., curve entry),
- Speed 250-ft upstream of the point of curvature, and
- Speed 400-ft upstream of the point of curvature.

Additionally, the number of heavy vehicles in the sample was small, which required combining across several test conditions, such that only the DSFS lateral installation position was assessed. The multiple linear regression results for speeds approaching and entering the exit ramp curve for passenger cars and heavy vehicles are shown in Table 16 and Table 17, respectively. To assist with visualization of the results, Figure 23 displays the parameter estimates and 95 percent confidence intervals for "Speed at PC" across all DSFS test conditions.

Several interesting findings were observed. First, as expected, the speed of vehicles measured 1,000 ft prior to the curve was strongly correlated with speeds approaching and entering the curve, and this effect was stronger at greater distances upstream of the PC. Specifically, this suggests that faster drivers tended to maintain such behaviors regardless of the DSFS presence at the site and is aligned with the prior field evaluation phases.

Table 16. Multiple linear regression results for speeds of passenger vehicles approaching and entering the ramp curve

		Speed At PC		Speed 250-ft Upstream of PC		Speed 400-ft Upstream of PC	
Parameters	**Activation Location (ft)**	**Estimate**	**p-value**	**Estimate**	**p-value**	**Estimate**	**p-value**
Intercept		19.461	<0.001	8.116	<0.001	0.936	0.342
Upstream Speed		0.367	<0.001	0.685	<0.001	0.841	<0.001
Without DSFS (prior to sign installation)				*Base Condition*			
Side-mount DSFS							
15-in TrafficCalm	<250	-3.290	<0.001	-0.876	0.032	0.401	0.278
	250-400	-4.698	<0.001	-2.431	<0.001	-1.100	0.053
	>400	-3.594	<0.001	-2.443	0.018	-1.430	0.127
18-in TrafficCalm	<250	-3.040	<0.001	-0.857	0.132	0.513	0.319
	250-400	-4.299	<0.001	-1.600	0.006	-0.054	0.918
	>400	-3.201	<0.001	-1.377	0.035	-0.407	0.493
18-in ATS Sign	<250	-2.676	0.174	-1.703	0.385	-1.481	0.405
	250-400	-4.554	<0.001	-2.065	0.003	-1.050	0.099
	>400	-4.173	<0.001	-2.179	<0.001	-1.365	<0.001
Forward-mount DSFS							
15-in TrafficCalm	<250	-2.738	<0.001	-1.379	0.004	-0.956	0.029
	250-400	-4.663	<0.001	-2.708	<0.001	-1.929	<0.001
	>400	-3.648	<0.001	-2.065	<0.001	-1.566	0.003
18-in TrafficCalm	<250	-3.538	<0.001	-0.602	0.219	-0.108	0.807
	250-400	-5.247	<0.001	-2.495	<0.001	-1.859	<0.001
	>400	-5.050	<0.001	-2.941	<0.001	-1.877	0.002
18-in ATS Sign	<250	-0.500	0.211	0.009	0.982	0.042	0.908
	250-400	-2.290	0.002	-0.913	0.227	-0.609	0.373
	>400	-3.260	<0.001	-1.347	<0.001	-0.858	0.003
Without DSFS (2 months after sign removal)		0.180	0.625	0.000	0.999	0.344	0.300

Note: Sample size = 1,983 passenger vehicles

Table 17. Multiple linear regression results for speeds of heavy vehicles approaching and entering the ramp curve

	Speed At PC		Speed 250-ft Upstream of PC		Speed 400-ft Upstream of PC	
Parameters	**Estimate**	**p-value**	**Estimate**	**p-value**	**Estimate**	**p-value**
Intercept	8.116	0.086	-4.659	0.278	-8.737	0.039
Upstream Speed	0.516	<0.001	0.842	<0.001	0.956	<0.001
Without DSFS	*Base Condition*					
Side-mount Setup	-4.019	0.010	-0.927	0.509	0.919	0.500
Forward-mount Setup	-3.519	0.016	-0.400	0.760	0.338	0.790

Note: Sample size = 64 heavy vehicles

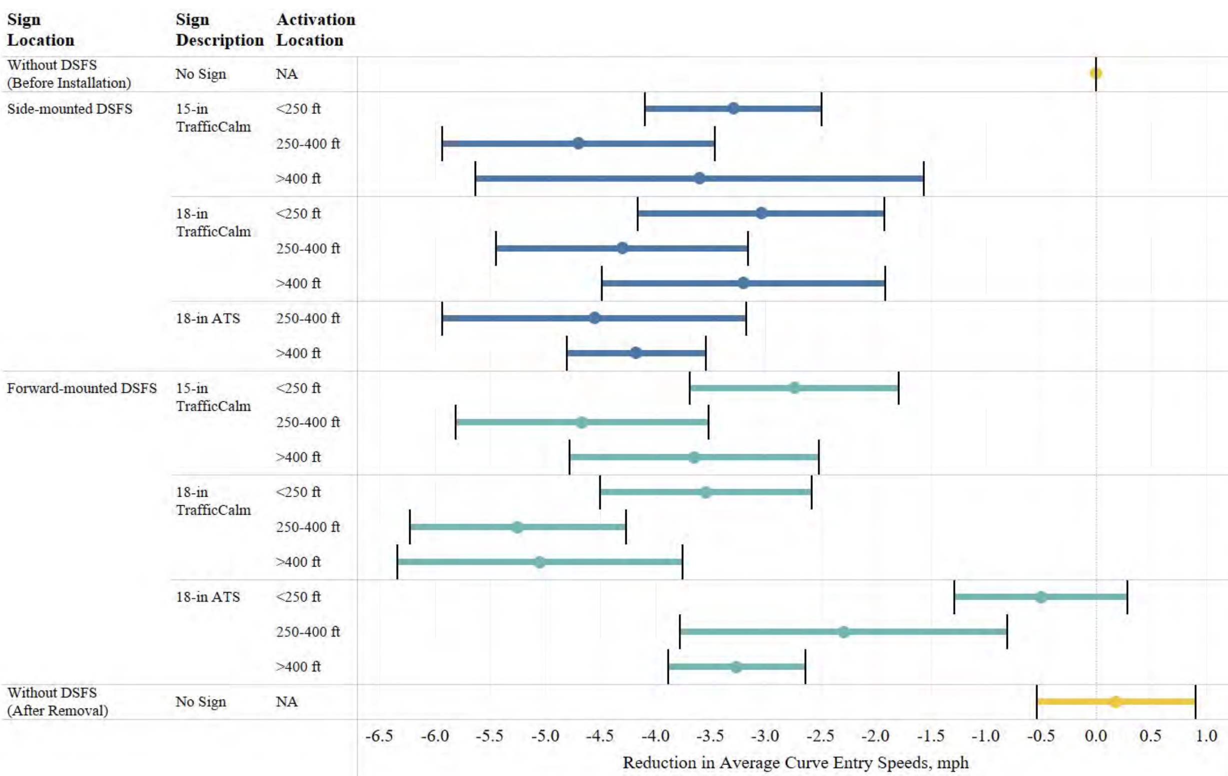


Figure 23. Linear regression parameter estimates for the reduction in curve entry speed (with 95% confidence intervals)

It is also clear that the DSFS tends to have a stronger effect on drivers as they proceed towards the curve. Considering passenger vehicles, speeds measured 400-ft prior to the curve PC were typically only marginally lower with the DSFS in place. By 250-ft prior to the PC, the speeds had become consistently lower with the DSFS in place, particularly for the forward-mount setup. The DSFS showed the greatest effect on speeds measured at the PC (e.g., curve entry point), where speeds were, on average, 3.5 mph lower with a DSFS present. Although the sample of heavy vehicles was small, the DSFS were similarly effective for reducing speeds of heavy vehicles at the curve entry point. It is also worth noting that vehicle speeds collected 2-months after removal of the DSFS had returned to their pre-existing levels. Further discussion of the primary variables of interest, including the effects of lateral sign position, sign size and type, and sign activation location are provided in the sections that follow. Please note that hereinafter, the discussion will primarily focus on the results pertaining to speeds measured at the PC, due to the magnitude of the speed reduction effects at this point.

6.3.1 Effect of sign lateral position

In general, both lateral DSFS installation positions elicited a similar effect on curve entry speeds. For passenger vehicles, the reduction in curve entry speed ranged between 3.5 and 4.2 mph for the side-mounted setup, and between 2.4 and 4.5 mph for forward-mounted setup, depending on the sign type and activation location. Although the sample of heavy vehicles was small, speed reductions of 3.5 and 4.0 mph were observed at the curve entry point for the forward-mounted and side-mounted installations, respectively.

6.3.2 Effect of sign border and display size

An important aspect of this study was to also compare the sign border type (prominent yellow border vs. no border) and size of the feedback display (15-inch vs. 18-inch). First, considering the size of the feedback display, the 15-inch and 18-inch TraffiCalm signs had a similar effect on curve entry speeds. However, there was evidence of a slight interaction effect between the sign border and lateral position. Specifically, the 18-inch TraffiCalm sign had a slightly stronger speed reduction effect than the ATS sign when utilized in the forward mount position. This may be due to the TrafficCalm's prominent yellow sign border attracting greater attention with the sign posted in the more visually cluttered gore area. Conversely, the ATS sign had a slightly stronger speed reduction effect than the TrafficCalm signs when used in the side-mount condition, which may be due to the more consistent upstream activation of the sign, which is explained in greater detail in the following section.

6.3.3 Effect of message activation location

The message activation location was found to have the strongest relationship with curve entry speed. The greatest reductions in curve entry speeds were observed for cases where the feedback message initially activated when subject vehicles were within 250 to 400 ft of the curve. For such cases, the curve entry speeds were approximately 4.5 mph lower compared to cases without the DSFS present. Interestingly, the DSFS was found to be slightly, but consistently, *less* effective at reducing curve entry speeds when initial activation occurred greater than 400 ft upstream of the curve.

Across all test conditions, the DSFS was least effective when the feedback message did not initially activate until the vehicle was within 250 ft of the curve. This was likely due to drivers not being afforded adequate time to react and respond to the message. In such cases, curve entry speeds were 1.3 to 2.5 mph higher than cases where the sign activated for vehicles that were within 250 to 400 ft of the curve. Generally speaking, the effect of sign activation location was dampened when the sign was side-mounted compared to forward-mounted. Late message activation resulted in particularly poor speed reduction performance for the ATS sign when utilized in the forward-mount position, possibly due to the lack of a conspicuous sign border.

6.4 Conclusion and Direction for Further Evaluation

This field evaluation phase tested several aspects of the DSFS, including physical characteristics (display size and border type), lateral installation position (side-mount vs. forward-mount), and vehicle detection range of the radar. The NB US-127 exit ramp to Round Lake Rd (Site 3) was singularly utilized for this entire evaluation phase to eliminate site-to-site heterogeneity that would potentially confound the analysis.

Compared to the existing site condition, installation of a DSFS near the start of the exit ramp curve resulted in lower speeds of vehicles approaching and entering the curve. Generally speaking, the speed reduction effects of the DSFS increased as the vehicles proceeded towards the curve. The greatest effects were observed at the curve PC (e.g., curve entry point), where overall speeds were 3.5 mph lower, on average, with a DSFS present. Reductions in curve entry speeds were observed across all DSFS test conditions, ranging from 0.5 mph to 5.2 mph depending on the test condition. Although the sample of heavy vehicles was relatively small, DSFS were similarly effective for reducing speeds of heavy vehicles at the curve entry point. It is also worth noting that speeds collected 2-months after removal of the DSFS had returned to prior levels, which further supports the effectiveness of the DSFS as a speed reduction countermeasure at exit ramps.

Regarding the effect of the lateral installation position, both the side-mounted and forward-mounted DSFS provided a similar level of effectiveness in reducing curve entry speeds, which was consistent for both passenger vehicles and heavy vehicles. Similarly, considering the size of the feedback display, there was no discernable difference in the speed reduction effects between the 15-inch and 18-inch displays. In terms of the sign border, there was evidence of a slight interaction effect between the sign border and lateral position. Specifically, considering the forward-mount position, the prominent yellow sign border produced a stronger speed reduction effect compared to no border, perhaps because due to the greater need for conspicuity with the sign was posted in the more visually cluttered gore area.

The most interesting results were related to the message activation location, which was found to have the strongest effect on curve entry speed across all of the sign-related variables considered. The DSFS were most effective when the feedback message was initially activated for vehicles that were between 250 and 400 ft upstream of the curve, and this finding was consistent across nearly all test conditions. For cases where the feedback message initially activated within this range, curve entry speeds were approximately 4.5 mph lower compared to cases without the DSFS present. Interestingly, the DSFS was found to be slightly *less* effective at reducing curve entry speeds when initial activation occurred for vehicles further than 400 ft upstream of the curve. This finding is consistent with earlier phases of this research project, which found the DSFS to lose effectiveness when installed 350 ft or further upstream from the curve, as drivers are more likely to disregard speed warning messages when provided too far in advance of the hazard. Not surprisingly, the DSFS was least effective when the feedback message did not activate until the vehicle was within 250 ft of the curve. This diminished effectiveness was likely due to drivers not being afforded adequate time to react and respond to the message.

The findings from this field evaluation phase provide further evidence that dynamic speed feedback signs are an effective countermeasure for reducing curve entry speeds at freeway exit ramps. Regarding the optimal sign design, radar calibration, and installation characteristics, the DSFS should be positioned near the start of the curve, with the radar calibrated such that the message activates when vehicles are at least 250 ft in advance of the curve in order to provide adequate time for drivers to react and decelerate prior to reaching the curve. In terms of sign size, 15-inch and 18-inch signs were found to be equally effective and may be used interchangeably at freeway exit ramps. A prominent yellow reflective border around the sign is recommended to help improve conspicuity during cases when the sign is activated late and/or when the sign is located in a visually cluttered environment. When necessary, due to obstructions or terrain issues that would otherwise prohibit the traditional right-side mount, the DSFS will likely be similarly effective when installed within the gore area of the ramp (e.g., forward-mount setup) between the green Exit sign and the initial chevron. However, caution should be exercised when positioning the sign in the gore area, due to the increased likelihood that an errant vehicle may collide with the sign in this position. Thus, if possible, installing the sign in the traditional right-side mounting position is preferred.

While the results of this evaluation were encouraging, a follow-up evaluation at additional locations was deemed necessary for further confirmation of the effects of both lateral and longitudinal sign installation position. Furthermore, because the DSFS was often activated by vehicles traveling on the mainline freeway, it was also deemed important to assess the effects of the feedback sign activation on mainline vehicle speed. This follow-up evaluation is described in the following chapter.

7. EVALUATION OF SIGN POSITION AND IMPACT TO MAINLINE TRAFFIC

7.1 Study Design and Site Characteristics

A field evaluation was performed at two additional freeway interchange ramp locations to further confirm the effects of both longitudinal sign position (at PC vs. upstream of the curve) and lateral sign position (right side-mount at PC vs. forward-mount within the gore area). This evaluation also considered the effect of the feedback sign on the speed of mainline vehicles, which were often observed to activate the feedback message. Two additional freeway exit ramp locations were selected for this phase of the study, including NB US-127 exit to Dunckel Road (Site 5), which was a service interchange, and EB I-96 to NB US-127 (Site 6), which was a system interchange. Both sites were selected due to the proximity of an overpass near the ramp curve, which would potentially require alternative sign installation locations. Both sites had a mainline speed limit of 70 mph and a ramp advisory speed of 25 mph. Both sites possess MUTCD compliant warning signage including W13-6, E5-1a, and W1-8R signs. Plan views of the study sites, including the various DSFS positions are provided in Figures 24 and 25 for sites 5 and 6, respectively.

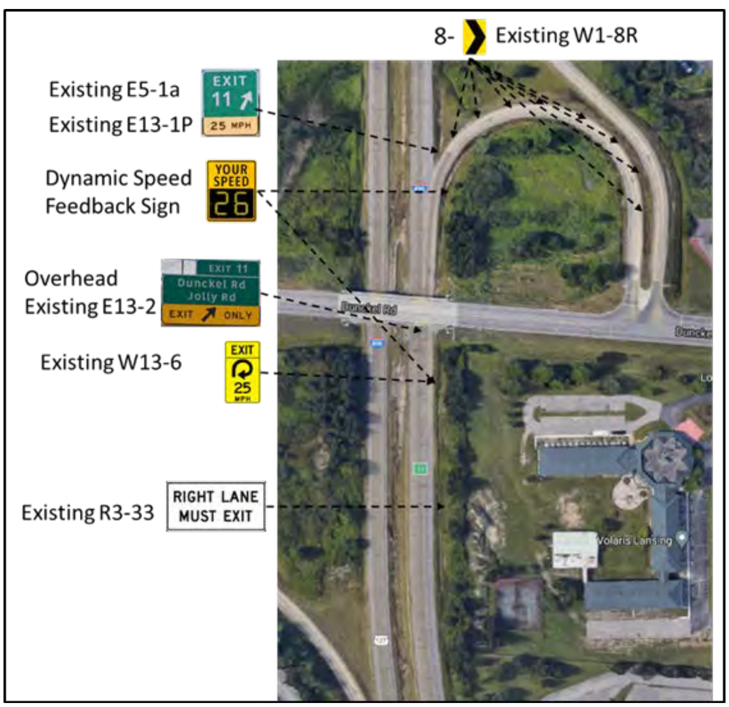


Figure 24. NB US-127 exit ramp to Dunckel Rd (Site 5)

Figure 25. EB I-96 exit ramp to NB US-127 (Site 6)

7.1.1 Sign test conditions

The field evaluation utilized the 15-inch TraffiCalm sign and the 18-inch TraffiCalm sign, each of which are described in further detail in Chapter 3. The 15-inch TraffiCalm sign was installed and evaluated at Site 5 and the 18-inch TraffiCalm sign was installed and evaluated at Site 6. At both sites, the DSFS was first installed beneath the existing exit advisory speed sign (W13-6) and then moved to the point of curvature, as depicted in Figure 26 for Site 6. The advisory speed signs were 485 ft and 580 ft upstream of the PC at sites 5 and 6, respectively, which presented greater upstream distances than had been previously evaluated in this research. In addition to the traditional right-side-mount at the PC, the DSFS was also evaluated in the forward-mount position beneath the Exit sign within the gore area at Site 6 (Figure 26c). The DSFS was not moved to the forward-mount position at site 5 due to safety concerns raised by the MDOT maintenance team regarding frequent gore-area intrusions at this location. Data were collected for the following conditions:

1. Without DSFS;
2. DSFS upstream of the PC (mounted beneath the exit advisory speed sign);
3. DSFS at the PC, right-side-mount; and
4. DSFS at the PC, forward-mount in the ramp gore area (Site 6 only).

a. DSFS at advisory speed sign **b. DSFS at PC (side-mount)** **c. DSFS at PC (fwd-mount)**

Figure 26. DSFS installation locations (Site 6)

The feedback message was displayed for approaching vehicles in the same manner employed during the prior evaluation phases, as follows:

- Display the measured speed if below 35 mph (i.e., advisory speed + 10 mph) and
- Display the measured speed alternating with a “SLOW DOWN” message at 1 hz cycles at 35 mph and above.

7.1.2 Mainline vehicle speeds

As mainline vehicles often activate the sign, it was of interest to evaluate the effect of DSFS messages on the speeds of mainline vehicles to determine any adverse impacts on behavior. In general, vehicles traveling in the right-most lane were more likely to trigger the DSFS because of their proximity to the sign. To test the effects of DSFS messaging on speeds of mainline vehicles, this evaluation phase included collection of spot-speed data at the upstream exit advisory sign for free-flowing mainline vehicles traveling in the right lane with and without DSFS present. The spot speed data for mainline vehicles were collected at sites 5 and 6 using a single handheld LIDAR gun, separately for passenger vehicles and heavy trucks. Data were collected only for mainline vehicles that activated the DSFS during the period that the DSFS was present.

7.2 Data Summary

The two-person LIDAR handoff method was utilized to collect vehicle speed profiles for exiting vehicles starting from the exit ramp taper to the PC. The speed profile data collected for each test condition were joined, organized, and coded into a single file for a comprehensive analysis separately for each site. The final data set included complete speed profiles for 456 and 737 vehicle observations from sites 5 and 6, respectively, with descriptive statistics shown in Tables 18 and 19, respectively.

Table 18. Descriptive statistics for ramp vehicles (Site 5)

Site 5: (NB) US-127 to Dunckel Road (n=456)				
Parameters	Min	Max	Mean	Std. Dev
Upstream Speed, mph	46.900	90.000	66.251	5.815
Speed at PC, mph	21.347	58.583	41.023	5.073
Passenger Vehicles	0	1	0.915	0.279
Heavy Vehicles	0	1	0.085	0.279
Average Deceleration Rate, ft/sec^2	0.663	3.799	1.810	0.425
Existing Site Condition (No DSFS)	0	1	0.430	0.476
DSFS at Advisory Speed Limit Sign	0	1	0.235	0.392
DSFS at PC (Side-mount)	0	1	0.335	0.445

Table 19. Descriptive statistics for ramp vehicles (Site 6)

Site 6: EB I-96 to NB US-127 (n=737)				
Parameters	**Min**	**Max**	**Mean**	**Std. Dev**
Upstream Speed, mph	46.833	79	65.859	0.177
Speed at PC, mph	20	59	34.400	0.145
Passenger Vehicles	0	1	0.959	0.007
Heavy Vehicles	0	1	0.041	0.007
Average Deceleration Rate, ft/sec^2	1.141	3.763	2.318	0.015
Existing Site Condition (No DSFS)	0	1	0.263	0.016
DSFS at Advisory Speed Limit Sign	0	1	0.201	0.015
DSFS at PC (Side-mount)	0	1	0.281	0.017
DSFS at PC (Forward-mount)	0	1	0.255	0.016

7.3 Results and Discussions

Two measures of effectiveness related to ramp vehicle speeds were analyzed to evaluate and further confirm the effects of the DSFS as a function of the longitudinal sign position relative to the PC and lateral sign position (site 6 only). The dependent variables for these analyses included:

- Speed at the point of curvature (i.e., curve entry), and
- Speed at the exit advisory sign (i.e., 485 ft [site 5] or 580 ft [site 6] upstream of the PC).

Preliminary models showed only minor differences in DSFS effectiveness between passenger vehicles and heavy vehicles and further analysis of vehicle-specific effects was not performed. For all models, the upstream approach speed was included as a covariate to control for general driving behavior. The linear regression results from sites 5 and 6 are presented in Tables 20 and 21, respectively.

Table 20. Multiple linear regression results for speeds approaching and entering the ramp curve (site 5)

	Speed at Exit Advisory Sign		Speed at PC	
Parameter	**Estimate**	**p-value**	**Estimate**	**p-value**
Intercept	8.727	<0.001	16.534	<0.001
Upstream Speed	0.778	<0.001	0.387	<0.001
Passenger Vehicles		*Base Condition*		
Heavy Vehicles	-4.395	<0.001	-5.551	<0.001
Existing Site Condition (No DSFS)		*Base Condition*		
DSFS 485 ft Upstream of PC	-1.960	<0.001	0.073	0.876
DSFS at PC (Side-mount)	-0.998	<0.007	-2.250	<0.001

Note: Sample size = 456 vehicles

Table 21. Multiple linear regression results for speeds approaching and entering the ramp curve (site 6)

	Speed at Exit Advisory Sign		Speed at PC	
Parameter	**Estimate**	**p-value**	**Estimate**	**p-value**
Intercept	2.483	0.147	14.878	<0.001
Upstream Speed	0.883	<0.001	0.315	<0.001
Passenger Vehicles		*Base Condition*		
Heavy Vehicles	-1.833	0.003	-3.789	<0.001
Existing Site Condition (No DSFS)		*Base Condition*		
DSFS 580 ft Upstream of PC	-1.535	<0.001	-0.300	0.409
DSFS at PC (Side-mount)	-1.172	<0.001	-1.939	<0.001
DSFS at PC (Forward-mount)	-2.011	<0.001	-1.714	<0.001

Note: Sample size = 737 vehicles

Several interesting findings were observed. First, as expected, the upstream speed of vehicles prior to the curve was strongly correlated with speeds approaching and entering the curve, and this effect was stronger for speeds measured at the exit advisory sign. Specifically, this suggests that faster drivers tended to maintain such behaviors regardless of the DSFS presence at the site and is consistent with the prior phases of this research. Further discussion of the primary variables of interest, including the effects of sign position longitudinal sign position from the PC, lateral sign position at the PC, and effect of the DSFS on mainline vehicle speeds are provided in the sections that follow.

7.3.1 Effect of longitudinal sign position

The parameter estimates in Tables 20 and 21 show that curve entry speeds were approximately 1.9 to 2.3 mph lower with the DSFS positioned directly at the point of curvature for sites 5 and 6, respectively, compared to when the DSFS was not present. On contrary, when DSFS was installed at the advisory speed signs, no significant reduction in the curve entry speeds was observed. These findings further strengthen the argument for positioning the DSFS at or near the PC for the greatest reduction in curve entry speeds.

The speeds measured at the exit advisory sign locations upstream of the PC were significantly lower for all DSFS installations compared to the site without the DSFS. But again, these effects were only sustained for cases where the DSFS was installed near the PC. Although one could argue that the DSFS positioned at the PC would not typically be able to detect vehicles at such great distances upstream of the radar (485 ft and 580 ft in this case). However, it was hypothesized that drivers of exiting vehicles may have been prematurely reacting to the activation of the DSFS caused by mainline vehicles. A graphical representation of the model results for speed at PC for the various longitudinal DSFS installation positions is shown in Figure 27.

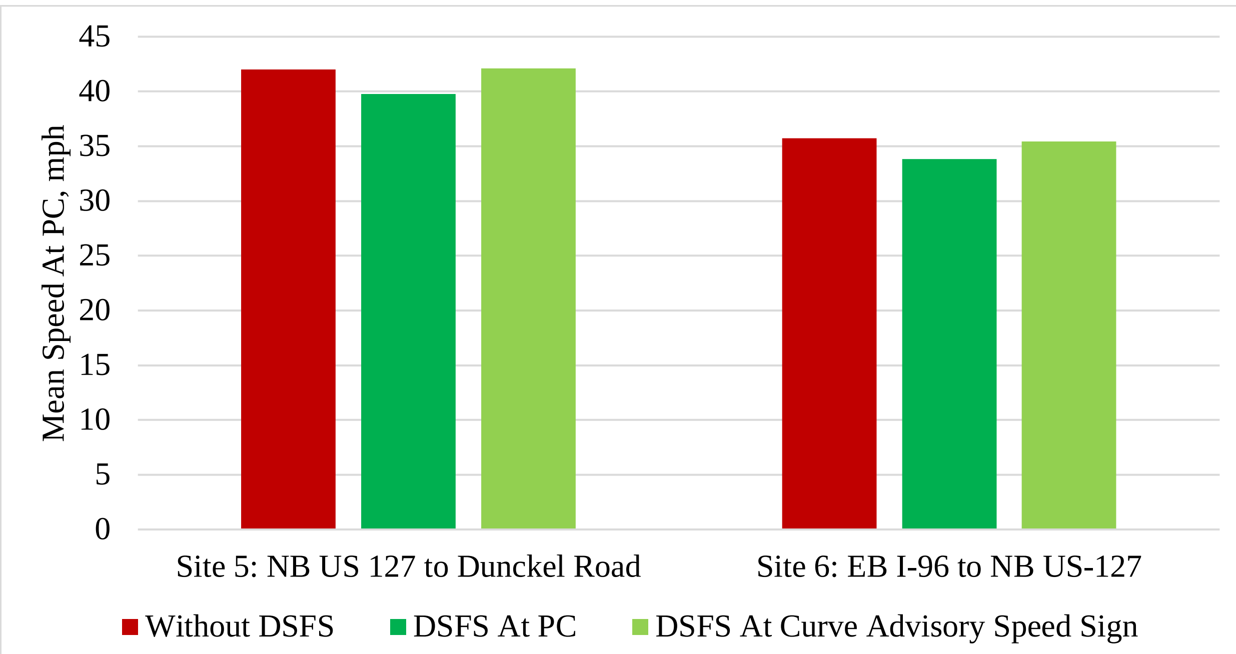


Figure 27. Mean curve entry speeds based on DSFS presence and longitudinal position

7.3.2 Effect of lateral sign position

Both side-mounted and forward-mounted sign positions showed a similar reduction in curve entry speeds. Compared to the site without the DSFS, curve entry speeds were 1.9 mph and 1.7 lower with the side-mounted and forward-mounted DSFS present, respectively. However, the forward-mounted installation resulted in greater speed reduction at the upstream exit advisory sign compared to the side-mounted installation, likely due to the improved upstream visibility of the sign when positioned in the gore area.

7.3.3 Effect on speeds of mainline vehicles

The mainline vehicle speed data with and without the DSFS present are displayed in Table 22. Again, while the DSFS was present, speeds were only measured for cases where the DSFS was activated by the mainline vehicle. The average speed at site 5 for passenger cars with and without the DSFS was 73.6 and 73.9 mph, respectively. The same measures for heavy vehicles were 65.3 and 65.5, respectively. For site 6, the average speed for passenger cars with and without the DSFS was 73.6 mph and 73.4 mph, respectively. For the heavy vehicles, the same measures were 64.7 mph and 64.5 mph, respectively. Two sample t-tests found these differences in average speeds to not be significantly different with respect to DSFS presence.

Table 22. Mainline vehicle speed summary

Mainline Vehicle Speed Summary by Vehicle Types, mph					
Site	Test Condition	Min	Max	Mean	Std. Dev
5	Existing Site Condition (No DSFS)-PSGR (n=90)	67	86	73.63	3.75
	DSFS Activated-PSGR (n=85)	67	88	73.89	3.74
	Existing Site Condition (No DSFS)-HV (n=19)	61	75	65.26	3.14
	DSFS Activated-HV (n=29)	60	70	65.48	2.46
6	Existing Site Condition (No DSFS)-PSGR (n=96)	63	82	73.63	3.44
	DSFS Activated-PSGR (n=73)	66	82	73.42	3.67
	Existing Site Condition (No DSFS)-HV (n=39)	60	68	64.68	2.19
	DSFS Activated-HV (n=30)	58	68	64.52	2.53

Note: PSGR-Passenger Vehicle, HV-Heavy Vehicle

7.4 Conclusion and Direction for Further Evaluation

This field evaluation phase further confirmed the effects of both longitudinal sign position (at PC vs. upstream of the curve) and lateral sign position (right side-mount at PC vs. forward-mount within the gore area). This evaluation also considered the effect of the feedback sign on the speed of mainline vehicles, which were often observed to activate the feedback message. The results found DSFS installed at the curve PC to produce significantly lower speeds for vehicles approaching and entering the curve compared to when the DSFS was not present. The average curve entry speeds were 1.7 mph to 2.3 mph lower with the DSFS installed at the PC compared to the existing site without the DSFS. However, positioning the DSFS at the upstream exit advisory sign proved ineffective, as curve entry speeds were not significantly different than when no DSFS was present. This finding provides further support for the hypothesis that drivers are more likely to disregard warning messages that are provided too early with respect to the hazard.

Collectively, these findings further confirm the results from the prior phases of this research, which found the DSFS to be most effective at reducing curve entry speeds when installed near the PC. Additionally, it was further confirmed that both the side-mount and forward-mount DSFS provided similar effects on driver behavior, with the forward-mount provided slightly earlier speed reductions, likely due to the greater visibility of the sign when position within the gore area. However, the likelihood of collision with the sign may increase when positioned in the gore area, and further investigation of the long term viability of DSFS installed in the gore area is recommended. Finally, the activation of the DSFS did not have any significant effect on the speeds of mainline vehicles.

8. TEMPORAL CHANGES IN DSFS EFFECTIVENESS

8.1 Study Design and Site Characteristics

In the early stages of the project, the Michigan DOT permanently installed a DSFS at the WB I-96 exit ramp to SB I-69 (Site 2). With this permanent installation, the research team was able to assess whether the driver behavior effects associated with the DSFS diminished with time. The permanent DSFS was a 15-inch TraffiCalm sign that was identical to the test sign utilized during all phases of this research project. The sign was programmed to display only speed of the vehicles traveling below 40 mph (advisory speed + 10 mph) and alternate with a "SLOW DOWN" message at 0.5-sec intervals for vehicles traveling 40 mph and above. The sign was positioned at the PC and also included a 30-inch square advisory speed panel, mounted immediately below the DSFS. The sign was equipped with a solar panel for a continuous power supply. The research team periodically collected data at this location before installation of the DSFS, and during the initial 14 months following installation.

8.2 Data Summary

Data were collected from the location in four phases: 1) prior to installation of the DSFS, 2) 3-months after the installation of the DSFS, 3) 9-months after the installation of the DSFS, and 3) 14-months after the installation of the DSFS. Data were collected using a series of three pole-mounted high-definition video cameras temporarily installed at specific points on the approach to and within the curve. The cameras were installed at the same locations and provided similar fields-of-view during each data collection period. The videos were reviewed to extract the relevant driver behavior data using procedures described in Chapter 3. The data were combined and coded into a single file for detailed analysis, and were screened to include only vehicle observations with a headway of 3 seconds or greater. A small number of cases where no feedback message was displayed on the DSFS for an approaching vehicle were also removed from the dataset. The final combined data set included a complete record for 759 vehicle observations collected during four data collection periods. Table 23 presents the descriptive statistics of the combined dataset.

Table 23. Descriptive statistics for evaluation of temporal effects of DSFS

Descriptive Statistics (N=759)				
Parameter	**Minimum**	**Maximum**	**Mean**	**Std. Dev**
Speed 1000-ft Upstream of the PC	32.468	83.832	55.978	7.637
Speed at the PC	19.461	52.395	35.963	5.676
Passenger Vehicle with No Trailer	0	1	0.665	0.472
Passenger Vehicle with Trailer	0	1	0.038	0.192
Single Unit Truck/ Bus	0	1	0.248	0.432
Tractor Trailer Truck	0	1	0.049	0.215
Without DSFS at the Site	0	1	0.510	0.500
DSFS at PC- After 3 Months	0	1	0.194	0.395
DSFS at PC- After 9 Months	0	1	0.211	0.408
DSFS at PC- After 14 Months	0	1	0.086	0.280

8.3 Results and Discussions

Two measures of effectiveness related to curve entry speeds were analyzed over time to determine the temporal effect of the DSFS. Separate models were developed using appropriate statistical procedures. The dependent variables for these models included:

- Speed at the point of curvature (i.e., curve entry), and
- Probability of a vehicle entering the curve with a speed <45 mph.

Preliminary models suggested only minor differences in DSFS effectiveness between passenger vehicles and heavy vehicles and further analysis of vehicle-specific DSFS effects was not performed. For all models, the upstream approach speed was included as a covariate to control for general driving behavior. The linear regression results for curve entry speeds (at the PC) obtained from the video data are displayed in Table 24, while the binary logistic regression results for excessive curve entry speeds are displayed in Table 25. A graphical representation of the curve entry speeds over time is presented in Figure 28.

First, the vehicle speed measured 1,000 ft upstream of the PC was strongly correlated with both driver response variables considered in this study. This indicates that faster driving vehicles largely maintain their behavior irrespective of the presence of DSFS, and was consistent with all other phases of the field evaluations. The following sections provide further discussion of the primary variables of interest.

Table 24. Linear regression results for curve entry speed

Response Variable: Speed at PC				
Parameter	**Estimate**	**Std. Error**	**t-value**	**p-value**
Intercept	15.342	1.321	11.610	<0.001
Speed 1000-ft Upstream of the PC	0.403	0.022	18.648	<0.001
Passenger Vehicle with No Trailer		*Base Condition*		
Passenger Vehicle with Trailer	-1.076	0.674	-1.598	0.111
Single Unit Truck/ Bus	-1.141	0.619	-1.841	0.066
Tractor Trailer Truck	-3.026	0.370	-8.173	<0.001
Without DSFS at the Site		*Base Condition*		
DSFS at PC- After 3 Months	-2.675	0.351	-7.610	<0.001
DSFS at PC- After 9 Months	-1.854	0.343	-5.405	<0.001
DSFS at PC- After 14 Months	-2.116	0.481	-4.402	<0.001

8.3.1 Curve entry speeds

The parameter estimates in Table 24 indicate that a significant reduction in curve entry speed following the installation of the DSFS, and the effect remained relatively consistent over the entire 14-month study period. The parameter estimates in Table 24 shows that the curve entry speeds were lowest immediately following DSFS installation (2.7 mph lower than before installation), and increased slightly 9 months and 14 months of installation. These findings clearly suggests that the DSFS does not lose its effectiveness towards reducing curve entry speeds with time.

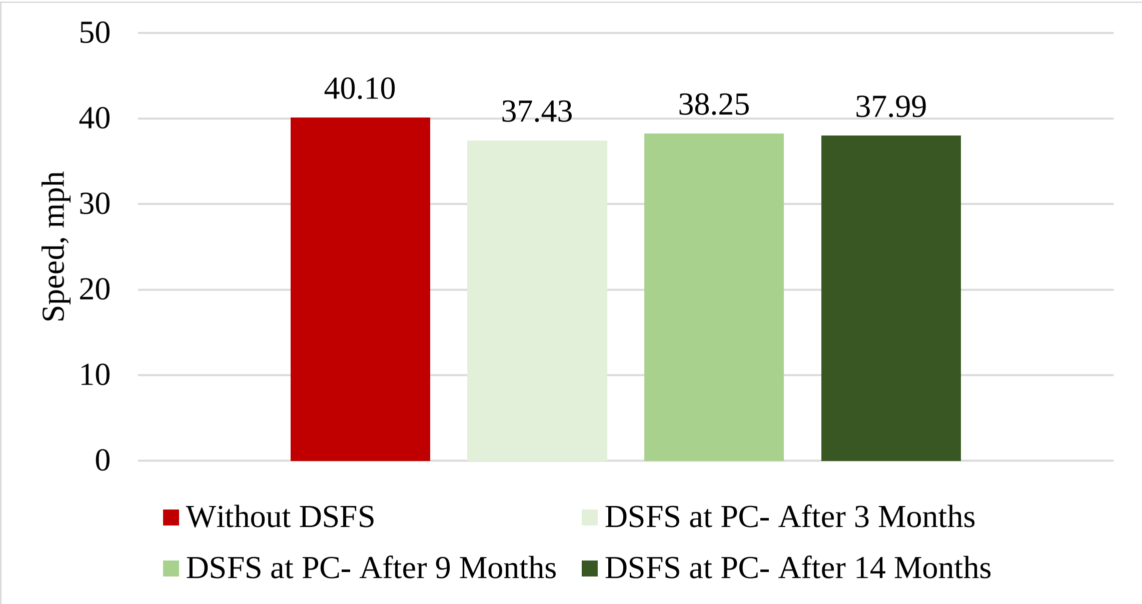


Figure 28. Average curve entry speeds before DSFS installation and during the 14-months after DSFS installation

8.3.2 Extreme curve entry speeds

The DSFS also decreased the occurrence of excessive curve entry speeds following the installation of the sign, and this effect also persisted over time. The elasticity values calculate from the parameter estimated in Table 25 show that vehicles were 4.2, 2.6, and 2.0 times more likely to enter the curve with a speed lower than 45 mph compared to the before condition without DSFS after 3, 9, and 14 months of installation, respectively.

Table 25. Binary logistic regression results for curve entry speed <45 mph

Response Variable: Speed at PC <45 mph					
Parameter	**Estimate**	**Std. Error**	**t-value**	**p-value**	**Exp(B)**
Intercept	15.265	2.165	7.052	<0.001	4259478
Speed 1000-ft Upstream of the PC	-0.214	0.033	-6.420	<0.001	0.807
Passenger Vehicle with No Trailer			*Base Condition*		
Passenger Vehicle with Trailer	-0.295	1.095	-0.269	0.788	0.745
Single Unit Truck/ Bus	15.819	2714.632	0.006	0.995	7418324
Tractor Trailer Truck	15.635	1172.820	0.013	0.989	6167362
Without DSFS at the Site			*Base Condition*		
DSFS at PC- After 3 Months	1.436	0.770	1.866	0.062	4.204
DSFS at PC- After 9 Months	0.960	0.765	1.254	0.210	2.611
DSFS at PC- After 14 Months	0.699	1.060	0.659	0.510	2.011

8.4 Conclusion and Direction for Further Evaluation

This research phase sought to evaluate temporal changes in the effect of DSFS on driver behavior during the initial 14-months after installation of a DSFS at a single system interchange ramp. Driver behavior data were collected before installing the sign, and 3 months, 9 months, and 14 months after installation of the sign. Compared to the period before DSFS installation, the DSFS reduced curve entry speeds both initially, and throughout the 14-months after installation. The DSFS also reduced the number of vehicles entering the curve at speeds of 45 mph or above. Although these data were only collected at a single site, the results suggest that the DSFS does not lose effectiveness towards reducing curve entry speeds over time. It is recommended that future research continue to monitor curve entry speeds both at this location and at future DSFS freeway exit ramp installations.

9. PRIORITIZATION OF POTENTIAL FREEWAY RAMP SITES FOR FUTURE DSFS INSTALLATION

This section focused on the identification and prioritization of potential freeway exit ramps for future DSFS installation. To do this, statewide crash data were collected and analyzed for freeway ramps throughout Michigan between the years 2014-2016 and 2018-2019. The 2017 data were excluded in the analysis as speed limit increases occurred in several stages throughout this year on more than 600 miles of rural freeways.

9.1 Eligible Ramp Sites

A total of 360 exit ramps were identified as potential candidates based on several factors including:

- presence of ramp advisory speed signs,
- ramps with advisory speeds less than or equal to 30 mph, and
- single-lane exit ramp.

The selected ramps include 253 service interchanges (freeway to non-freeway), and 107 system interchanges (freeway to freeway).

9.2 Data Collection

Three different data sources were utilized in this study, which include: crash data from Michigan State Police (MSP), Traffic Data Management System (TDMS) from MDOT, and manual data collection using satellite imagery from Google Earth. Total crashes and lane departure crashes were collected for each analysis year from the MSP annual crash database. The lane departure crashes were identified based upon the field from the MSP crash report form. For the purpose of this study, any crash categorized as involving some form of lane departure was considered as a target crash. Annual traffic volume information for each exit ramp was obtained from MDOT's TMDS website. Due to the limited information available for exit ramps characteristics, substantive manual data collection was conducted using Google Earth satellite imagery. The information collected includes exit ramp advisory speed, mainline speed limit, ramp length, and radius of curvature. Finally, data were integrated into one coherent format using a combination of ArcMap and Microsoft Excel.

9.3 Data Summary

The average traffic volume for the service interchange ramps ranged from a minimum of 141 veh/day to a maximum of 14,952 veh/day, with a mean of 3,116 veh/day. On average, 9.6 total crashes and 3.5 lane departure crashes occured per service interchange ramp during the 5 year analyses period. For the system interchanges, the average traffic volume ranged from 657 veh/day to 22,516 veh/day, with a mean of 7,678 veh/day. On average, 20.2 total crashes and 10.5 lane departure crashes occured per system interchange ramp during the 5 year analyses period.

9.4 Crash Rate Calculation and Ranking Method

Prioritization of the 253 exit ramps for potential future DSFS installation was based on raking of the lane departure crash rate (per million ramp vehicles) during the 5-year study period. The ramp lane departure crash rate was calculated using the following Equation 4:

$$R_{ramp} = = \frac{C\ X\ 10^6}{AADT * 365 * T} \quad (4)$$

Where,

R_{ramp} = Ramp lane departure crash rate (per million vehicles)

C = Lane departure crashes during the 5-year analysis period,

AADT = Average Annual Daily Traffic volume (vehicle/day)

T = Study period (5 years)

Tables 26 and 27 display the top 50 service and system interchanges based on the 5-year lane departure crash frequency. Please note that further assessment of each site is necessary in order to determine the suitability for DSFS installation. Additional information on assessing the suitability of a site for DSFS installation is provided in Section 10.2 in the following chapter. An aerial image for each of these 50 service and system interchanges is provided in Appendix B and C, respectively.

Table 26. Prioritized list of potential ramps for future DSFS installation (service interchanges)

Rank	Ramp Description	Ramp advisory speed	Mainline speed limit	5-year total crash frequency	5-year lane departure crash frequency	AADT	Lane departure crash rate (per million vehicles)
1	EB I-94 to Friday Rd	25	70	61	47	2745	9.38
2	SB US-23 to North Rd	30	70	40	35	1686	11.38
3	EB I-94 to 23 Mile Rd	30	70	102	34	14952	1.25
4	EB I-94 to 16 Mile Rd	30	70	68	32	6146	2.85
5	EB I-94 to N River Rd	25	70	43	28	5709	2.69
6	WB I-94 to Shook Rd	25	70	25	21	3809	3.02
7	SB I-75 to Swan Creek Rd	30	70	30	18	3707	2.66
8	NB I-75 to Westside Saginaw Rd	25	70	48	17	3477	2.68
9	NB US-127 to E Washington Rd	25	75	19	14	1354	5.66
10	EB I-96 to Highland Rd	30	70	15	13	4572	1.56
11	NB I-675 to Davenport Ave	30	70	16	13	8289	0.86
12	NB I-75 to N Adams Rd	25	70	15	12	3091	2.13
13	WB I-69 to S Sheridan Ave	25	75	13	12	3151	2.09
14	NB US-127 to Trowbridge Rd	25	70	12	11	1924	3.13
15	NB US-127 to Dunckel Rd	25	70	15	10	2723	2.01
16	NB I-75 to Corunna Rd	30	70	80	10	9398	0.58
17	NB US-131 to 12th St	25	70	11	9	1051	4.69
18	WB I-196 to Chicago Dr SW	30	70	10	9	1134	4.35
19	EB I-94 to Harper Ave	20	70	32	9	3903	1.26
20	WB I-94 to Little Mack Ave	25	70	27	9	4028	1.22
21	SB I-75 to N Meridian Rd	25	75	10	8	719	6.10
22	EB I-94 to Harper Ave	25	70	28	8	1568	2.80
23	WB I-94 to Rotunda Dr	20	70	10	8	3051	1.44
24	WB I-69 to Morrish Rd	25	70	10	8	3476	1.26
25	EB I-94 to Little Mack Ave	25	70	19	8	3672	1.19
26	EB I-96 to Plainfield Ave NE	25	70	15	8	10247	0.43

Table 26 (Continued). Prioritized list of potential ramps for future DSFS installation (service interchanges)

Rank	Ramp Description	Ramp advisory speed	Mainline speed limit	5-year total crash frequency	5-year lane departure crash frequency	AADT	Lane departure crash rate (per million vehicles)
27	EB I-94 to William P Rosso Hwy	30	70	8	8	13189	0.33
28	NB US-127 to E Lincoln Rd	25	75	7	7	859	4.47
29	SB I-75 to Holly Rd	25	70	8	7	1318	2.91
30	WB I-94 to Scottdale Rd	25	70	12	7	1781	2.15
31	EB I-94 to M 40	30	70	25	7	2695	1.42
32	NB US-127 to Springport Rd	25	70	7	7	2816	1.36
33	WB I-96 to 68th Ave	25	70	31	7	3335	1.15
34	SB I-75 to Joslyn Rd	30	70	13	7	3463	1.11
35	NB M-53 to 23 Mile Rd	25	70	70	7	3500	1.10
36	NB US-131 to Allegan St	25	70	10	7	5200	0.74
37	WB I-94 to W Michigan Ave	30	70	12	7	6272	0.61
38	NB US-23 to Dixie Hwy	25	70	13	6	2034	1.62
39	WB I-94 to Harper Ave	15	70	27	6	2403	1.37
40	WB I-94 to Gratiot Ave	20	55	21	6	3382	0.97
41	WB I-94 to M 51	25	70	13	6	3833	0.86
42	EB I-96 to Aurelius Rd	25	70	9	6	4018	0.82
43	SB US-23 to W Silver Lake Rd	30	70	12	6	4321	0.76
44	EB I-94 to 11 Mile Rd	25	70	14	6	4331	0.76
45	WB I-96 to N Fowlerville Rd	25	70	12	6	4888	0.67
46	EB I-96 to E Saginaw Hwy	25	70	13	6	7370	0.45
47	NB I-69 to Miller Rd	25	70	10	5	1092	2.51
48	WB US-10 to M 47	25	75	6	5	1655	1.66
49	EB I-94 to Sargent Rd	30	70	5	5	1971	1.39
50	NB US-31 to Fruitvale Rd	25	70	6	5	2449	1.12

Table 27. Prioritized list of potential ramps for future DSFS installation (system interchanges)

Rank	Ramp Description	Ramp advisory speed	Mainline speed limit	5-year total crash frequency	5-year lane departure crash frequency	AADT	Lane departure crash rate (per million vehicles)
1	EB I-96 to NB US-131	25	70	58	50	6642	4.12
2	SB M-10 to EB M-8	30	70	45	34	13594	1.37
3	EB M-5 to EB I-696	30	70	31	27	8288	1.78
4	SB I-75 to WB US-10	30	70	27	26	3206	4.44
5	NB M-39 to EB I-96	30	70	48	26	17768	0.80
6	SB US-131 to WB I-196	30	70	47	25	11242	1.22
7	EB I-96 to NB US-127	25	70	30	24	5700	2.31
8	WB I-96 to SB US-131	25	70	25	23	5350	2.36
9	WB I-94 to SB US-23	25	70	28	23	9450	1.33
10	NB I-75 to WB M-59	25	70	35	22	6541	1.84
11	WB M-14 to SB I-275	25	70	27	20	15752	0.70
12	EB I-75 to NB M-10	25	70	35	19	8894	1.17
13	EB I-94 to NB I-69	25	70	22	19	9573	1.09
14	EB I-196 to NB US-131	30	70	33	19	12634	0.82
15	WB I-196 to SB US-131	30	70	37	19	12667	0.82
16	WB I-75 to NB M-10	20	70	25	18	4553	2.17
17	WB I-96 to SB M39	30	70	31	18	10188	0.97
18	NB US-127 to WB I-96	25	70	20	17	4425	2.11
19	NB US-131 to WB I-196	30	70	34	17	5683	1.64
20	SB US-131 to EB I-196	30	70	27	17	9707	0.96
21	SB US-23 to EB I-94	25	70	22	17	13102	0.71
22	WB M-59 to SB I-75	25	70	39	17	14070	0.66
23	NB I-275 to WB I-94	30	70	24	16	7011	1.25
24	NB I-75 to EB I-94	30	70	60	16	15962	0.55
25	SB US-31 to EB I-94	30	70	18	14	981	7.82
26	SB I-75 to EB M-8	30	70	31	14	1771	4.33
27	EB M-6 to NB US-131	30	70	17	14	6214	1.23
28	SB M-39 to EB I-96	30	70	26	14	9784	0.78
29	SB I-75 to EB M-59	25	70	42	14	16815	0.46
30	EB I-675 to NB I-75	25	70	16	13	946	7.53

Table 27 (Continued). Prioritized list of potential ramps for future DSFS installation (system interchanges)

Rank	Ramp Description	Ramp advisory speed	Mainline speed limit	5-year total crash frequency	5-year lane departure crash frequency	AADT	Lane departure crash rate (per million vehicles)
31	WB I-94 to SB I-75	30	70	38	13	15300	0.47
32	SB I-75 to WB I-94	30	70	97	13	18046	0.39
33	NB M-10 to WB M-8	30	70	23	12	2163	3.04
34	WB I-96 to NB US-131	25	70	19	12	5965	1.10
35	WB I-96 to NB US-131	25	70	17	12	8076	0.81
36	NB I-375 to WB I-75	30	70	22	12	10141	0.65
37	WB I-94 to NB I-96	30	70	25	12	22516	0.29
38	WB I-96 to SB I-69	30	70	15	11	3500	1.72
39	NB US-131 to EB I-96	25	70	15	11	4745	1.27
40	EB I-196 to SB US-131	30	70	19	11	6305	0.96
41	EB US-10 to NB I-75	25	75	11	10	2460	2.23
42	NB I-75 to EB US-10	30	70	16	10	3804	1.44
43	EB I-94 to NB I-131	25	70	16	10	4730	1.16
44	NB M-5 to SB I-275	30	70	12	10	4902	1.12
45	EB I-94 to NB US-23	25	70	13	10	8055	0.68
46	NB I-75 to WB US-10	25	70	13	10	8876	0.62
47	NB M-10 to EB M-8	30	70	18	10	12954	0.42
48	EB I-94 to NB I-75	30	70	29	10	18436	0.30
49	WB US-10 to NB I-75	30	70	10	9	1911	2.58
50	WB I-696 to SB M-5	30	70	14	9	5742	0.86

10. CONCLUSIONS AND RECOMMENDATIONS

10.1 Conclusions

A series of field evaluations were performed at six freeway interchange ramps to assess the impacts of speed feedback signs on various measures of driver behavior, particularly speed on the approach and entry to the ramp curve. Three commercially available speed feedback signs, which varied in size, border type, and radar detection range, were utilized during the field evaluations. The field evaluations were performed across multiple phases, each of which assessed important aspects related to the design, operation, and/or installation of the DSFS, including:

- sign messaging strategy,
- longitudinal positioning of the sign relative to the ramp curve,
- lateral positioning of the sign with respect to the side of the ramp,
- sign dimensions and other physical characteristics,
- radar activation range,
- time of day,
- interchange type, and
- temporal changes in driver behavior.

Considering all phases of the field evaluation, it was concluded that dynamic speed feedback signs are an effective countermeasure for reducing speeds of vehicles approaching and entering horizontal curves on freeway exit ramps. The most critical aspect influencing the effectiveness of the DSFS as a speed reduction countermeasure was the longitudinal positioning of the sign relative to the ramp curve. Generally speaking, the DSFS was effective across all sites and all test conditions as long as the sign was positioned within 250 ft of the start of the curve. Specifically, a DSFS positioned near the start of the curve resulted in curve entry speeds that were, depending on the condition, 1.5 mph to 4.0 mph lower than without a DSFS present. In contrast, the DSFS was consistently ineffective when positioned at greater distances upstream of the curve, perhaps due to drivers' tendencies to disregard warning messages that are provided too far in advance of the hazard.

Regarding the lateral sign position, the DSFS provided similar effects on driver behavior when installed in either the traditional right-side-mount or forward-mount positions, although the forward-mount contributed to speed reductions beginning further upstream. This was likely due to the greater visibility of the sign when positioned within the gore area, particularly for locations where a bridge overpass or other sight-obstruction immediately proceeds the ramp curve.

The strongest sign-related effects were associated with the radar detection range. With the DSFS installed near the start of the curve, the lowest curve entry speeds were observed for cases where the DSFS was positioned so feedback message activated for vehicles that were within 250 to 400 ft of the start of the curve. Activation of the display panel for vehicles further than 400 ft upstream of the curve did not provide additional speed reduction benefits. Not surprisingly, the DSFS was least effective when the feedback message did not activate until the vehicle was within 250 ft of the curve. This diminished effectiveness was likely due to drivers not being afforded adequate time to react and respond to the feedback message.

In terms of sign size, 15-inch and 18-inch display panels were found to be equally effective and may be used interchangeably at freeway exit ramps. A prominent yellow reflective border around the sign is recommended to help improve conspicuity during cases when the sign is activated late and/or when the sign is located in a visually cluttered environment. Interestingly, there was little difference in the speed reduction effects between the various sign messaging strategies, although slight benefits were observed when the speed number was alternated with a SLOW DOWN message, perhaps due to increased conspicuity of the alternating message frames. However, including an advisory speed panel within the DSFS assembly did not have a substantive impact on driver behavior.

Finally, while this research primarily evaluated the short-term effectiveness of DSFS, the speed reduction effects were sustained during the initial 14-months of operation for the lone permanent DSFS installation included in this study. Although the sample of heavy vehicles was somewhat limited across the field evaluations, the DSFS was similarly effective for heavy vehicles and passenger vehicles. In terms of interchange characteristics, the DSFS was equally effective irrespective of the mainline speed limit or ramp advisory speed. Additionally, the effectiveness of DSFS was similar between system interchanges and service interchanges. Finally, the DSFS did not show any significant effect on the speeds of mainline vehicles when activated.

10.2 Recommendations

Based on the study findings, the continued use of DSFS as a speed reduction treatment at freeway exit ramp curves is recommended. A series of specific recommendations related to the sign characteristics, operational performance, and installation details are provided in the following list.

These recommendations were developed on the basis of providing optimal DSFS performance towards reducing curve entry speeds, lane departures, and associated crashes, along with practical considerations. Further, these recommendations may be utilized by MDOT towards development of guidelines for the use of DSFS at freeway ramps and other highway warning curve applications, which are not addressed in the current MDOT special provision for speed feedback signs.

- **Site Selection:** Potential freeway exit ramp sites may be appropriate for 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 sign near the curve; the ramp gore area may be used as alternative
    - Clear visibility of the roadside within 20 feet of the traveled way for at least 600 ft in advance of the ramp curve (not necessary if sign is to be installed in the ramp gore area)

  <u>Related guidance within the current MDOT Draft Special Provision for DSFS:</u> None

- **Longitudinal sign installation position relative to the point of curvature:** Install the DSFS as close to the point of curvature as practical, but not more than 250 ft upstream of the curve.

  <u>Related guidance within the current MDOT Draft Special Provision for DSFS:</u> None

- **Lateral sign installation position:** Install the DSFS on the right-side of the ramp. When necessary, due to obstructions or terrain issues that would otherwise restrict the traditional right-side mount, the DSFS may be installed within the gore area of the ramp between the green Exit sign and the initial chevron. However, caution should be exercised when positioning the sign in the gore area, due to the increased likelihood that an errant vehicle may collide with the sign in this position. Thus, if possible, installing the sign in the traditional right-side mounting position is preferred.

Related guidance within the current MDOT Draft Special Provision for DSFS: None

- **Sign messaging strategy:** Program the sign to display the following messages:
    - For speeds at or below the advisory speed + 10 mph, display the speed number;
    - For speeds exceeding the advisory speed + 10 mph, display the measured speed alternating with a "SLOW DOWN" message. The message frames should be alternated at 0.5 second to 1.0 second intervals.
    - No maximum cap for 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.
    - Do not flash the display or utilize the strobe beacon, as the MUTCD specifically prohibits the use of flashing displays (Paragraph 1 in Section 2L.04 of the 2009 MUTCD) and strobe effects (Paragraph 4 of Section 2A.15 of the 2009 MUTCD) on changeable message signs, which the FHWA officially interprets to include radar speed feedback signs.

Related guidance within the current MDOT Draft Special Provision for DSFS: Similar messaging specifications are provided, but also include a provision to flash the speed number, which should be eliminated per the MUTCD.

- **Sign characteristics:** The DSFS should include a full matrix amber LED feedback display capable of displaying characters that are a minimum of 15 inches in height. To help improve conspicuity, the sign should include a prominent border (i.e., warning plaque) that includes microprismatic reflective yellow sheeting with black "YOUR SPEED" text. A supplemental advisory speed plaque with a black legend and border on a yellow background is optional.

Related guidance within the current MDOT Draft Special Provision for DSFS: Similar messaging specifications are provided, although no mention is made regarding the inclusion of a supplemental advisory speed plaque.

- **Sign activation range:** Ensure that the feedback panel activates for approaching vehicles a minimum of 250 ft in advance of the point of curvature.

  Relevant guidance on MDOT Draft Special Provision for DSFS: The special provision requires that the radar unit detect approaching vehicle speeds at a minimum distance of 600 ft, which is a sufficient detection range for timely activation of the feedback panel.

10.3 Limitations and Direction for the Future Research

While this research provided substantial evidence of the effectiveness of DSFS as a speed reduction countermeasure at freeway exit ramps across a variety of contexts, a future evaluation should assess the effectiveness of DSFS towards reducing the frequency/severity of ramp lane departure crashes. Furthermore, additional long-term evaluations should be performed to further confirm whether the speed reduction effects of DSFS remain consistent or diminish with time.

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APPENDIX A: STATE AGENCY SURVEY

QUESTIONNAIRE FORM

General

1. Does your state utilize Dynamic Speed Feedback Signs (DSFS) for <u>curve warning</u> on high speed roadways? Some examples are provided below, although other signs and/or messages (e.g., “REDUCE SPEED”, “TOO FAST”, etc.) are also acceptable.

2. If so, on what types of roadways (i.e., freeways, two-lane highways) are they used?
    a) Are they used at interchange exit ramp curves?

Sign Specifications and Operation

3. Does your state have a specification or special provision for these signs used for curve warning? If so, please attach the specification/special provision or provide a reference number. Also, if available, please attach some example vendor products/spec sheets/installation photos of such signs that have been utilized in your state along with approximate costs.

4. For high speed curve warning, especially freeway ramps, what types of message(s) or warning(s) are displayed and what are the speed thresholds for vehicles to trigger the message(s)/warning(s)?

5. Do the signs have the ability to communicate with the operations center and/or are the signs integrated with other components, such as ice or pavement sensors?

6. Are you able to collect and analyze the speed data from the sign's radar unit; alternatively, do you collect speed data using an add-on device? If so, what type of device?

Site Selection and Sign Installation

7. How are the curve sites selected?

8. Where is the sign positioned with respect to the curve (at the curve PC, XX ft upstream of PC, etc)?

9. For freeway exit ramp curve installations only - is there any particular location of the sign that best isolates exiting vehicles, while limiting detection of mainline vehicles in order to prevent false triggering of the sign?

10. How often do the signs need to be maintained or replaced due to vehicle strikes or other damage?

11. Do you have any feedback (formal or informal; written or anecdotal) regarding the benefits, drawbacks, lessons learned, driver behavioral impacts, etc regarding the use of the DSFS for curve warning?

SUMMARY OF SURVEY RESPONSES, BY STATE

State DOT	Key Findings
DSFS Use	
Arizona	• Started using temporary DSFS signs on mobile trailers for treatment at high crash locations on the state highway system • Started development of a statewide project to deploy the temporary DSFS signs on all types of roadways including ramps and two-lane highways
California	• Used DSFS on two-lane rural highway curves, but not too often
Florida	• Used DSFS on two-lane rural highway curves
Illinois	• Used DSFS on two-lane rural highway curves and freeway interchange ramps
Iowa	• Used DSFS and curve warning signs exclusively on two-lane rural highway curves as part of several research projects
Mississippi	• Used DSFS on two-lane rural highway curves and freeway interchange ramps
Missouri	• Used flashing beacons on overhead static warning signs on two-lane rural highway curves and freeway curves • Used height detection systems to detect trucks and activate flashers on truck tipping sign in advance of curves
New Mexico	• Used DSFS on two-lane rural highway curves
Oregon	• Used DSFS on two-lane rural highway curves and freeway curves • Used curve warning signs at the interchange ramps that display messages according to a weather responsive system (using temperature) indicating hazardous roadway conditions such as low visibility or slippery surface
Pennsylvania	• Used DSFS on two-lane rural highway curve and freeway to freeway interchange ramps
South Dakota	• Used DSFS on two-lane rural highway curves

Texas	• Used DSFS on two-lane rural highway curves and four-lane divided highways
Wisconsin	• Used DSFS on two-lane rural highway curves and freeway curves
Sign Specifications and Operation	

Arizona	• Sign is programmed in a way that
	  • Speeds 1-10 mph above the advisory speed will blink at the driver
	  • Speeds 11-20 mph above will also trigger a strobe light

California	• Follows sign specifications provided in section 87.14 of STANDARD SPECIFICATIONS published by Caltrans and recommendations include
	  • Comply with the California MUTCD, Chapter 2B
	  • Light Emitting Diode (LED) character display must be capable of displaying the detected vehicle speed within 1 second and remain blank when no vehicles are detected within the radar detection zone
	  • Have the option to flash the pre-set speed limit when the detected vehicle speed is 5 mph higher than the pre-set speed
	  • Characters must be a minimum 15 inches in height and visible from a minimum distance of 1,500 feet and legible from a minimum distance of 750 feet
	  • LEDs must be amber and have a wavelength from 590 to 600 nm and rated for a minimum of 100,000 hours
	  • Radar unit must be able to detect up to 3 lanes of approaching traffic and have a speed accuracy of ±1 mph

Illinois	• Used full matrix LED displays with 18-inch display digit height • Mounted on an 18-foot aluminum pedestal and added a custom 48-in by 18-in plaque stating “YOUR SPEED” • Positioned the sign on the curve, but prior to the point where the curve radius sharpens • Displayed amber lighted “SLOW DOWN” message and the minimum threshold to display a feedback message is generally 5 to 10 mph over the advisory speed

	• No speed feedback is provided for speeds 20 mph over the advisory speed, and instead only the “SLOW DOWN” message is displayed
Iowa	• Used speed feedback sign capable of displaying approaching vehicle speed alternating with speed limit information and curve warning sign displaying SLOW DOWN feedback along with a curve sign for vehicles above a certain threshold • Signs were set to activate when an oncoming vehicle’s speed >50th percentile speed for the curve
Mississippi	• Used static “YOUR SPEED” sign with the dynamic speed feedback display whenever installed • Used curve warning sign and accompanying advisory speed sign on curves
Missouri	• Used truck tipping (if truck related) horizontal alignment arrows or a text message like “Watch Your Speed”.

New Mexico	• Follows special provision for speed feedback sign that include
	  • LED display with attached sign or sign unit in combination with LED displays in compliance with the MUTCD
	  • Programmable sign with the capacity to display violator alerts including speed numbers and 'SLOW DOWN' text
	  • Sign display characters maybe 9", 12", 15", 18", and 22" in height
	  • Red-Blue flashing bars or white LED flashing strobes

Oregon	• Developed an ITS application that runs on the Advanced Transportation Controller and allows the controller to do a variety of ITS things including weather warning systems, queue warning systems, over height warning systems, and curve warning systems • Utilized a forward-facing radar unit and set custom speed thresholds to activate a blank-out sign, flashers, or activate a custom message on a variable message sign • Used a curve warning sign consists of a yellow arrow warning message with a “SLOW DOWN” feedback message underneath the arrow

	• Integrated radar gun with variable message sign (VMS) to provide curve waring on freeway curves using overhead VMS sign. Programmed the sign to display “SLOW DOWN, SHARP CURVE AHEAD” when approaching vehicles are traveling within the recommended advisory speed (50 mph) for the curve, display “SLOW DOWN, YOUR SPEED IS XX MPH” when a vehicle is traveling between 50-70 mph, display “YOUR SPEED IS OVER 70 MPH” when detected speed is over 70 mph • Used curve warning signs on freeway ramps indicating slippery or icy conditions via establishing communication with roadside RWIS and pavement sensors
Pennsylvania	• Used a curve warning sign consists of a yellow arrow warning message with a “SLOW DOWN” feedback message underneath the arrow.

South Dakota	• Follows provision for solar-powered speed feedback sign that include
	  • Sign should have a 28-in by 33-in “YOUR SPEED” faceplate and consist of a white or yellow background with 4-in lettering
	  • The height of the LED numeral on sign display should be 12-inch
	  • Sign should be programmed not to flash at drivers at any time
	  • Sign should provide a solid display of the driver speed followed by a solid display of “SLOW DOWN” as drivers exceed the speed limit of the area

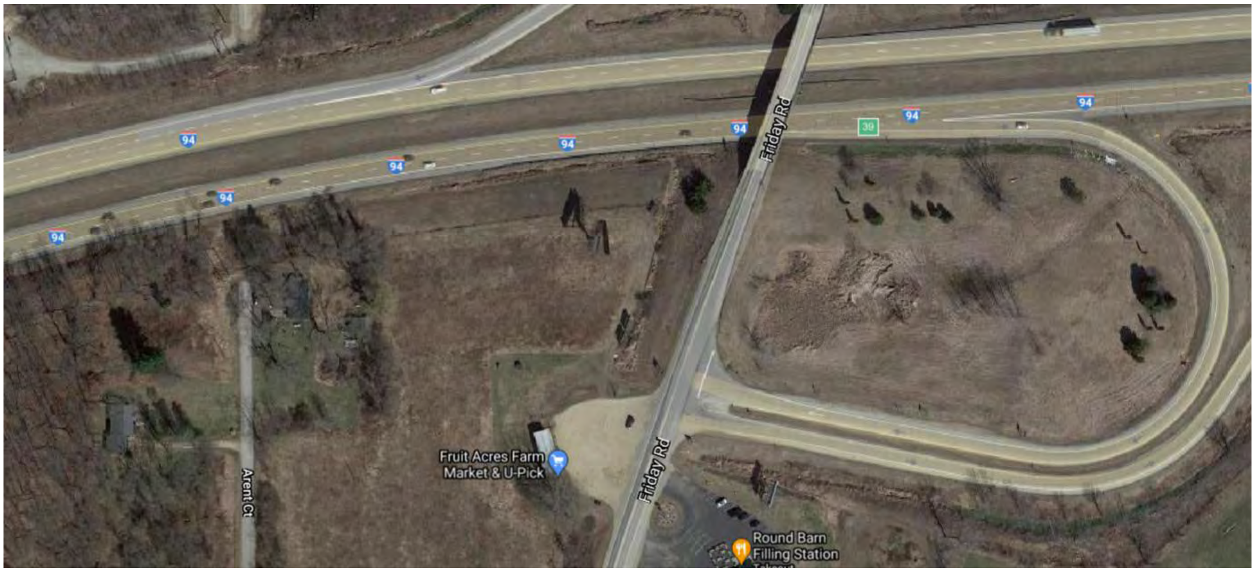
Texas	• Follows provision for solar powered speed feedback sign that include
	  • Furnish displays that flash the LEDs, when the detected vehicle speed exceeds the posted speed
	  • Sign display capable of displaying “YOUR SPEED” or “SLOW DOWN” in two lines of min 4 in. height
	  • The sign background shall be black and numeric speed display characters shall be 10 inches in height
	  • Radar controller should be FCC compliant K band radar microwave vehicle detector integrated with the sign with a factory preset range of 600 feet

	- Speed range of at least 5 to 99 mph should be used and the trigger speed shall be adjustable from the DFSS control - Controllers should be capable of providing local control of the unit and shall provide: on/off toggle control of the sign, and a changeable message that reads: “YOUR SPEED” or “SLOW DOWN” which shall be toggle switchable or keypad adjustable • Used dynamic curve warning system to warn and guide motorists through a curve once activated with radar by directing the chevrons to flash sequentially. Follows provision for a dynamic LED curve warning system that includes - LED chevron must be capable of detecting a compact vehicle within 300 feet and it must occur within 112 milliseconds of the vehicle arrival - Signals should be wirelessly transmitted to sequential signs to trigger a predetermined flash duration - Has the capacity to monitor and control the LED chevron signs through a web-based system that allows for management of device settings such as solar and battery output, flash durations, and counting the number of activations
Wisconsin	• Used overhead curve warning sign for mainline freeway vehicles • Programmed the sign to activate the message “TOO FAST FOR CURVE” at different speed thresholds based on vehicles types • The speed threshold for message activation for car/motorcycle is 67 mph, van/pick-up truck is 65 mph, bus/truck is 55 mph, and semi-trailer/tractor-trailer is 50 mph on a 50 mph roadway with 45 mph curve advisory speed
Site Selection and Sign Installation	
Arizona	• Curve sites selected based on crash data filtered for single vehicle roadway departure crash with a possible secondary filter of roll-over crashes

	• Sign positioning will be dependent on the geometry but will be positioned to provide information to drivers as they enter the curve
California	• Segments are selected based on crash data • Warning signs should be placed so that they provide an adequate perception reaction time and should not be placed too far in advance of the condition, such that drivers might tend to forget the warning because of other driving distractions, especially in urban areas
Illinois	• Sites selected based on crash analysis, particularly considering overturn and run-off the road crashes at the curve • Sign installation position must be designed for each location • The sign must be visible at a point where the feedback is actionable by the motorist and should avoid providing feedback too early, where the motorist does not see the need to act • The detection area of the sign must be considered as well • Shielding a portion of the radar detection area can be utilized to limit mainline interference when installed on ramps
Iowa	• Sites are selected based on crash history, suitability of location to install a sign and collect speed, and willingness of the agency to install the sign • Signs are placed at the same location a static curve advisory sign would be placed following the guidelines
Mississippi	• Sites are selected based on need and engineering study • Position the sign just in advance of the PC
Missouri	• Signs are installed to address specific concerns • Signs are placed at the same location a static curve advisory sign would be placed following MUTCD guidelines
New Mexico	• Signs are installed normally per request • Signs are positioned based on engineering judgment
Oregon	• Sites are selected based on crash history • Signs are positioned mostly after the static curve warning signs which are typically placed at or just before the point of tangent

South Dakota	• Sites are selected based on geometrics and crash history • Signs are positioned at the advance curve warning sign and advisory speed plaque according to the MUTCD.
Texas	• Sites are selected based on crash history, suggestions from law enforcement, and local compliant • Signs are positioned at the advance warning sign
Wisconsin	• Sites are selected on a case-by-case basis • Signs are positioned near the PC

APPENDIX B. POTENTIAL FREEWAY EXIT RAMP LOCATIONS FOR FUTURE DSFS INSTALLATION (SERVICE INTERCHANGE)



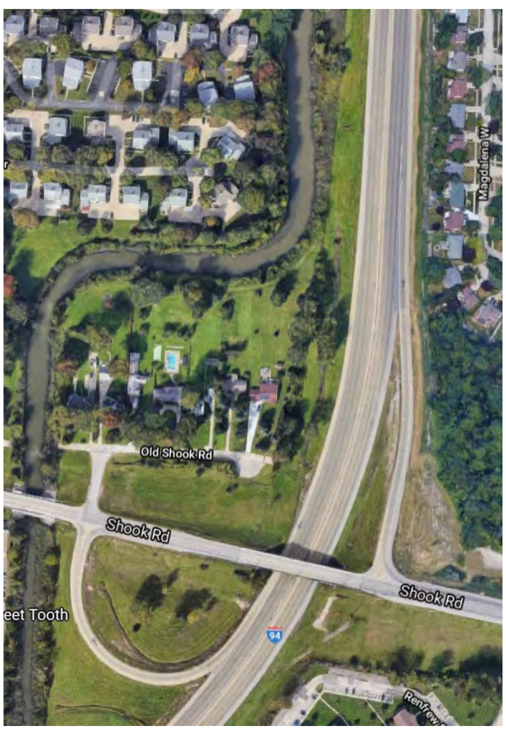
Rank 1: EB I-94 to Friday Rd

Rank 2: SB US-23 to North Rd

Rank 3: EB I-94 to 23 Mile Rd

Rank 4: EB I-94 to 16 Mile Rd

Rank 5: EB I-94 to N River Rd



Rank 6: WB I-94 Shook Rd

Rank 7: SB I-75 to Swan Creek Rd

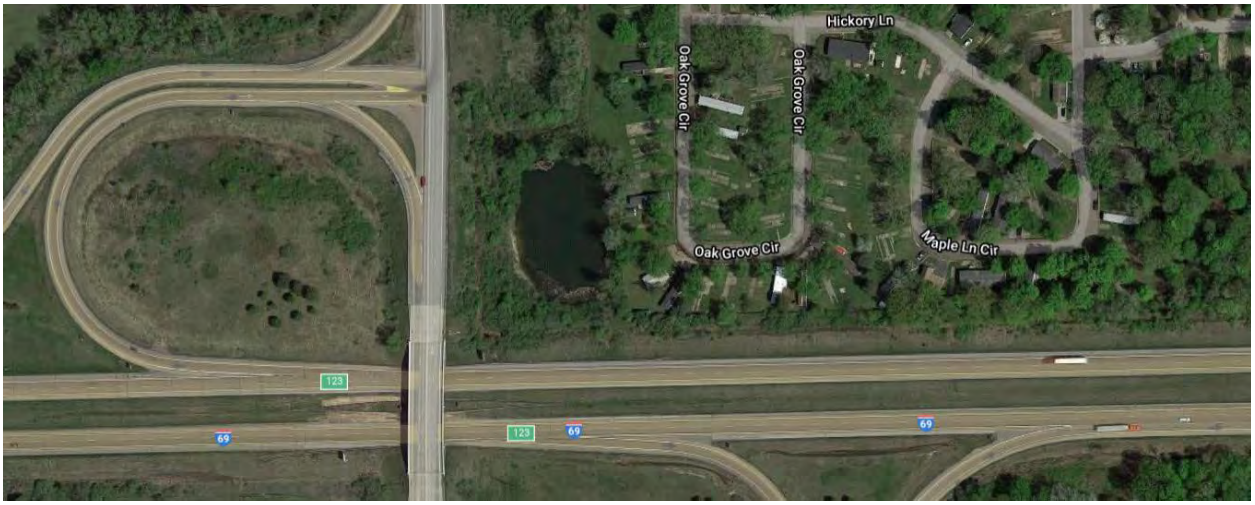
Rank 8: NB I-75 to Westside Saginaw Rd

Rank 9: NB US-127 to E Washington Rd

Rank 10: EB I-96 to Highland Rd

Rank 11: NB I-675 to Davenport Ave

Rank 12: NB I-75 to N Adams Rd



Rank 13: WB I-69 to S Sheridan Ave

Rank 14: NB US-127 to Trowbridge Rd

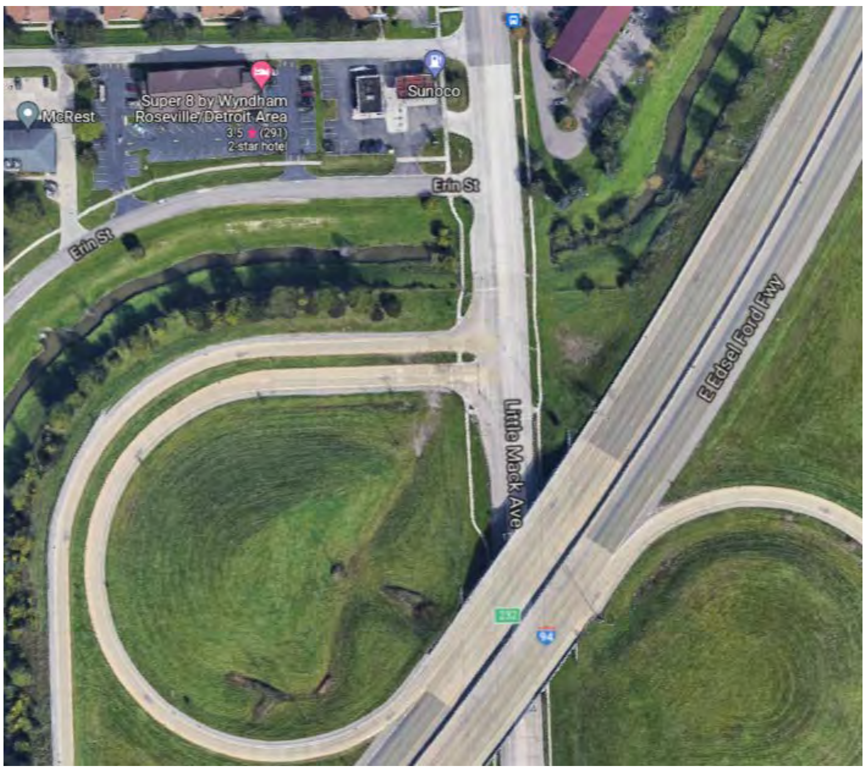
Rank 15: NB US-127 to Dunckel Rd

Rank 16: NB I-75 to Corunna Rd

Rank 17: NB US-131 to 12th St

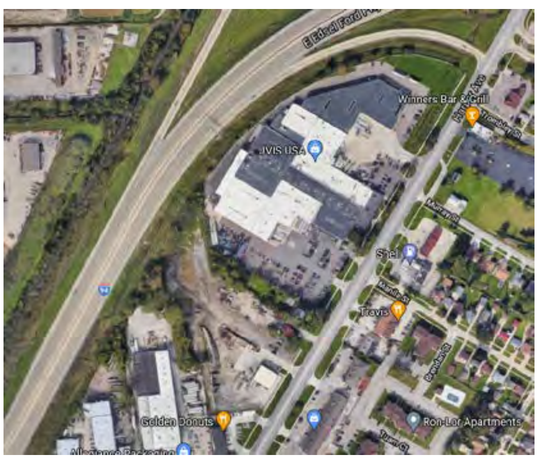
Rank 18: SB I-196 to Chicago Dr SW

Rank 19: EB I-94 to Harper Ave

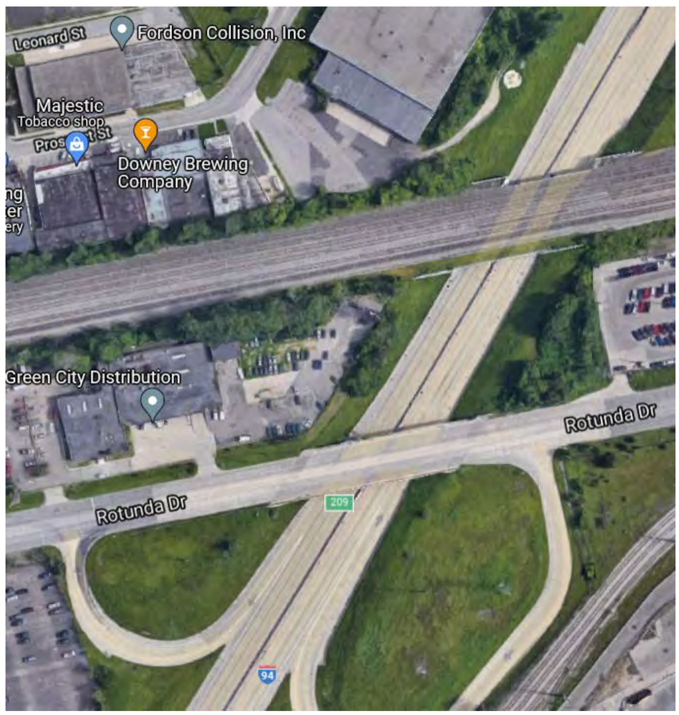


Rank 20: WB I-94 to Little Mack Ave

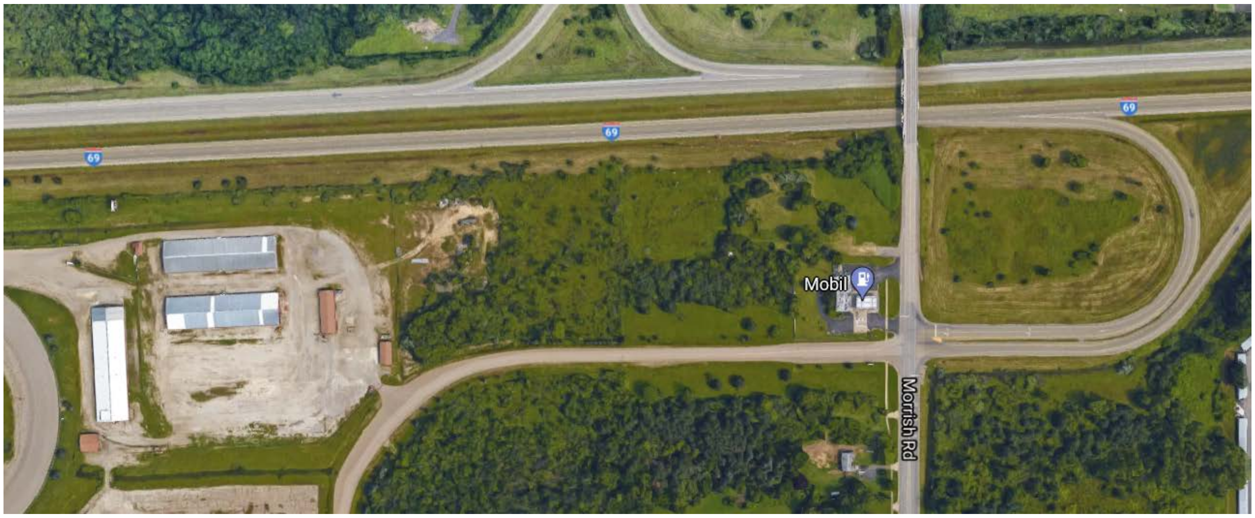
Rank 21: EB US-10 to N Meridian Rd



Rank 22: EB I-94 to Harper Rd



Rank 23: WB I-94 to Rotunda Dr



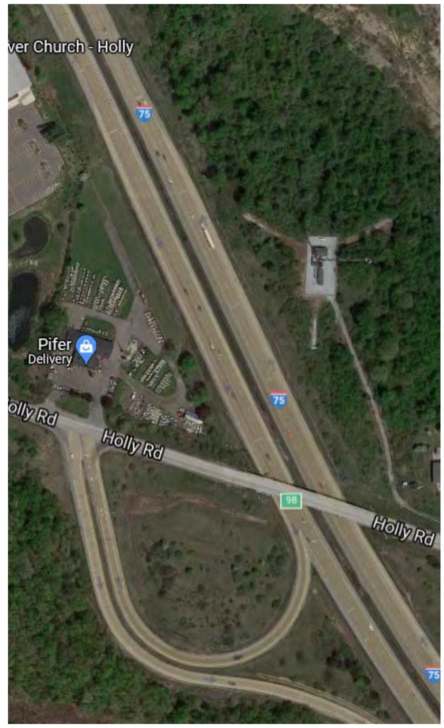
Rank 24: EB I-69 to Morrish Rd

Rank 25: EB I-94 to Little Mack Ave

Rank 26: EB I-96 to Plainfield Ave NE

Rank 27: EB I-94 to William P Rosso Hwy

Rank 28: NB US-127 to E Lincoln Rd

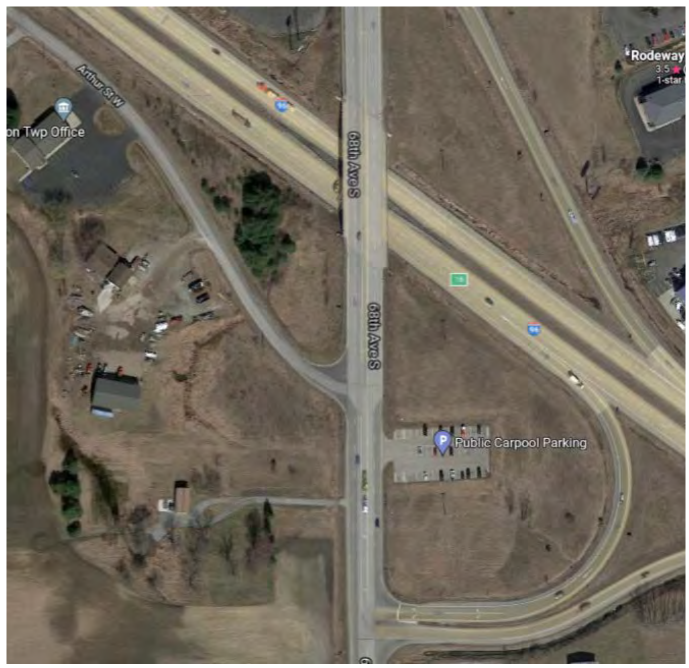


Rank 29: SB I-75 to Holly Rd

Rank 30: WB I-94 to Scottdale Rd

Rank 31: EB I-94 to M 40

Rank 32: NB US-127 to Springport Rd



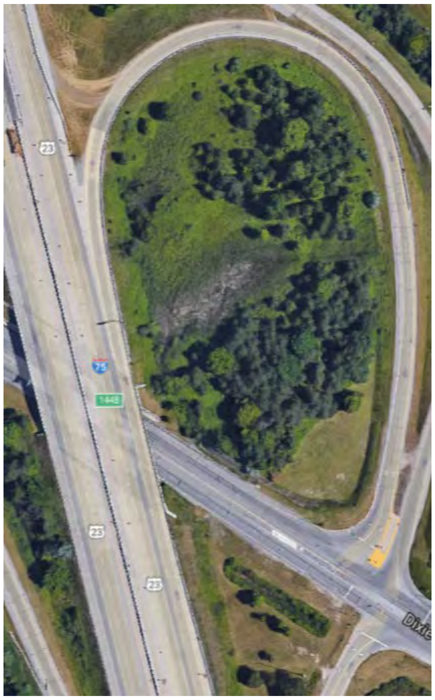
Rank 33: WB I-96 to 68th Ave

Rank 34: SB I-75 to Joslyn Rd

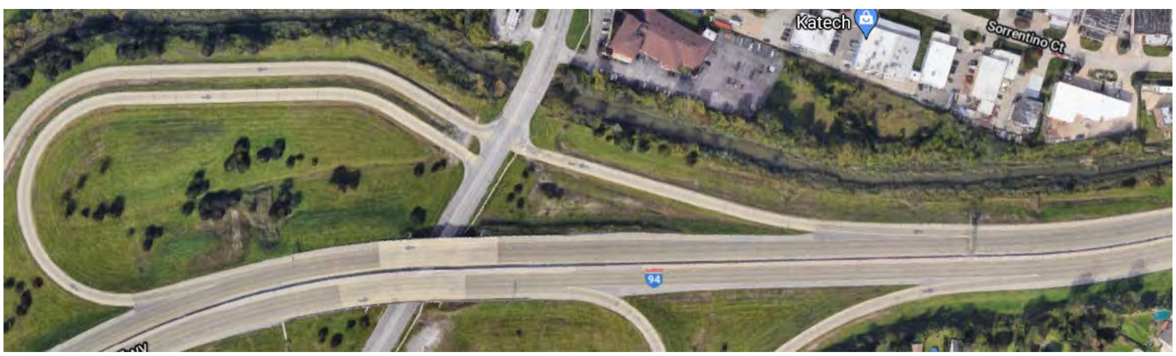
Rank 35: NB M-53 to 23 Mile Rd

Rank 36: NB US-131 to Allegan St

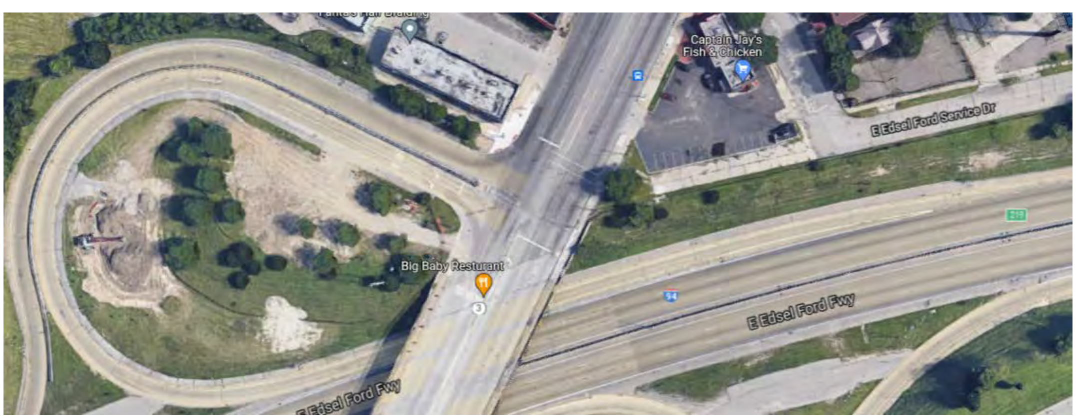
Rank 37: WB I-94 to W Michigan Ave



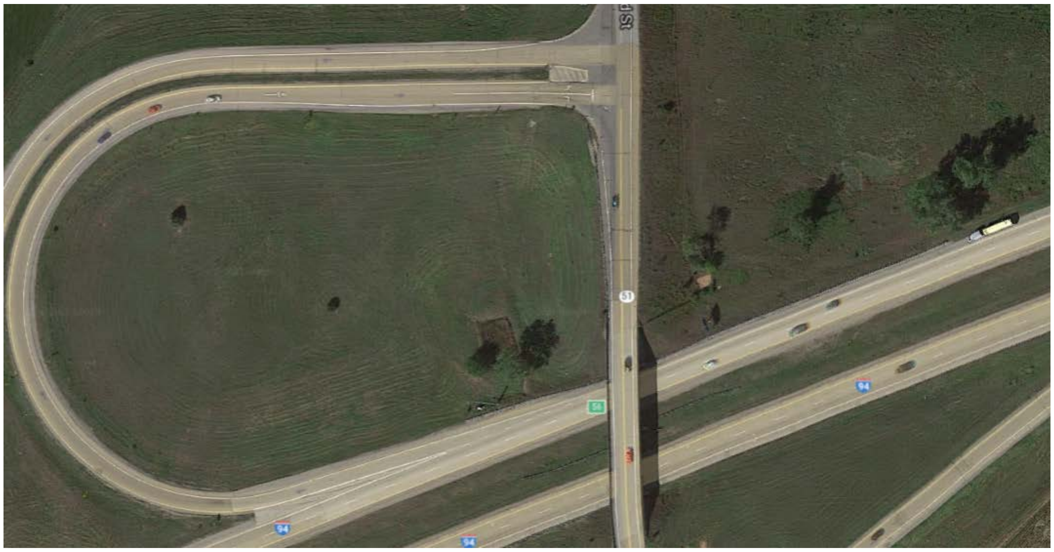
Rank 38: NB US-23 to Dixie Hwy



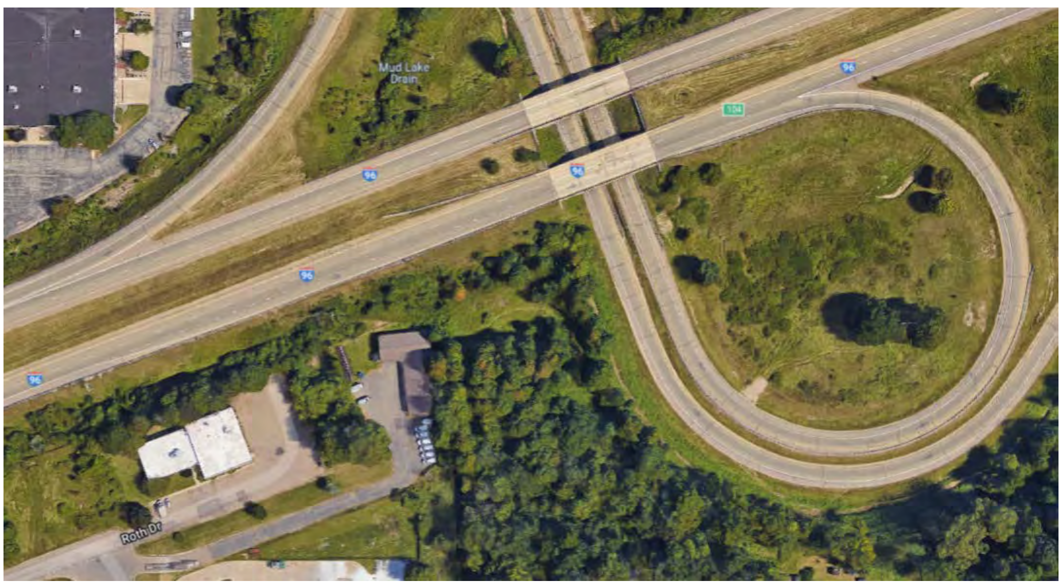
Rank 39: WB I-94 to Harper Ave



Rank 40: WB I-94 to Gratiot Ave

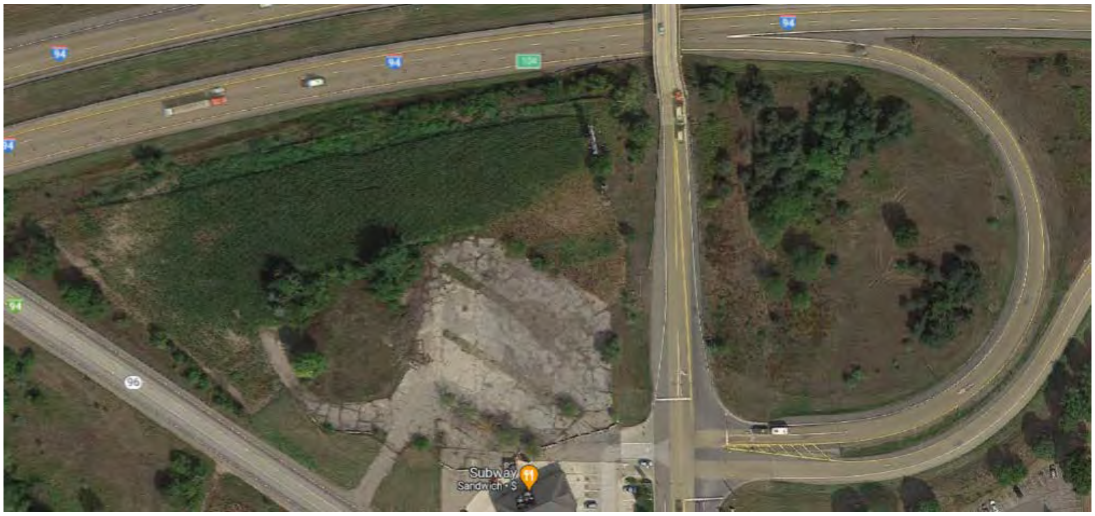


Rank 41: WB I-94 to M 51

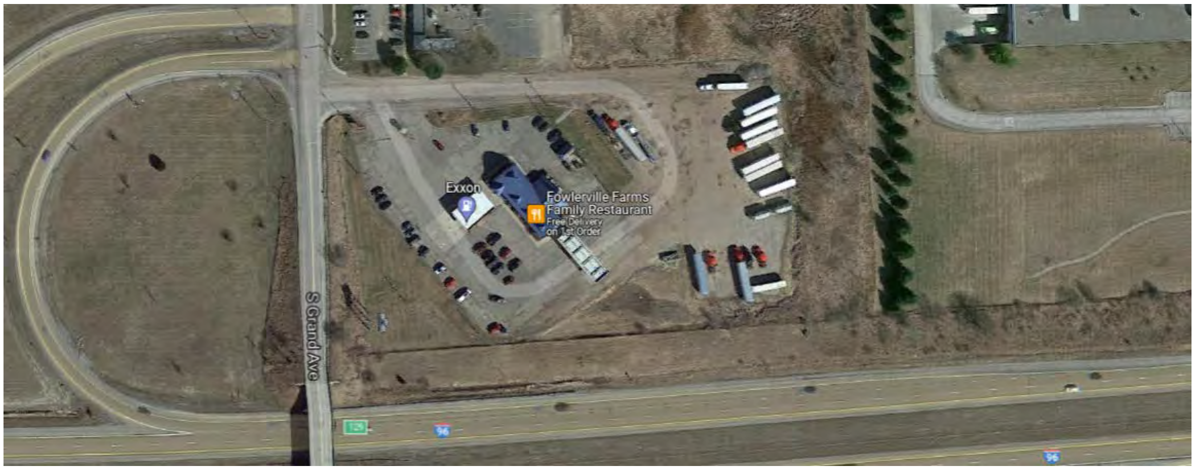


Rank 42: EB I-96 to Aurelius Rd

Rank 43: SB US-23 to W Silver Lake Rd

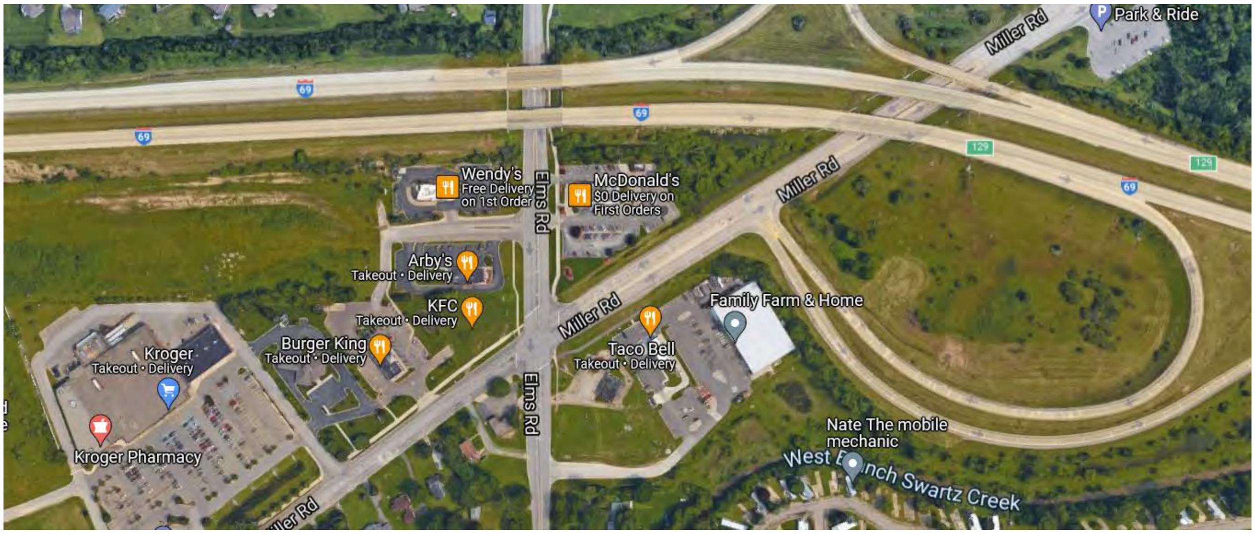


Rank 44: EB I-94 to 11 Mile Rd



Rank 45: WB I-96 to N Fowlerville Rd

Rank 46: EB I-96 to E Saginaw Hwy



Rank 47: EB I-69 to Miller Rd

Rank 48: WB US-10 to M 47

Rank 49: EB I-94 to Sargent Rd

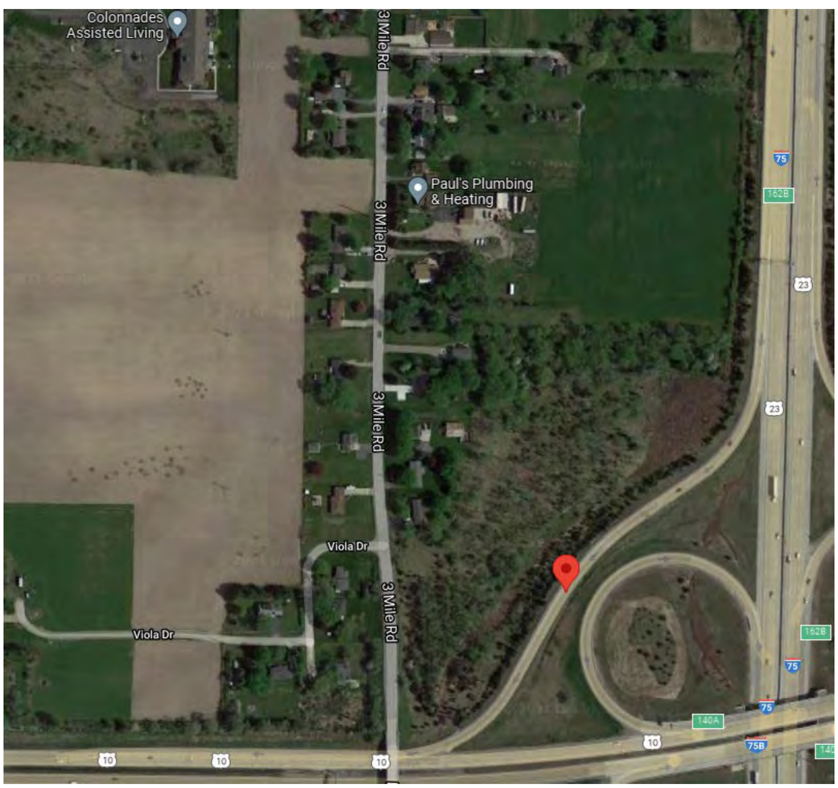
Rank 50: NB US-31 to Fruitvale Rd

APPENDIX C. POTENTIAL FREEWAY EXIT RAMP LOCATIONS FOR FUTURE DSFS INSTALLATION (SYSTEM INTERCHANGE)

Rank 1: EB I-96 to NB US-131

Rank 2 SB M-10 to EB M-8

Rank 3 EB M-5 to EB I-696



Rank 4 SB I-75 to WB US-10

Rank 5 NB M-39 to EB I-96

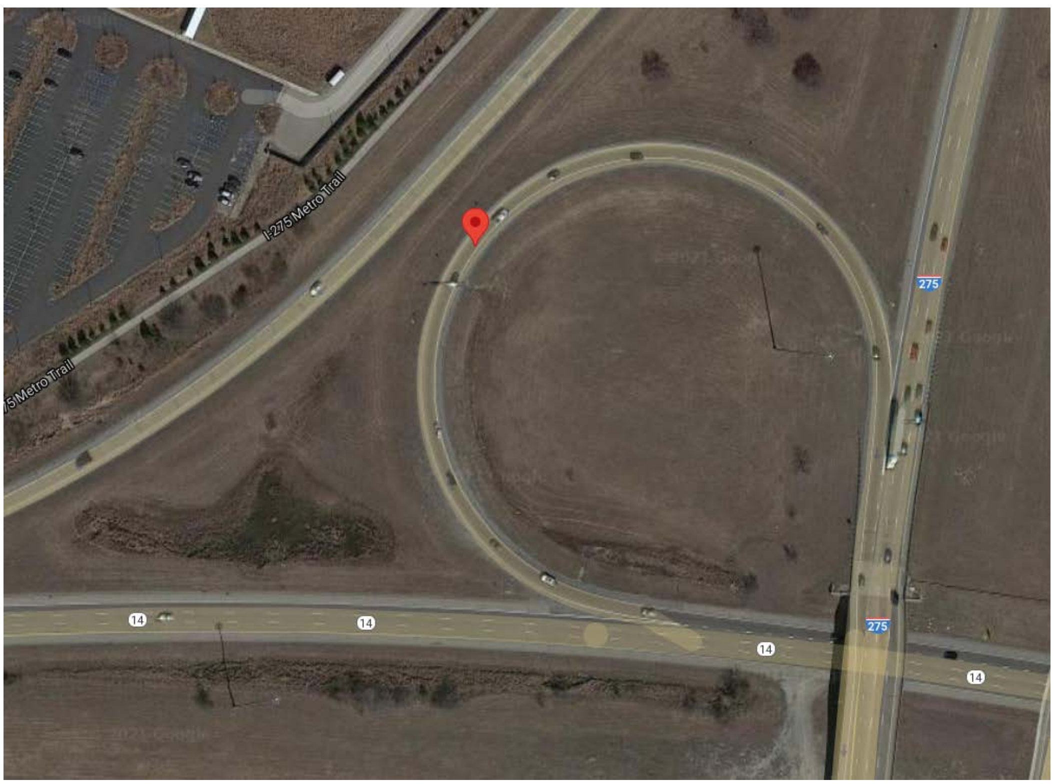
Rank 6 SB US-131 to WB I-196

Rank 7 EB I-96 to NB US-127

Rank 8 WB I-96 to SB US-131

Rank 9 WB I-94 to SB US-23

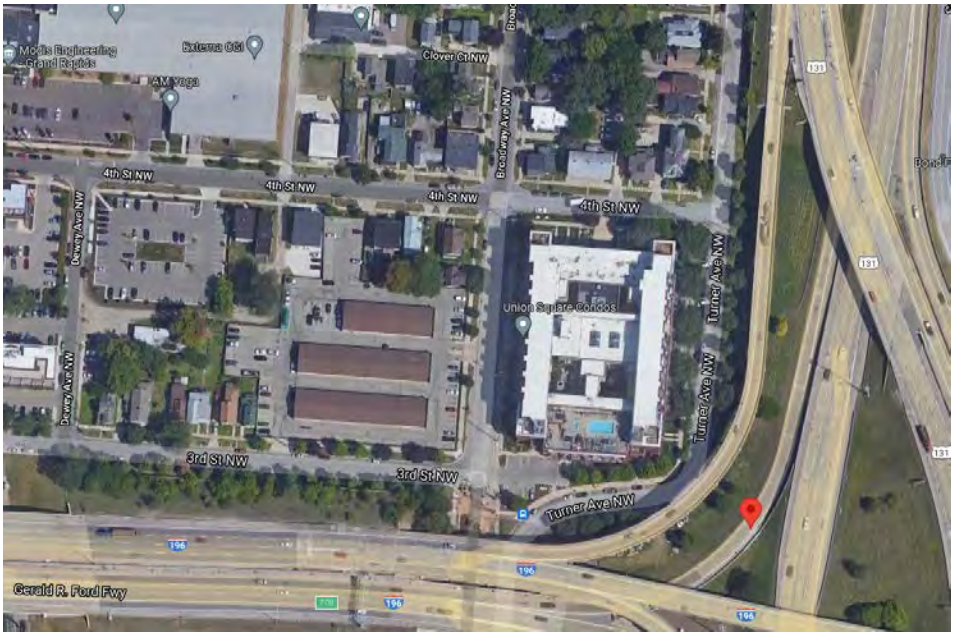
Rank 10 NB I-75 to WB M-59



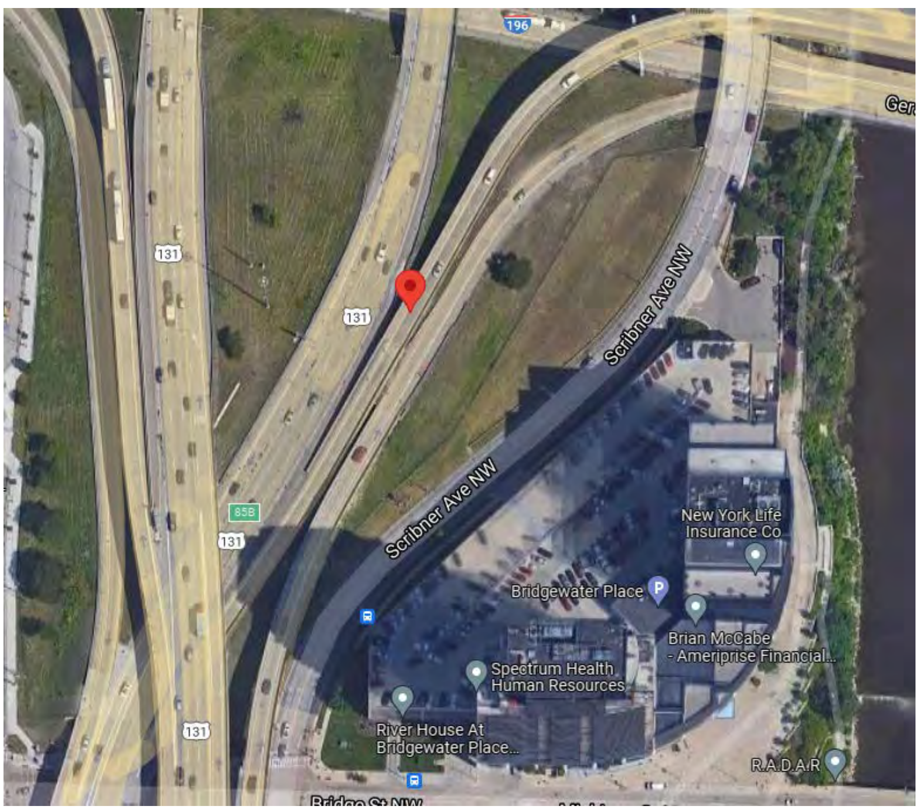
Rank 11 WB M-14 to SB I-275

Rank 12 EB I-75 to NB M-10

Rank 13 EB I-94 to NB I-69

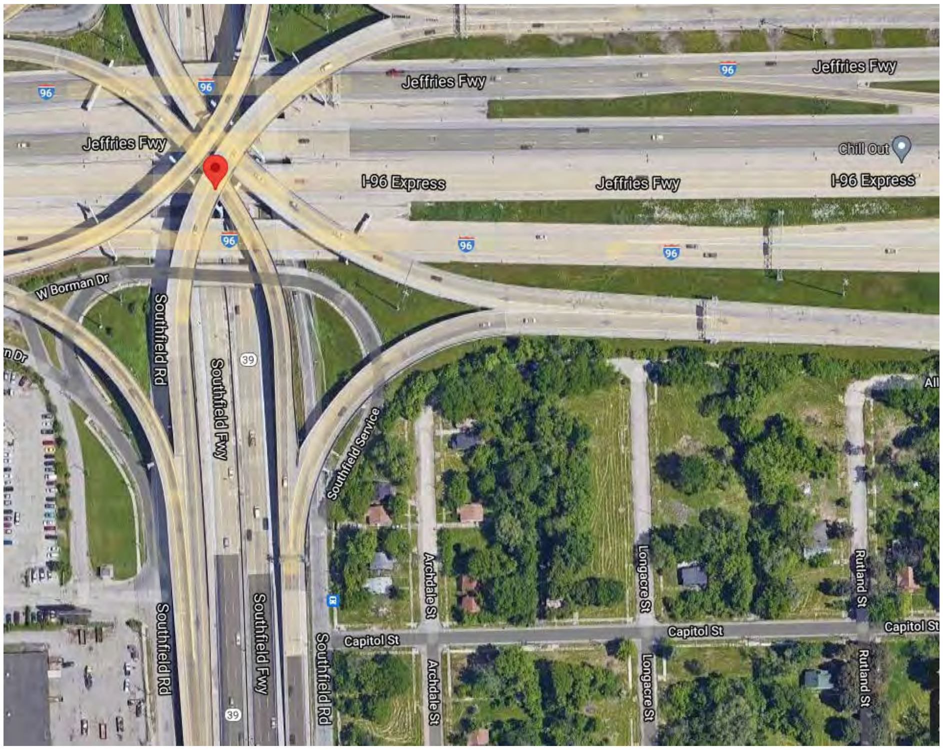


Rank 14 EB I-196 to NB US-131



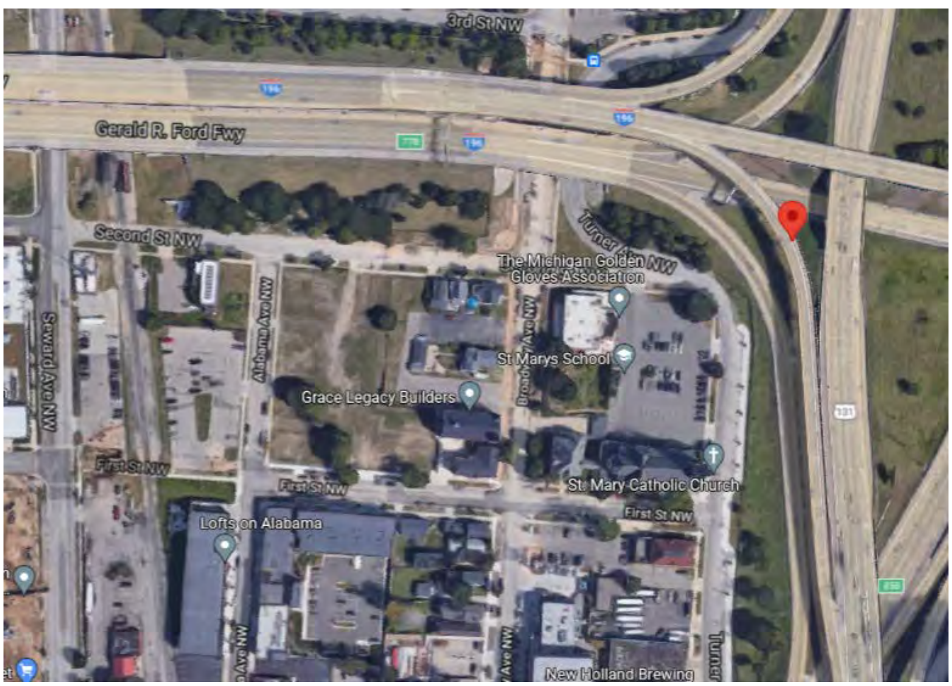
Rank 15 WB I-196 to SB US-131

Rank 16 WB I-75 to NB M-10



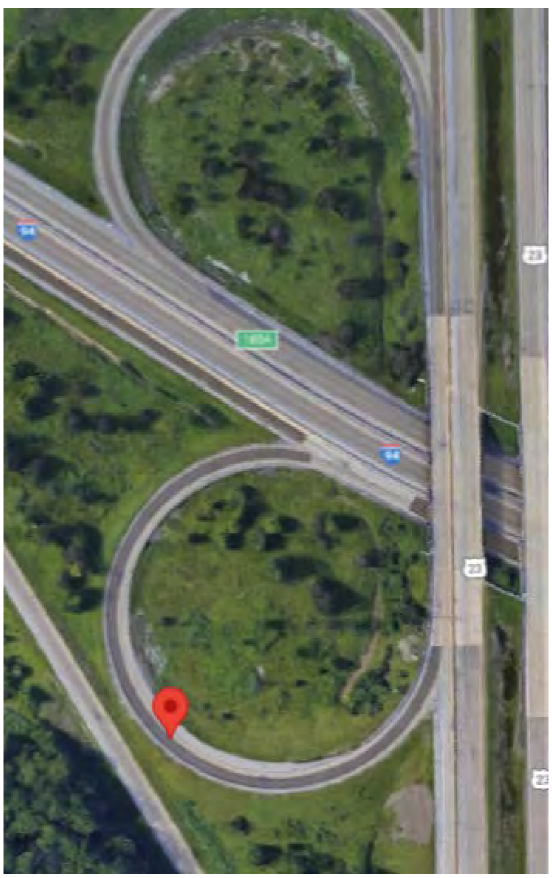
Rank 17 WB I-96 to SB M-39

Rank 18: NB US-127 to WB I-96



Rank 19: NB US-131 to WB I-196

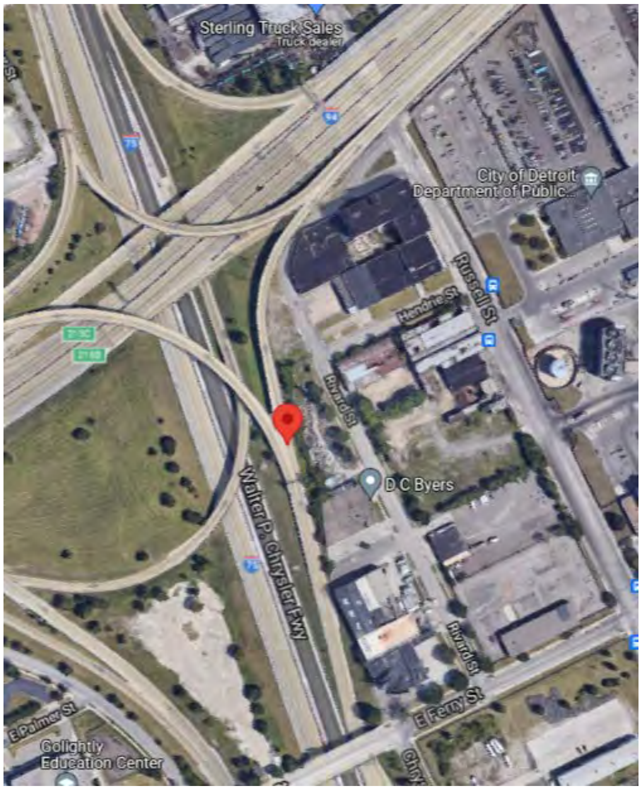
Rank 20: SB US-131 to EB I-196



Rank 21: SB US-23 to EB I-94

Rank 22: WB M-59 to SB I-75

Rank 23: NB I-275 to WB I-94

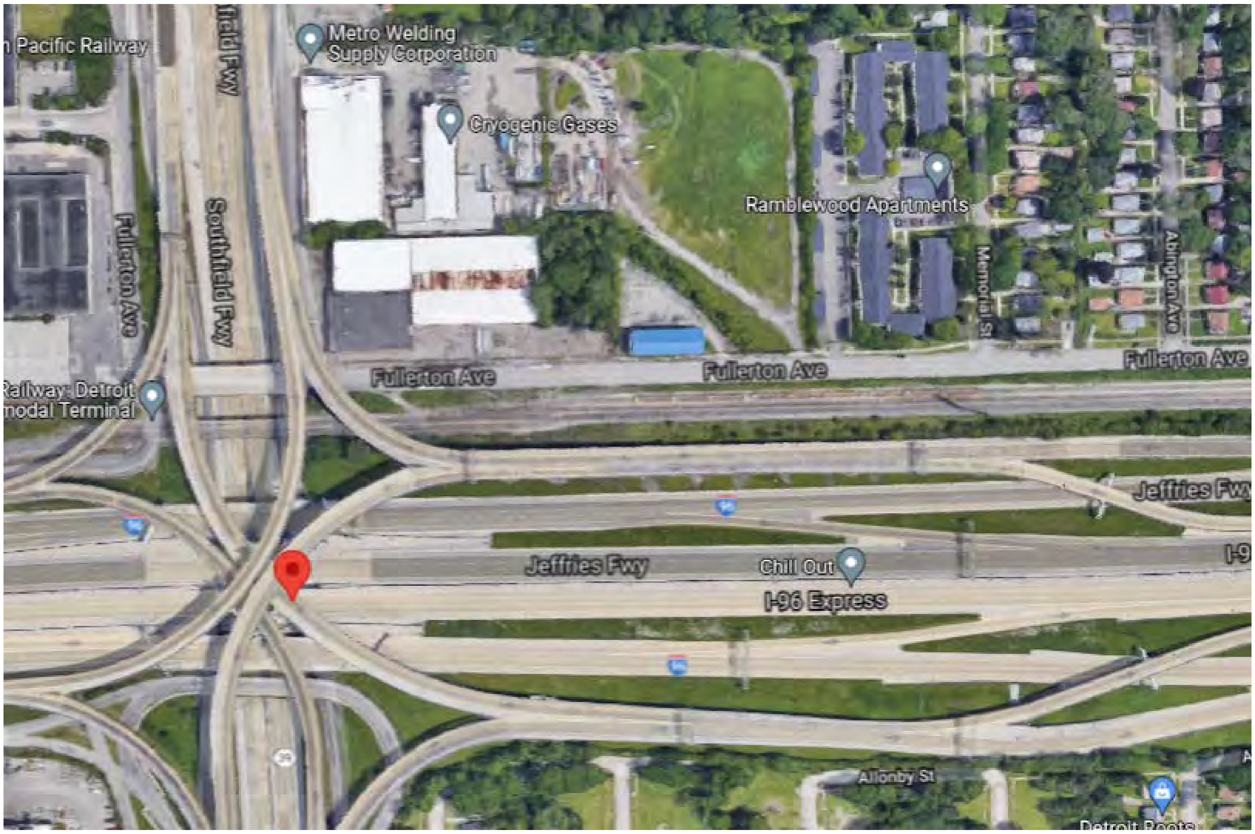


Rank 24: NB I-75 to EB I-94

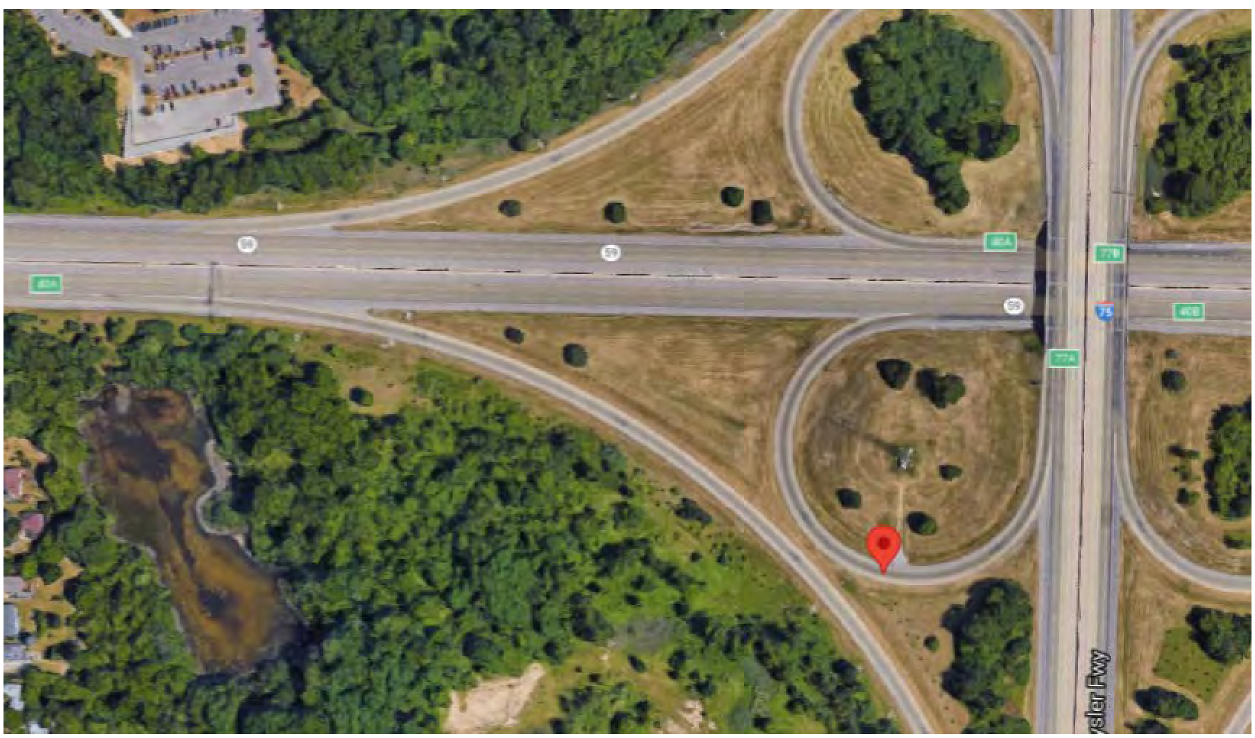
Rank 25: SB US-31 to EB I-94

Rank 26: SB I-75 to EB M-8

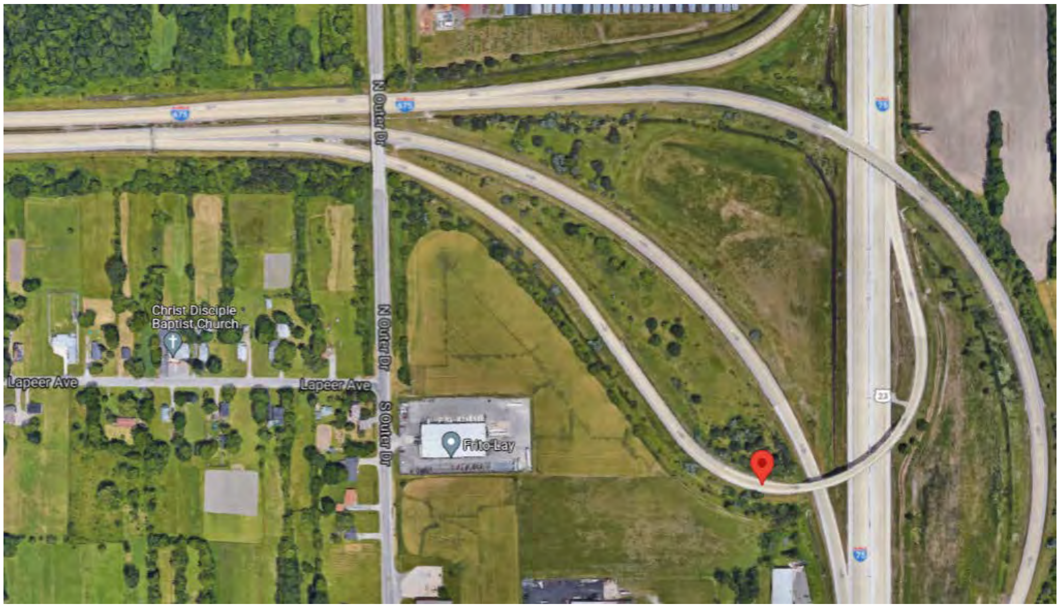
Rank 27: EB M-6 to NB US-131



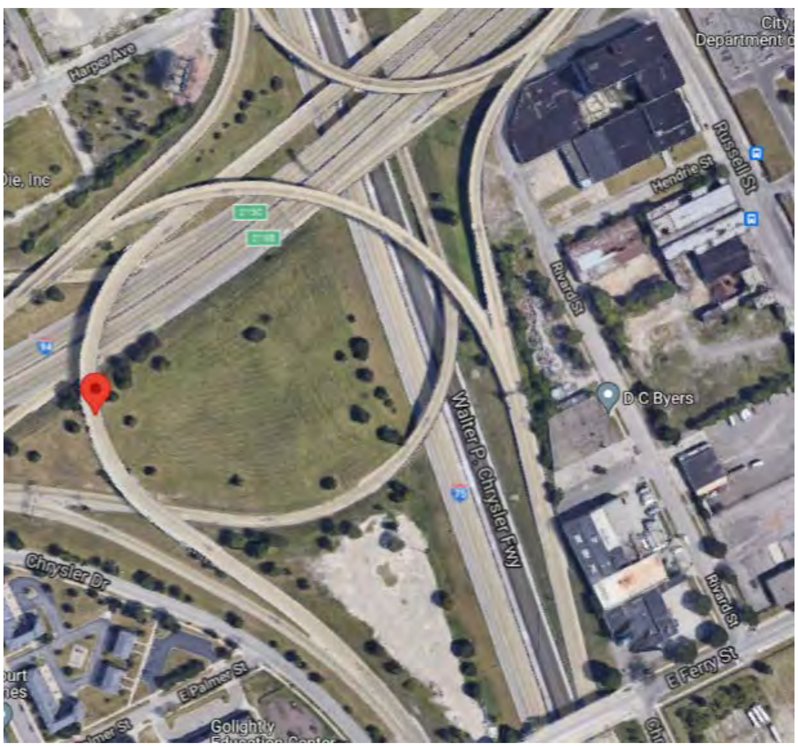
Rank 28: SB M-39 to EB I-96



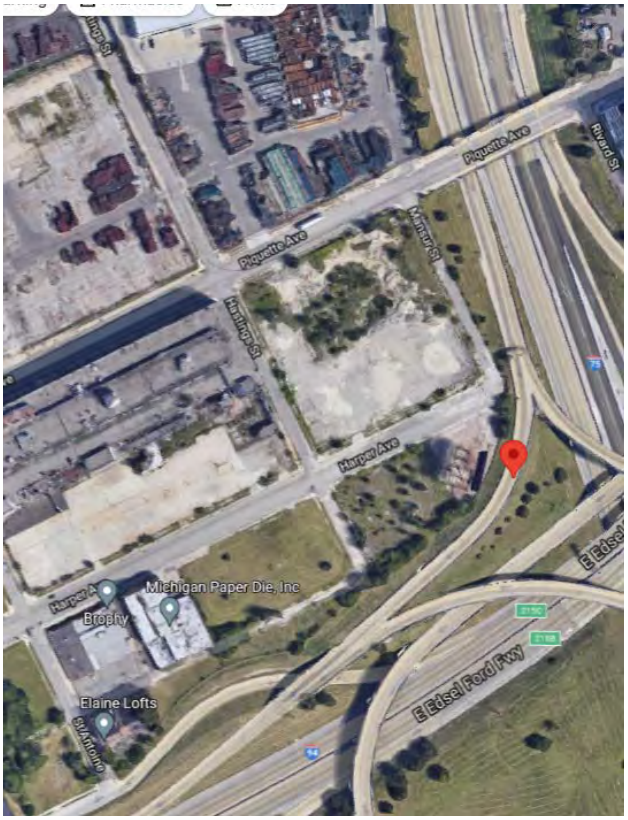
Rank 29: SB I-75 to EB M-59



Rank 30: EB I-675 to NB I-75



Rank 31: WB I-94 to SB I-75



Rank 32: SB I-75 to WB I-94

Rank 33: NB M-10 to WB M-8

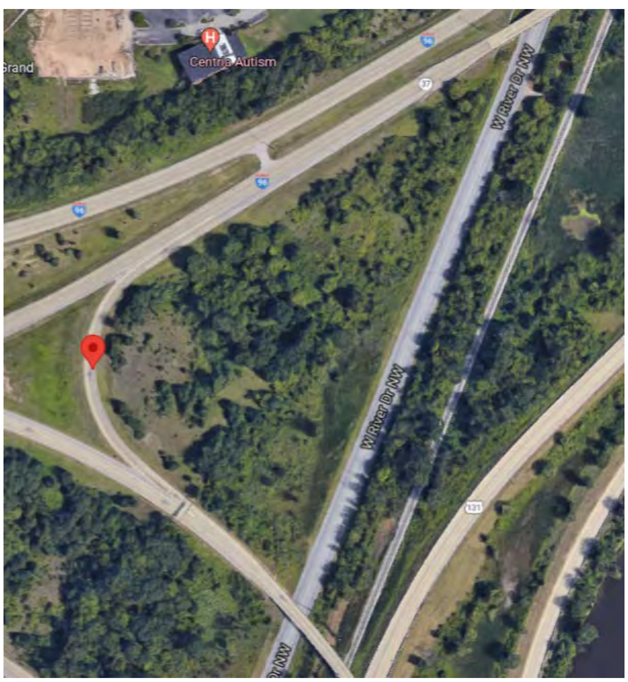
Rank 34: WB I-96 to NB US-131

Rank 35: WB I-96 to NB US-131

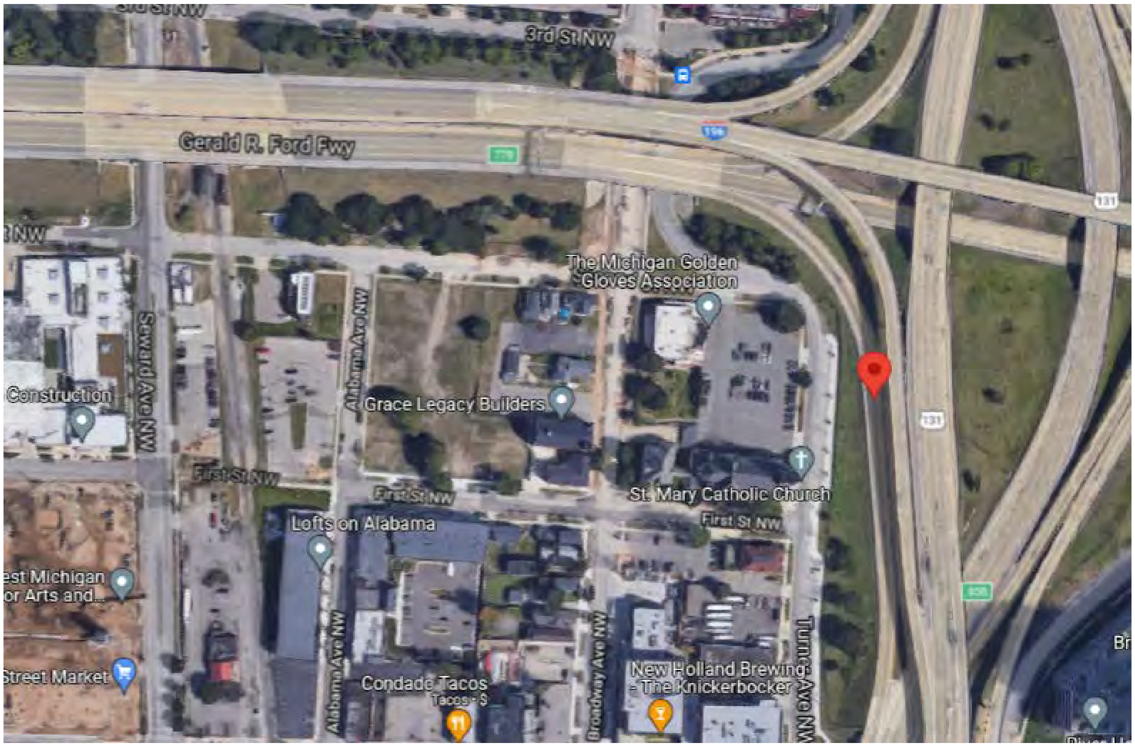
Rank 36: NB I-375 to WB I-75

Rank 37: WB I-94 to NB I-96

Rank 38: WB I-96 to SB I-69

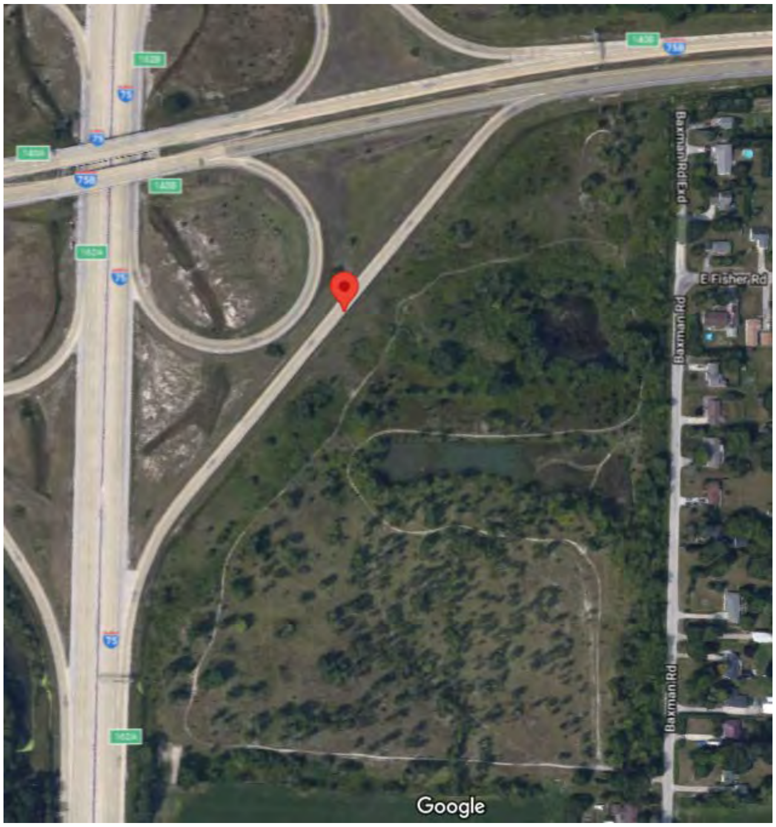


Rank 39: NB US-131 to EB I-96



Rank 40: EB I-196 to SB US-131

Rank 41: EB US-10 to NB I-75



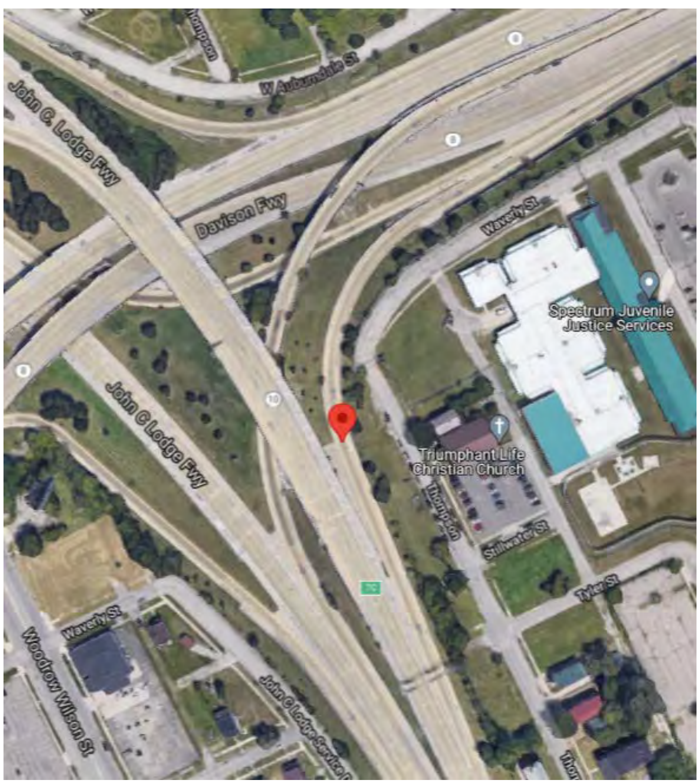
Rank 42: NB I-75 to EB US-10

Rank 43: EB I-94 to NB I-131

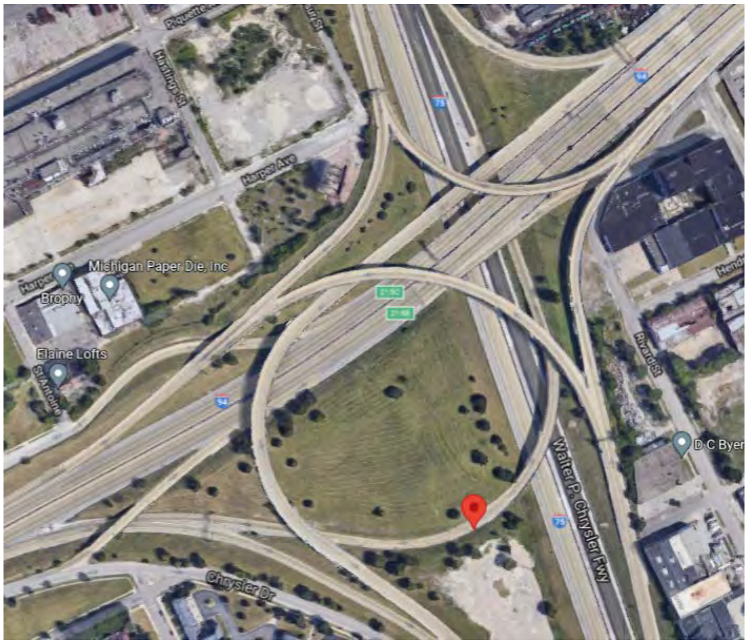
Rank 44: NB M-5 to SB I-275

Rank 45: EB I-94 to NB US-23

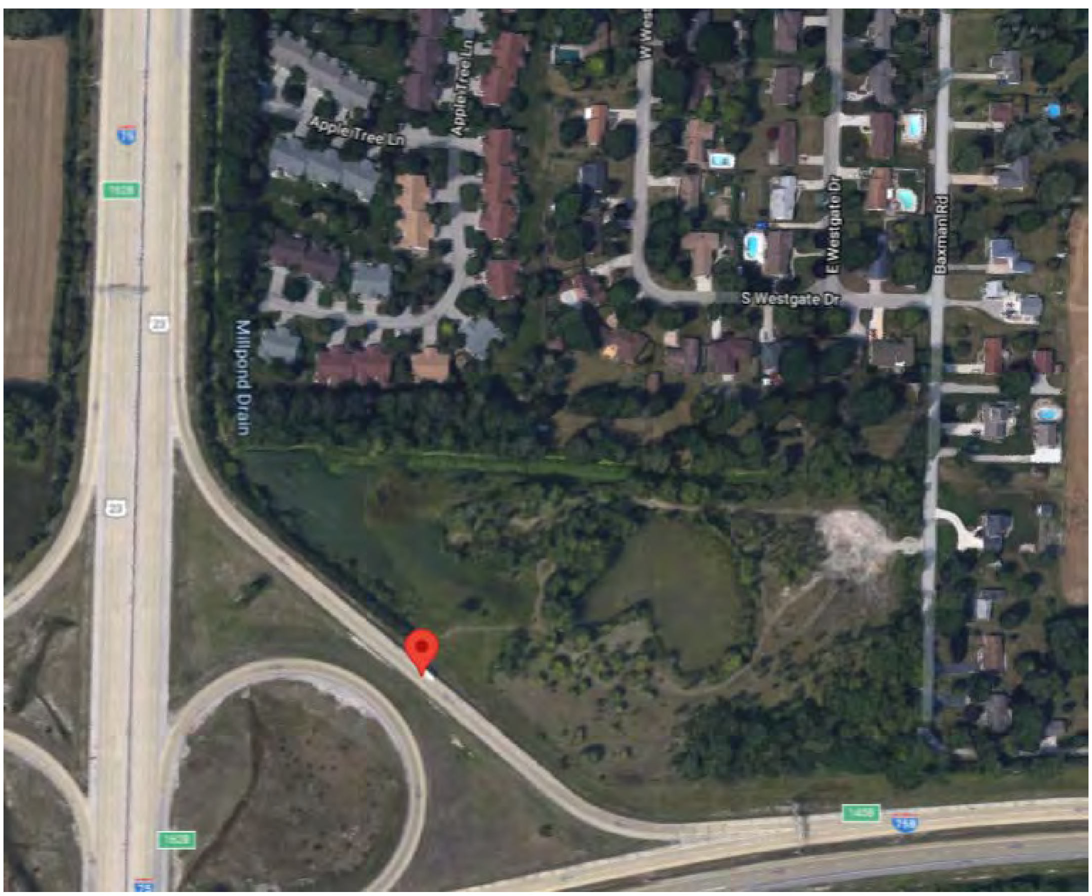
Rank 46: NB I-75 to WB US-10



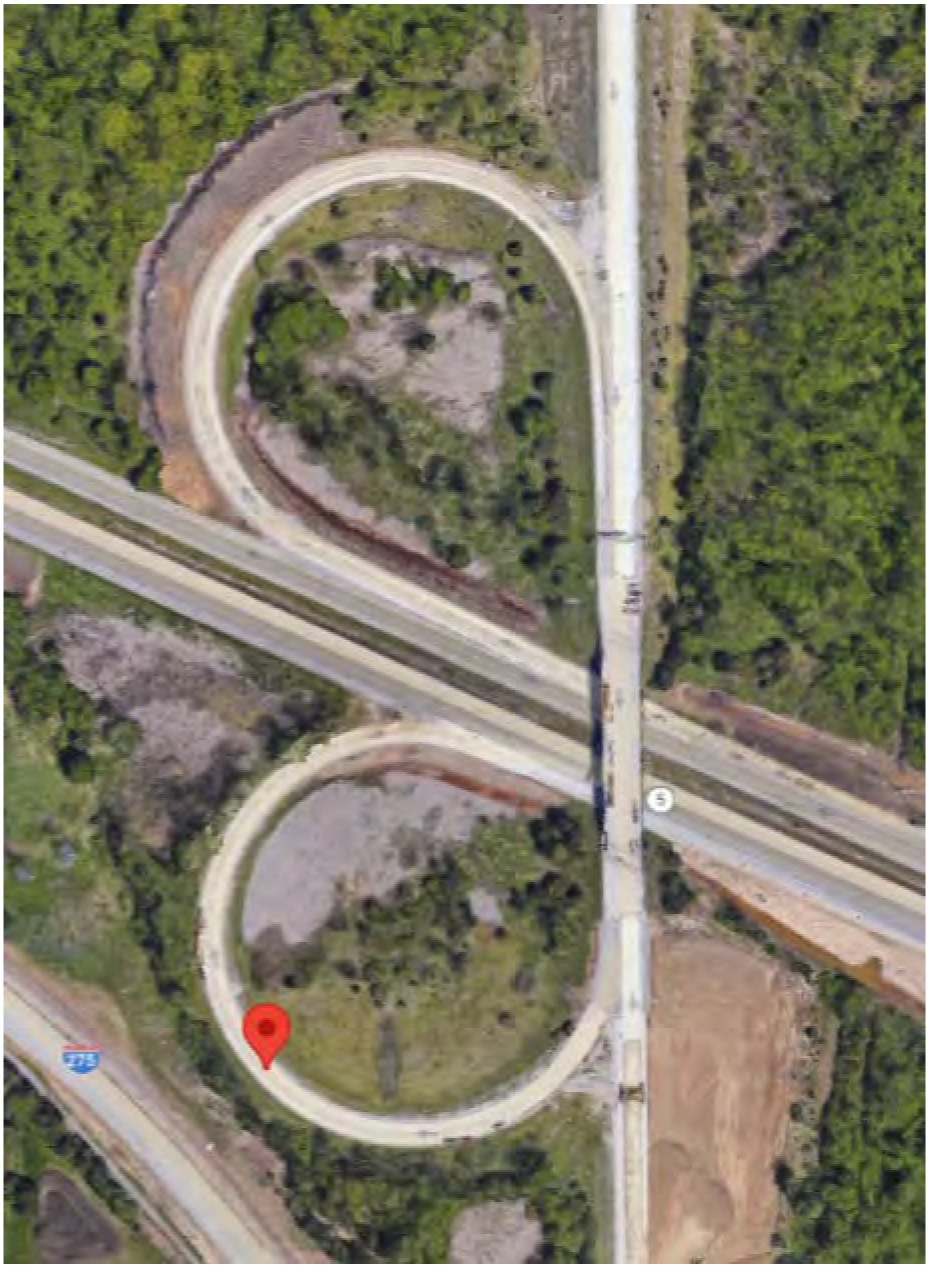
Rank 47: NB M-10 to EB M-8



Rank 48: EB I-94 to NB I-75



Rank 49: WB US-10 to NB I-75



Rank 50: WB I-696 to SB M-5